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EVOLUTION AND DYNAMICS OF GHIACCIAIO NORD DELLE LOCCE (VALLE ANZASCA, WESTERN ALPS) FROM 1854 TO THE PRESENT

ABSTRACT: MAZZA A., *Evolution and dynamics of Ghiacciaio Nord delle Locce (Valle Anzasca, Western Alps) from 1854 to the Present.* (IT ISSN 0391-9838, 1998).

Taking into consideration the available documentation (maps and literature), a tentative is made to outline the evolution of Ghiacciaio Nord delle Locce since 1854. The unit examined is the third largest glacier in the Ossola valleys (within the Italian border); however the glaciological information on it has been scarce and unsatisfactory until the investigations of VAW/ETH, following to the outburst of Lago delle Locce in 1979.

Some geographical information on the present Ghiacciaio Nord delle Locce, together with its glacial deposits, is first given. Then the map sources on which a part of the present investigation is based are carefully and critically reviewed, stressing on the problem of elevations.

As no precipitation data for the upper, glacierized Valle Anzasca are available, some data from the ENEL dams in neighbouring Valle Antrona are presented: they show that there is a continuous decrease of precipitations since 1978, causing the present glacier retreat after a short time span of steady state and even short glacier advance.

The available literature concerning Ghiacciaio Nord delle Locce is then critically reviewed and the investigations of the glaciologists of the VAW/ETH of Zurich, Switzerland, on Lago delle Locce and Ghiacciaio Nord delle Locce, are also recognized. Among the glaciological results of this research program, we underline the assessment of the dynamical behaviour of Ghiacciaio Nord delle Locce after sinking of Lago delle Locce level.

A final section describes the present terminal and confluence condition of the investigated glacier.

KEY WORDS: Tide-water glaciers, Glacier mechanics, Glacial deposits, Val Anzasca (Western Alps).

RIASSUNTO: MAZZA A., *Il Ghiacciaio Nord delle Locce (Valle Anzasca, Alpi Occidentali): evoluzione e dinamica del 1854 ad oggi.* (IT ISSN 0391-9838,

Facendo ricorso alla documentazione cartografica e bibliografica reperibile, si è tentata la ricostruzione dell'evoluzione del Ghiacciaio Nord delle Locce dal 1854 ad oggi. Si tratta del terzo maggior ghiacciaio nelle valli dell'Ossola (in territorio italiano), per il quale i dati propriamente glaciologici sono stati piuttosto scarsi e generici fino all'intervento del VAW/ETH, dopo la rotta del Lago delle Locce nel 1979.

Vengono dapprima forniti dati geografici sull'attuale Ghiacciaio Nord delle Locce, compresi i notevoli depositi glaciali. Quindi vengono passate in rassegna critica le sorgenti cartografiche sulle quali si basa parte del presente studio; si sottolinea in particolare il problema delle quote.

Non essendovi dati sulle precipitazioni per l'alta Valle Anzasca, si fa ricorso a quelli raccolti alle dighe dell'ENEL nella vicina Valle Antrona: a partire dal 1978, vi è un continuo decremento di precipitazioni, con effetti sui ghiacciai che segnano dapprima una certa stazionarietà, poi un leggero progresso, quindi una fase di ritiro tuttora in atto.

Segue un'elencazione critica della bibliografia esistente sul Ghiacciaio Nord delle Locce; particolare rilievo viene dato alle ricerche del VAW/ETH di Zurigo, al Lago e al Ghiacciaio delle Locce. Tra i risultati glaciologici di questa ricerca si sottolinea l'interpretazione dell'evoluzione dinamica del Ghiacciaio Nord delle Locce, dopo l'abbassamento artificiale del livello del Lago delle Locce.

Un capitolo finale descrive la condizione attuale del Ghiacciaio Nord delle Locce, per quanto concerne il settore frontale in acqua e la confluenza nel Ghiacciaio del Belvedere.

TERMINI CHIAVE: Ghiacciai terminanti in acqua, Meccanica dei ghiacciai, Depositi glaciali, Val Anzasca (Alpi Occidentali).

THE GHIACCIAIO NORD DELLE LOCCE

The Ghiacciaio Nord delle Locce [No. 321 of Catasto dei Ghiacciai Italiani (CGI, 1959-1962)] flows down from the top of Punta Grober, 3 498 m, according to the «Carta Tecnica Regionale del Piemonte» (1:10 000; in the following quoted as CTR), surveyed in 1991 by aerial photogrammetry; the terminus elevation of the tide-water glacier reach, as we will see later, is presently given with values between 2 209 and 2 223 m, according to the available map sources (IGM, CTR, LK and VAW/ETH sketches), as well as to our leveling. Concerning the spelling of the word «Locce», also quoted as «Loccie», we remark that the new CTR map uses the spelling «Locce», considering the local (Valle Anzasca) pronunciation; the meaning of this word, probably of celtic origin, is unknown. The spelling «Locce» had been already chosen for the map «Il Cervino e il Monte Rosa», in scale 1:50 000, published by the Touring Club Italiano (latest issue: 1981; see later).

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FIG. 1 - View on Ghiacciaio Nord delle Locce with its glacial deposits (1998).

The same spelling is also used in the report «Ricerche glaciologiche al Lago delle Locce, Macugnaga, Italia» (VAW/ETH, 1984) which will be later widely quoted.

The subject glacier has a North aspect; its UTM coordinates are 32TMR16208720, corresponding to the 2 700 m-contour of the IGM map 29 I N.E., Monte Rosa, 1:25 000, surveyed of 1934 and updated in 1968 by aerial photogrammetry. According to Catasto dei Ghiacciai Italiani (volume 2, Piemonte CGI, 1961), its surface area amounted to 2.38 km^2 in 1958; this value has not undergone large variations as, the in meantime, a phase of advance followed by one of retreat have taken place; both have been unfortunately only partially surveyed.

The following areal losses are recognized:

– area reduction of the short tongue on the left glacier bank, West from the point quoted 2 799 m IGM (top of a rock buttress); concerning this detail, both IGM and CTR maps are not updated; on the CTR map, in correspondence to the IGM point 2 799 m, an elevation of about 2 870 m can be guessed; no more exact value can be determined, as the contour interval of the CTR map in this area is but 50 m;

– total melting of the small tongue flowing from Ghiacciaio SW della Grober (Mazza, 1991); according to the documentation of Sacco (1930), the confluence was still existing in 1919;

– hence, it is likely that the present surface area of the investigated glacier amounts to 2.2 km^2.

The length of the glacier is presently about 2 350 m in horizontal projection from the top of Punta Grober, 3 498 m CTR, to the tide-water terminus (Lago delle Locce, 2 210 m CTR), in direction 350°. Different interpretations are also possible, as, actually, the terminus plunged into Lago delle Locce is but a side margin of the glacier, similar to that of Ghiacciaio del Miage (No. 213 of Catasto dei Ghiacciai Italiani, vol. 2, Piemonte; CGI, 1959-1962), where the ice is exposed at Lago del Miage.

However, if the length of the glacier is taken, as far as possible, from Punta Grober to the confluence into Ghiacciaio del Belvedere, according to the CTR map (1991) it amounts to about 2 550 m. The maximum width of the glacier, upvalley from Lago delle Locce, corresponding to the North-East extension, exceeds 1 km; downvalley from Lago delle Locce, where the glacier shows a vertical ice cliff, before joining Ghiacciaio del Belvedere, its width diminishes to 350-400 m (CTR map, Section 071070, Monte Rosa, 1991).

In topographic continuity with Ghiacciaio Nord delle Locce, there is a side extension with its direct snow supply, at the toe of the North-Eastern ridge of Punta Grober, having a long and indented terminus; it is likely that this glacier reach is dinamically independent. However, as our concept of glacier is based of the fundamental idea of «continuum», introduced in glaciology by De Marchi (1895) and later confirmed by all modern treatises on glaciology (Hutter, 1983; Paterson, 1994; Hooke, 1998), we do not think that this glacier section should be presently considered as an independent glacier.

The snow line, which is currently considered coincident with the equilibrium line, lies at about 2 750 m (± 50 m); this is just a guess, owing to the strongly crevassed surface of the glacier, which prevents a more definite value to be assessed.

THE GLACIAL DEPOSITS

To the complicated terminal reach and present morphology of Ghiacciaio Nord delle Locce corresponds a consequently articulated morphology of the glaciel deposits, mainly terminal moraines.

Starting from the right glacier Northeastern section - with its own snow feed, mainly from avalanche, we meet first its terminal moraines, well shown on the CTR map, with some short morainic ridges between which there is a water pool, at the elevation of 2305 m CTR;

– after the water pools, from a hill 2339 m CTR, begins the big terminal, arcuate moraine encompassing Lago delle Locce; the main ridge has some internal, lower and smaller morainic ridges, between which some narrow flat areas can be recognized;

– downvalley (North) from the main morainic ridge, Sacco (1930), in the map enclosed to its report, has drawn some older, external and arcuate (toward North) moraines, as down as Alpe Pedriola, 2065 m IGM, which, today, are difficult to identify;

– the main, above described morainic ridge, South of the artificial cut (see later), the gap elevation of which is 2217 m CTR, ends where Ghiacciaio delle Locce converges into Ghiacciaio del Belvedere, with its right, increasingly high side moraine;

– closed the to tide-water terminus, on the right glacier bank, an ice-cored moraine should be related to the advance of the glacier, probably begun before 1979 and ended in unknown time, as the measurements of VAW/ETH embrace a time span of only 4 years (1979-1983).

We shall later come back to glacial deposits, concerning their content in buried ice (Haeberli & Epifani, 1986).

AVAILABLE GLACIER MAPS

1854 - The first relatively reliable map, concerning the upper reach of Valle Anzasca and, hence the glaciers flowing down from the Northeastern slope of Monte Rosa, is the sheet No. XXIII of «Carta degli Stati Sardi in Terraferma», surveyed in 1854 and published in 1857.

The glaciers are but sketched; however on the left bank of Ghiacciaio Nord delle Locce one can identify the buttress separating the subject glacier from Ghiacciaio del Signal (No. 322 of Catasto dei Ghiacciai Italiani, CGI, 1959-1962), both flowing into Ghiacciaio del Belvedere (No. 325 of the same inventory). The uncertain drawing does not allow to assess, and even to guess, the glacier area, in order to make a comparison between the 1854 situation with that shown by the following maps; the same applies to the confluence of Ghiacciaio Nord delle Locce into Ghiacciaio del Belvedere.

1859 - The Swiss Topographic Service publishes the first edition of the sheet XXIII, section 5, Zermatt, of the Dufour map, in scale 1:50 000, surveyed by Bétemps, but the NE slope of Monte Rosa, Italian side, is blank.

1878 - The above map, Zermatt, is published in a revised edition, showing also the Italian glaciers of Valle Anzasca, but the drawing is somewhat uncertain so that the map is of little help for the present investigation; in any case no Lago delle Locce and no quotation of the topographic source for the Italian area are reported.

1884 - In this year the Italian Istituto Geografico Militare (in the following quoted as IGM) carried out the first surveying of the area, followed by the publication of the sheet 29 I, Monte Rosa, in scale 1:50 000. The map shows correctly the glaciers Nord delle Locce, Signal, Monte Rosa and Nordend, which build the common accumulation area of the tongue called Ghiacciaio del Belvedere. The map is based on a previous geodetic work but, concerning the glaciers, their uncertain margins and the lack of contours do not yet allow any metric comparison with the future maps; in any case the map represents a big progress with respect to «Carta degli Stati Sardi in Terraferma», and builds the very starting point to reconstruct the evolutions of Valle Anzasca glaciers. The geographic grid is shown but no reference datum is quoted on the map.

1919 - Sacco (1930) visits the area in August 24 and 25, 1919; he assesses the actual extension of the glaciers of Valle Anzasca. To his paper, published in 1930, practically an inventory of the Ossola past and present glaciers, he encloses a section of a map which should be a part, even if not quoted, of the IGM map 29 I, Monte Rosa, edition of 1884, revision of 1914, in scale 1:50 000. The area shown corresponds to that of the IGM map 29 I N.E., Monte Rosa, in scale 1:25 000, surveyed in 1934; unfortunately Sacco's map does not quote either the surveying or revision date, but only the year in which the geologist carried out his visit.

1934 - In this year the map 29 I N.E., Monte Rosa, has been surveyed by IGM by stereophotogrammetry; the result is a very accurate document of the glaciers as existing 65 years ago in Valle Anzasca; the drawing is clean; the terminus elevation of some glaciers is given and a good reproduction of the glacial deposits is also to be aknowledged. The geographic grid in drawn on the map by solid lines, but no quotation of the reference datum is given.

1941 - The Swiss Topographic Service publishes the first edition of the sheet 284, Mischabel, of Landeskarte der Schweiz (in following quoted as LK, with kilometric Swiss grid and build in Oblique Mercator Projection) in scale 1:50 000. In 1965 a revised edition of the same sheet has been released, with the remarks «Partial updating of 1965» and «Foreign areas according to the Italian map»; however the Italian map referred to, had been surveyed in 1934; there was at that time no Lago delle Locce. This means that some changes in the local topography had been taken into consideration, as Lago delle Locce is shown with the elevation of 2 223 m.

1957 - Within the activities of Comitato Glaciologico Italiano during the International Geophysical Year 1957 - 1958, the lower reach (tongue) of Ghiacciaio del Belvedere has been surveyed by terrestrial stereophotogrammetry (EIRA, 1963); the resulting map, in scale 1:5 000, shows also the confluence area of Ghiacciaio Nord delle Locce into

Ghiacciaio del Belvedere. The map, surveyed and drawn in a local grid, does not give any geodetic data to relate its grid to that of any official map (IGM, CTR, and LK).

1967 - The Swiss Topographic Survey publishes the first edition of the sheet 1348, Zermatt, of LK, in scale 1:25 000; the map is highly accurate and updated; in a following revision (1981), the elevation of Lago delle Locce and, hence, that of the tide-water terminus of Ghiacciaio Nord delle Locce, is quoted 2 215 m; and the latest revision of this map, published in 1988, shows the same elevation.

1970 - A new edition of the IGM map 29 I N.E., Monte Rosa, with revision based on aerial photogrammetry of 1968, is released. Of course it shows Lago delle Locce but with an elevation of 2 209 m, clearly too low before the outburst of Lago delle Locce, which made it necessary to carry out the artificial sinking of the lake level; some new details of the glacial deposits on the glacier right bank, corresponding to the Nordwestern reach of Ghiacciaio Nord delle Locce are also reported. The terminus elevations of the other glaciers, where quoted, are unaltered, notwithstanding the strong retreat which had taken place in the meantime. Only the new terminus position of Ghiacciaio del Belvedere has been recorded, but without elevation figure; the quality of the drawing is not so good as that of the 1934 edition. Its geographic grid is referred to the Bessel ellipsoid; the UTM grid is fully reported with solid lines and referred to the International (Hayford) ellipsoid; the reference datum is the ED50.

1979 - The Azienda Autonoma di Soggiorno of Macugnaga publishes the 2nd revision of the map «Macugnaga e il Monte Rosa». It is but a reduction in scale 1:35 000 of the IGM map; the updating, concerning the glaciers, is limited to the terminus of Ghiacciaio del Belvedere, to the confluence area of Ghiacciaio Nord delle Locce into Ghiacciaio del Belvedere and to Lago delle Locce; practically this map is a color edition of the IGM map «Monte Rosa» of 1934. For these reasons the map, easy to read in comparison to the IGM map, cannot be taken into consideration in studying the glaciers of Valle Anzasca. The elevation of Lago delle Locce is quoted in 2 209 m, of course in accordance with the IGM map; but, when the 2nd edition of this map had been published, the outburst of Lago delle Locce had not yet taken place. No geodetic data complete the map.

1981 - The Touring Club Italiano releases a revised edition of the map «Il Cervino e il Monte Rosa», in scale 1:50 000. It is a nice colour map, but the glaciers are shown as they were just after the latest local glacial maximum (about 1922-1925) and, hence, not updated except the drawing of Lago delle Locce, with rather uncertain banks; hence, even if easy to read, it has no interest for the glaciology of the area. The geographic grid ticks are given on the map margins.

1984 - Within the investigations carried out by the VAW/ETH (1984) following to the outburst of Lago delle Locce (July 19, 1979) a lot of surveying work has been carried out, with the following editing of some sketch maps and cross-sections of the terminal area of Ghiacciaio Nord delle Locce, and of its confluence into Ghiacciaio del Belvedere. The elevation of the water level of Lago delle Locce is given in values between 2 229.24 and 2 223.24 m. We come back later to this surveying work, basic to understand the glacier dynamics and the related glacial deposits. Concerning the elevation values, there is no data of the bench mark used for the local leveling; the values quoted are much higher that those of the official maps (IGM, CTR and also the Swiss LK). No geodetic data of this survey are given.

1991 - The Carta Tecnica Regionale del Piemonte is surveyed by aerial photogrammetry. The Ghiacciaio Nord delle Locce is shown on the maps No. 071070, Monte Rosa, and No. 071080, Punta delle Locce. This large-scale map, 1:10 000, represents a great improvement with respect to the IGM national map; the scale could make it highly interesting for the local glaciology, but the dashed contours on glaciers, and, frequently, with interval of only 50 m instead of 10 m, makes it sometimes difficult to read; of course this impairs its value for glaciological purposes. In any case the CTR is one of the two reliable documents (the other is LK map) today available and showing the correct size of the present glaciers in Ossola valleys. Some elevation figures have been duly corrected, with reference to the IGM maps, and are in good agreement with those surveyed and calculated by the present writer. The grid is in accordance with the Italian Gauss-Boaga projection, but the ticks of the UTM grid are also shown at the map margins. The geographic grid is referred to the ED50.

THE PROBLEM OF ALTIMETRY

After the map listing and comments, we cannot avoid to enhance a troublesome problem for every glaciological investigations, and only for those, of the whole mapping in Ossola region: the problem of elevations. It is surprising the different values, for the same spots, given on official Italian IGM maps, on Swiss LK map, on VAW/ETH sketches and on CTR regional maps concerning Lago delle Locce and, hence, the tide-water terminus of Ghiacciaio Nord delle Locce, even if, presently (1997) only about 50 m long, but still showing some calving.

The elevation figures are the following:

– water level of Lago delle Locce:

IGM (1970): 2 209 m (before the water outburst and the following moraine cut, to lay a large-diameter tube, to hinder the water level of Lago delle Locce to rise to the former value;
LK (1967, 1977, 1988): 2 215 m (before the moraine cutting;
VAW/ETH (1984): 2 229 m (always before the above intervention);
CTR (1991): about 2 210 m (the value is not shown but easily got from the map contours); the elevation of the artificial moraine gap is 2 217 m CTR;
present writer's leveling (1994-1997): 2 210 m.

– point 2 257 m IGM, moraine top North of the cut area

This morainic hill, separated from the remaining terminal moraine after the gap cutting, has been always used as a bench mark and a photographic station from the beginning of the present writer's investigation in this area; its elevation is quoted 2 278.72 m by the VAW/ETH; the moraine top is not quoted on the sheet No. 1 348, Zermatt, of the LK (revisions of 1977 and of 1988) but, from the contour interval, its altitude can be estimated just over 2 260 m.

The CGI map (1957) in scale 1:5 000, gives an elevation of 2 260.9 m of a point which could correspond to the IGM point quoted of 2 257 m, but, as this map had been surveyed and drawn in a local reference system, there is no possibility of relating the planimetric coordinates of this point to those of the official maps (IGM and CTR) for the same point.

The leveling of the present writer, carried out many times between 1994 and 1997, both from Belvedere (1 945 m IGM) and from the subject moraine top, 2 257 m IGM (hence leveling from both ends of the base-line) gives, for the moraine top, an elevation of 2 262 m; on this base, the elevation of Lago delle Locce in the Summer of 1997 could be evaluated lower than 2 210 m.

For the same morainic hill the CTR gives an elevation of 2 265 m; and the same value can be obtained from our trigonometric leveling, if, as altitude of the Belvedere moraine top, used as bench mark, the CTR value of 1 948 m is assumed instead of the IGM value (1 945 m).

– main terminal moraine top, 2 271 m IGM (2 272 m CTR)

The two official maps (IGM and CTR) are in good agreement concerning the maximum altitude of the terminal moraine of Ghiacciaio delle Locce; the elevation given by VAW/ETH is 2 287.9 m; a gap in the terminal moraine is quoted 2 250.6 by VAW/ETH; the estimated elevation on CTR is 2 235 m, i.e. a difference of level of about 37 m, same as the difference of the two elevation values of VAW/ETH.

– level difference between moraine top (2 257 m IGM; 2 265 m CTR) and Lago delle Locce:

VAW/ETH measurements: about 54 m;
IGM maps: 48 m (before level sinking of Lago delle Locce);
present writer's measurement by an electronic altimeter (resolution: 1 m): 56 m ± 1;
present writer's leveling from the moraine top (2 265 m, CTR) gives a level difference of 55 m, in good agreement with the altimeter value as well as with the elevation of Lago delle Locce as estimated from the CTR map, and, in any case, close to the value obtained by VAW/ETH.

Within the surveying work carried out at Ghiacciaio Nord delle Locce, and as check for the elevation values of the surveyed area, the present writer has measured the altitude of Colle delle Locce (based on the moraine top, 2 257 m IGM); even considering the measurement error associated with the leveling, the elevation of Colle delle Locce resulted to be 3 322 m (± 2 m), that is about 11 m less than IGM value. But, once again, assuming the moraine top at 2 265 m (CTR), the elevation of Colle delle Locce results as 3 330 m, in very good agreement with CTR value, 3 331 m. The IGM map of 1884 gave a value of 3 353 m.

CONFLUENCE OF GHIACCIAIO NORD DELLE LOCCE INTO GHIACCIAIO DEL BELVEDERE

A topic of great dynamical interest for Ghiacciaio Nord delle Locce is its confluence, at elevation between 2 280 m (left glacier bank) and 2 200 m (right bank), into Ghiacciaio del Belvedere. The elevations are but estimated on the base of CTR map, being of course somewhat arbitrary to establish a contact line where the two ice streams meet without merging as the ice flow in glaciers is laminar, as stated by the literature on this subject (Paterson, 1994; Gudmundsson, 1994). The continuity principle would even lead us to consider the confluent glaciers as a single unit.

The tension (either compressing or stretching) conditions of the confluence area deserve a physical investigation, for which one needs data now lacking. The application of the Finite Element Analysis (FEM) to the confluence area of Nord delle Locce, Signal and Belvedere glaciers could be of great interest, but, to produce the necessary grid, one needs data on thickness, velocity and its variation in space (strain rate tensor) and time (acceleration); all these data could be gathered from repeated aerial photogrammetric surveying, at regular and short (say 4-6 month) intervals.

A very nice example on this subject is the application of a three-dimensional FEM with display of the graphic results on a computer screen, carried out at the Storglaciären in Kebnekaise, Sweden (Hanson, 1995), and based essentially on velocity measurements at the glacier surface and depth, taking into consideration the temperature distribution and the water flow from ice melting.

The same applies to the compilation of a Digital Elevation Model (DEM), combined with the FEM; this could be prepared on the base of existing maps but, although there are four map sources for the area, of different dates, they can be hardly used for this purpose as different in scale, drawing quality, projection, reference datum and coordinates, namely:
– IGM maps, 1934 and 1970, in scale 1:25 000: the contours on glaciers are drawn with interval of 100 m; the reference ellipsoid is the Bessel-one for the geographic grid, and the Hayford-one for the UTM grid (this last only in 1970 edition);
– CGI map, 1957 (EIRA, 1963), in scale 1:5 000, only for the confluence area of Nord delle Locce and Belvedere glaciers; as already said, there is no geodetic data to relate the map to the official (IGM and CTR) documents;
– LK, 1982, in scale 1:25 000; grid according to the Swiss system; Mercator oblique projection;
– CTR, 1991, in scale 1:10 000: the contour on glaciers are dashed and the interval is sometime 10 m, sometimes 50 m. Grid according to Gauss-Boaga Italian projection; the reference datum is the ED50.

Conditions of compressive flow can cause, as assessed by VAW/ETH (1984) and by Gudmundsson (1994), an in-

crease in glacier surface elevation. In fact, with reference to CGI map (1:5 000, 1957) the surface of Ghiacciaio Nord delle Locce, according to VAW/ETH, has undergone an elevation increase of 40-50 m, but this should be related also either (1) to a kinematic wave travelling along the glacier at that time or (2), to the values of VAW/ETH leveling (1984), higher than the IGM and even LK values for the same area, or to both causes.

PRECIPITATION IN THE UPPER VALLE ANZASCA

For the upper reaches of Valle Anzasca we miss a station collecting meteorological data, mainly precipitations and temperatures, closed to the glacierized area. Some data published by ISTAT for Borca station (1 194 m) are discontinuous and taken at an altitude not representative of the mean glaciers elevation; even worse, for our research, are the data collected at Bannio-Anzino (687 m) station, in the lower Valle Anzasca. Hence we use some data taken at ENEL Cingino (2 255 m) and of Camposecco (2 327 m) dams, in the neighbouring Valle Antrona, reasonably, but not absolutely, representative of the actual meteorological condition in the upper Valle Anzasca, and, of course, valid only for the time span considered (1972-1986).

In tab. 1 one can remark that, after some hydrographic years with precipitations exceeding the average value (1972-1981 or 1983, depending on the meteorological data set choosen), in 1984 a sudden decrease of Winter precipitations took place. Later the Winter seasons of 1986/87 to 1990/91 have been characterized by still lower precipitation values; the effect on Ghiacciaio Nord delle Locce can be seen starting, as far as known, from 1979: first there was an advance of 26 m (VAW/ETH), then, after a time span during which no measurement had been made (1983-1992), between 1992 and 1997 a side-terminal retreat of 7 m has been measured, but more meaningful, a reduction on the terminal slope height from 31 m to 20 m, i.e. –11 m in 4 years has been recorded.

TABLE 1 - Precipitation data at ENEL Cingino (2 255 m) and Camposecco (2 327 m) dams

Average	CINGINO 1025 mm (12 years) mm deviation	CAMPOSECCO 1049 mm (13 years) mm deviation
1972/73	1198 (+173)	1055 (+6)
1973/74	1352 (+227)	1049 (=)
1974/75	1401 (+376)	1396 (+347)
1975/76	1149 (+124)	834 (–215)
1976/77	2341 (+1316)	1890 (+841)
1977/78	1272 (+247)	1249 (+200)
1978/79	826 (–199)	874 (–175)
1079/80	1302 (+277)	1115 (+66)
1980/81	1507 (+482)	1339 (+290)
1981/82	889 (–136)	1173 (+124)
1982/83	—	1213 (+164)
1983/84	—	—
1984/85	498 (–527)	632 (–417)
1985/86	621 (–404)	870 (–179)

But the terminal glacier fluctuation must be partially related to the change of glacier dynamics, as Ghiacciaio Nord delle Locce, formerly mainly of tide-water and calving type (see fig. 2), was gradually transforming, after Lago delle Locce level sinking, in a grounded type, as we will later see. Paterson (1994, p. 3) writes: «That glaciers advance and retreat in response to change in climate is a common knowledge, but the relationship is more complex than usually assumed; ... an understanding of the meteorological problems is not enough; the flow characteristics of each particular glacier determine how its reacts to a climate change».

THE TERMINUS FLUCTUATIONS OF GHIACCIAIO NORD DELLE LOCCE

1915 - The first known visit of this dynamically highly interesting glacier is due to Monterin (1918). In 1915 he set a reference mark 38.5 m from the terminus, in a position which cannot be recognized today, as no coordinate and elevation data had been communicated.

We take this opportunity to enhance that the glacier terminus fluctuation data, referred to marks with unknown coordinates and elevation, as not connected by surveying procedures to recognized IGM (or CTR) fixed points, and the elevation of which is generally determined by altimeters, show later uncertainties in interpretation, specially after long time spans, with the consequence that long data sets loose a good deal of their value. This happened in Valle Anzasca at Ghiacciaio del Belvedere (Mazza, in print).

Today the problem coordinate and altitude determination can be easily solved by GPS surveying with two premises:

a) more accessible prices for the dual-frequency P-code GPS receivers, presently highly expensive and, hence, outside the financial possibility of single surveyors;

b) more accurate C/A-code receivers, suitable for the task only when and if the S/A (selective availability, the error function which impairs the accuracy of the small one-frequency GPS receivers) will be switched off, or if the GPS-GLONASS (the Russian satellite system) single-frequency receivers become available at reasonable prices.

Monterin's outline of the glacier is generic and does not help us to reconstruct the glacier terminus position with respect to its terminal deposits, the most typical of which is the terminal arcuate moraine, with maximum elevation of 2 271 m IGM (2 272 m CTR). No picture can help us in establishing the glacier limits in 1915: it probably reached the terminal moraine, but not at its maximum elevation as the internal main moraine slope is interrupted by some other lower moraines, at different levels. No data on the snow line are given in Monterin's report.

1919 - Sacco (1930) visits the subject glacier on August 24 and 25 and gives some very interesting information on it. He writes, among other observations: «Such terminus, expanding (1919), was going to fill a lake-shaped depression left by the former glacier retreat». This information is highly interesting, but the lake is not shown on the en-

closed map the date of which - August 1919 as already written - is that of Sacco's visit and not that of the IGM survey (probably 1884); both Monterin and Sacco do not say if some survey has been done during their visits.

1934 - Luzzatto (1935) visits the glacier on August 27, 1934; he looks for Monterin's reference mark which he does not find and places his own mark 61 m from the glacier terminus, with reference to the moraine top 2 257 m (IGM) high. Luzzatto does not indicate where he could get this elevation value which is not given on the 1934 edition of IGM map 29 I N.E., Monte Rosa, but which is reported on the 1970 revision of the same map.

His remark is however important, as it enables us to approximately assess where the glacier terminus was in 1934 (about –150 m from Monterin's reference mark). Luzzatto's glacier description is very accurate and in close agreement with the drawing of IGM map of 1934. No data of snow line are given in Luzzatto's report.

As already written, the survey of the IGM map 29 I N.E., Monte Rosa, has been carried out in 1934; the map shows quite neatly the terminal area of Ghiacciaio Nord delle Locce, but its elevation can be read only with uncertainty: probably close to 2 240 m. Lago delle Locce was not yet established (or reestablished according to Sacco, 1930).

1940 - Vanni (1941) visits the glacier; he does not find Luttazzo's reference mark; he established new marks and, which is more important, he outlines the formation of Lago delle Locce, saying «... it is going to take place at both sides of the glacier tongue, between ice and the moraine ridges, which last cover quite big masses of dead ice...». No data on elevations (terminus, water level, snow line, etc.) are given. Making a comparison between Sacco's (1930) and Vanni's (1940) reports, it is evident that Ghiacciaio Nord delle Locce, in the same way of Ghiacciaio del Belvedere, had undergone an advance (till 1921-1922?) and later a retreat, but no metric data had been collected.

1941 - Pracchi (1942) visits the subject glacier, confirming the expansion of Lago delle Locce, as consequence of the glacier retreat. He finds some reference marks which allow him to assess a terminus retreat of 15.5 m from 1940. He confirms that there is some ice buried under the moraines; its presence will be later detected by geophysical sounding (VAW/ETH; Haeberli & Epifani, 1986).

1948 - Aliverti (1950), after visiting Ghiacciaio Nord delle Locce in 1948, makes some remarks on the confluence of the subject glacier into Ghiacciaio del Belvedere; a picture (No. 5 of her paper) shows the glacier terminus retreated in a position not too much different from the present-one, plunged into Lago delle Locce, with a low, calving terminus. No metric data, once again, are given (elevations, coordinates, snow-line, etc.).

1953 - Within the yearly glaciological surveys of Comitato Glaciologico Italiano (CGI), Demaria (1953) just writes that the terminus is in steady state, with reference to the 1952 position.

1961 - The Catasto dei Ghiacciai Italiani (CGI, 1959-62), concerning Ghiacciaio Nord delle Locce, says: «... Its terminus spreads on a morainic plain, occupied by a small lake. On its left bank, it merges with the big Ghiacciaio del Belvedere ...». In a picture, dated 1937, the terminus looks like to be retreated, in respect with Lago delle Locce. Further it says: «... Presently (1958) [the glacier terminus] lies some tens of meters from the small lake». The tide-water terminus elevation is given in 2 350 m, and, if true, it would support the hypotesis of a remarkable retreat, of 350-400 m, but only on the glacier right side, which is questionable; the glacier length is given as 2 200 m, i.e. about 150 m less than the present value. Probably the right terminal reach of the glacier tongue, consisting of stagnant or moraine-covered ice, as been interpreted as the «morainic plain» quoted by Catasto dei Ghiacciai Italiani, vol. 2, Piemonte (CGI, 1961).

1962 - During a visit on September 17, 1962, the present writer could assess the actual position of the glacier terminus, plunged in Lago delle Locce, showing a low, vertical ice cliff. In comparison with the remarks of Catasto dei Ghiacciai Italiani (CGI, 1959-1962, based on data of 1958) it could seem to us that a strong advance of Ghiacciaio Nord delle Locce had taken place.

Considering that between 1958 and 1962 the most alpine glaciers were retreating, and, surely, the two glaciers of Valle Anzasca at that time measured - Nordend and Belvedere - it is hardly possible to suppose a remarkable advance of Ghiacciaio Nord delle Locce during this time span; on this subject, two possible suggestions can be done:
a) either the «morainic plain» reported by Catasto dei Ghiacciai Italiani (CGI, 1959-62) is nothing else but the lower glacier tongue consisting of stagnant ice on which the dynamic terminus is lying, as it could be drawn from the IGM map, but surveyed in 1934; hence, this suggestion should be discarded;
b) or the terminus position as described by Catasto dei Ghiacciai Italiani (CGI, 1959-1962) could result from a low level of Lago delle Locce, with emersion of ground and following modification of the terminus shape; but in this case the terminus elevation given by the Italian Glacier Inventory, 2 350 m, is to be rejected; the subject glacier has never had such terminus elevation as confluent, at least from last century (see «Carta degli Stati Sardi in Terraferma») into Ghiacciaio del Belvedere, at an average elevation of 2 200 m, as stated also by the same Italian inventory.

1975 - Between 1975 and 1988 the subject glacier has been observed by Tettamanti (1976, 1980, 1981, 1982, 1984, 1985, 1987, 1988 and 1990) who took some pictures; his reports are only qualitative. The terminus elevation is given in 2 100 m (confluence into Ghiacciaio del Belvedere), but the values of 2 212 m in 1975 (before the outburst of Lago delle Locce) and 2 240 m (after the above event) are quite questionable; the value of 2 240 m after the frontal moraine cut, to keep constant the level of Lago delle Locce is, of course, wrong. Tettamanti gives some information on the outburst of Lago delle Locce and on the work carried out by VAW/ETH.

1979 - On July 19, 1979, the water outburst from Lago delle Locce through Ghiacciaio del Belvedere takes place; it caused the failure of the right moraine of Ghiacciaio del Belvedere, left (West) from Alpe Pedriola, 2 065 m IGM,

FIG. 2 - Tide-water terminus of Ghiacciaio Nord delle Locce in 1981, just after the level sinking of Lago delle Locce.

at the same spot where a similar event had already occurred in 1916 (see picture in Sacco, 1930), and, probably, in 1904 (Sacco, 1930). But a picture of Vittorio Sella, taken from Monte Moro in 1895 (Sacco, 1930), already shows a gap along the right morainic ridge of Ghiacciaio del Belvedere, corresponding to the investigated spot.

1981 - During a visit on August 18, the present writer, remarks that the glacier terminus is in a position not too much different from the present-one (1997), but with 30 m-high ice cliff, showing deformation structures, already present in his picture of 1962.

DYNAMICS OF GHIACCIAIO NORD DELLE LOCCE AS ASSESSED BY VAW/ETH SURVEYING

The outburst of Lago delle Locce of July 19, 1979, with some destructive effects on the Belvedere chairlift, set the problem of keeping under control the water level of the subject lake, and, possibly, at a lower elevation. A first tentative has been made in 1979 installing a large-diameter tube, close to the right bank of Ghiacciaio delle Locce, between the tide-water terminus and the confluence into Ghiacciaio del Belvedere.

The advance of Ghiacciaio Nord delle Locce, as response to the better snow feed, specially between 1972 and 1978, was already operating in 1979.

As a complementary addition to the precipitation data previously given, we would like to mention the increase in ice thickness at Colle Grifetti (Haeberli & alii, 1988) which proves and confirms the better accumulation conditions, taken place between 1972 and 1978 on the glaciers of Ossola valleys (Mazza & Mercalli, 1992), before the recorded event. For the time span 1979-1982 VAW/EHT gives the following terminus fluctuations.

TABLE 2 - Terminus fluctuations of Ghiacciaio Nord delle Locce 1979-1983

24.08.79 - 11.08.80	+ 6.25 m
11.08.80 - 27.07.81	+ 5.00 m
27.07.81 - 14.10.81	+ 4.00 m
14.10.81 - 14.10.82	+ 1.75 m
14.10.82 - 19.10.83	+ 12.50 m
Totale advance 1979-1983	+ 29.5 m

Unfortunately we do not have any data on the very beginning of the terminus advance of Ghiacciaio Nord delle Locce; the recorded advance, starting from 1979, partially overrode the tube installed closed to the glacier right bank and damaged it. Hence, after a geophysical sounding, it has been decided to cut the moraine between the points 2 257 m IGM, and 2 271 m IGM, a saddle where no buried ice had been detected.

Here we are not interested in the work done but in the surveys carried out on Ghiacciaio Nord delle Locce and Ghiacciaio del Belvedere, as well on the related glacial deposits (mainly terminal moraine).

On the base of aerial photogrammetry, the Swiss researchers (VAW/ETH, 1984) assessed an increase in elevation of 50 m in correspondence to the fix point 2 275 m

LK (2 286 m of IGM map); but this increase, as already said, may be due in part to the different bench mark elevation for the local Swiss leveling.

In Autumn 1983 ten stakes had been installed, five close to the tide-water terminus of Ghiacciaio Nord delle Locce and five at its confluence into Ghiacciaio del Belvedere. The results of the measurements at the stakes are highly interesting as they allow us to state:

a) the glacier velocities close to the tide-water terminus are relatively high (between 15 and 34 m a^{-1}, against a value of the 5-7 m a^{-1}, if calculated from the average thickness of the glacier, according to Paterson (1994, p. 252); the thickness has been measured by the Swiss surveyors, assessing, by radar sounding, the glacier bed shape. The high velocities recorded depend on the glacier ending, in part, in water, hence showing a behaviour in accordance with the literature on the tide-water glaciers (Brown, Meier & Post, 1982; Mazza & Mercalli, 1992);

b) in the terminal reach of the subject glacier, the flow is in part compressive and in part extending, as it is to be expected from the tension condition of Ghiacciaio Nord delle Locce, partially ending in water and partially confluent into Ghiacciaio del Belvedere. Where the glacier ends in water, there is low basal ice/bed friction and, hence, a strong reduction of the basal shear stress, owing to the water interface; here we would like to remember that the strain rate is related to shear stress according to the following classical equation (Paterson, 1994):

$$de/dt = [A]\ \tau_b^n \qquad (1)$$

where:
e = strain;
de/dt = strain rate;
A = parameter of tensor character, which takes into account the response of ice to the stresses in elastic and viscoplastic field, depending on its mechanical properties, which, in turn, depend on temperature, grain size, meltwater at the grain boundaries, stress type (compressive or extending), and stress rate;
τ_b = basal shear stress (2nd stress deviator invariant);
n = exponent generally set = 3.

The above quoted equation is but a simplified one; a more rigorous expression, better corresponding to the physical reality of glaciers, can be found in any modern treatise of glaciology (Hutter, 1983; Paterson, 1994; Hooke, 1998).

The numerical calculation of the basal shear stress in glaciers can be carried out by the following empirical formula:

$$\tau_b = r\ g\ f\ h\ \sin(\alpha) \qquad (2)$$

where:
τ_b = basal shear stress;
r = ice specific gravity, about 0,910;
g = gravity acceleration (9.81 m/sec^2);
f = shape factor of the glacier bed (0.6 - 0.8 for valley glaciers);
α = average glacier slope;
h = average glacier thickness.
(the last two values are to be chosen in single cases.)

The value of the basal shear stress has been calculated by the Swiss researchers in about 1 to 1.5 bar (100-150 hPa), in accordance with the average values reported by the glaciological literature (Paterson, 1994; Hooke, 1998).

From the measured surface velocity values (15-34 m a^{-1}), quite high considering the assessed glacier thickness (60 to 70 m in the glacier terminal area), and even taking into consideration the bed water interface already discussed, the hypothesis can be made that a kinematic wave (Paterson, 1994; Hooke, 1998) was arriving at the glacier terminus. The event is somewhat confirmed by the surface velocity, also quite high (about 50 m a^{-1}, with a maximum of 105 m a^{-1}), measured on Ghiacciaio del Belvedere.

A response time of Ghiacciaio Nord delle Locce to the climate fluctuations, mainly precipitation, based on available data and on a present writer's model (Mazza, 1996), should be about 4-5 years, in accordance with the values given by the Swiss researchers; of course this value does not take into consideration the diffusion of the kinematic wave (Paterson, 1994; Hooke, 1998) which makes the response time much longer or even annihilate it.

Very significant are also the radar soundings already quoted, carried out on the glacier (assessing the ice thickness, which resulted, as already said, in 60-70 m in the glacier middle) and on the glacial deposits encompassing Lago delle Locce: even if carried out for practical reasons (looking for an area without buried ice along the terminal moraine ridge, to cut it and install a tube to keep constant the level of Lago delle Locce), the sounding results have had a big impact on the knowledge of the glacier dynamics (Haeberli & Epifani, 1986). The results confirm Vannis's observation of 1940 (Vanni, 1941).

As conclusion for their investigations, the Swiss researchers (VAW/ETH) presented the following mathematical model, which tries to forecast the future evolution of Ghiacciaio Nord delle Locce:

$$\sum_{t=0}^{t=I} \Delta x = \frac{e\,Q(t) - b \sum_{t=0}^{t=I-1} \Delta x}{h_f} \qquad (3)$$

where:
b = ablation;
h_f = terminus height;
e = constant;
Q = glacier flux;
x = glacier length;
t = time.

Three possible alternatives have been calculated:
1) the glacier conditions remain as assessed in 1983, i.e. Q(t) = q(1983) = cost;
2) the present trend goes on, i.e. dQ/dt = +0.28 a^{-1};
3) the present trend is suddenly inverted, i.e. dQ/dt = –0.28 a^{-1}.

This last conditions, which was most likely to happen, considering the general glacier retreat, is now confirmed by present writer's measurements (Mazza, in print) in 1997.