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RETREAT OF AURINE AND PUSTERESI ALPS GLACIERS IN THE LAST DECADES FROM A LANDSAT TM IMAGE ON 2003 AND PREVIOUS RESULTS

ABSTRACT: RAMPINI A., ROTA NODARI F., SERANDREI BARBERO R. & BRIVIO P.A., *Retreat of Aurine and Pusteresi Alps Glaciers in the last decades from a Landsat TM image on 2003 and previous results.* (IT ISSN 1724-4757, 2005).

This paper presents the results obtained from the analysis of one recent Landsat TM image for the study of the status of some glaciers on Eastern Italian Alps. Then these results are compared with a set of multitemporal Landsat images from the Eighties. A fuzzy set based classification technique permitted to quantify snow and exposed ice extents in glaciated areas. Integration with topographic information allowed to derive the elevation of glacier terminus, although the result is overestimated due to some problems with digital elevation data and frontal debris coverage. A comparison of front altitude changes data derived from satellite image processing with elevation measured during field surveys supports the knowledge of the size of glacier reduction of the last decades. On Aurine and Pusteresi Alps glaciers, the changes in the last twenty years result to be a reduction corresponding to the 40% of the glaciated surface in the '80s, but a lot of the glaciers are now characterized by a new extent debris coverage in the frontal zones.

KEY WORDS: Glacier retreat, Aurine and Pusteresi Alps, Remote Sensing, Debris cover.

RIASSUNTO: RAMPINI A., ROTA NODARI F., SERANDREI BARBERO R. & BRIVIO P.A., *Il ritiro dei ghiacciai delle Alpi Aurine e Pusteresi delle ultime decadi dedotto da un'immagine Landsat TM del 2003 e da risultati precedenti.* (IT ISSN 1724-4757, 2005).

Questo articolo presenta i risultati ottenuti dall'analisi di una recente immagine Landsat TM per lo studio dello stato di alcuni ghiacciai delle Alpi Italiane Orientali. Tali risultati sono stati poi confrontati con un set multitemporale di immagini Landsat degli anni '80. Una classificazione di tipo *fuzzy* ha permesso di quantificare le estensioni di neve e ghiaccio scoperto relative alle aree glacializzate. L'integrazione con le informazioni topografiche ancillari ha permesso di ottenere la quota delle fronti, anche se il risultato è soggetto sovrastima per problematiche legate al modello di elevazione del terreno e alla recente copertura detritica delle fronti. La riduzione areale dei ghiacciai in esame nelle ultime decadi viene confermata dal confronto effettuato tra le variazioni di quota stimate da satellite e le misure effettuate durante le campagne al suolo. Negli ultimi vent'anni, le Alpi Aurine e Pusteresi hanno subito una apparente riduzione delle superfici glacializzate del 40% rispetto al valore del 1980, ma molti dei ghiacciai considerati sono caratterizzati da una recente copertura detritica che maschera interamente larghi tratti del settore frontale.

TERMINI CHIAVE: Ritiro dei ghiacciai, Alpi Aurine e Pusteresi, Telerilevamento, Copertura detritica.

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INTRODUCTION

Mountain glaciers are highly sensitive, large scale and representative indicators for the energy balance at the earth's surface in high altitude areas. Glacier signals from mountain areas are key element of early detection strategies for dealing with possible man-induced climate change (Becker & Bugmann, 2001). Except for too short advances in the Twenties and in the Seventies of the last century, glaciers in the Alps are retreating since their last Holocene maximum extent (around 1860). Mountain glaciers are linked to the atmosphere through mass and energy exchange which determine accumulation (gain of mass) and ablation (loss of mass) throughout the year (Paul, 2002). Thus, glaciers integrate atmospheric conditions over some years and are able to convert a gain of snow of a few metres thick to a change in length. Therefore, glaciers are considered as sensitive climatic indicators (Haeberli, 1995).

In order to better understand changes, world glaciology and global change communities, need a long term monitoring program, aimed at establishing a uniform baseline of the status and dynamics of the world's glaciers. This long term monitoring program requires spatially based information, which are intrinsically geographically homogeneous. The availability of long time series of high resolution satellite imagery as Landsat and SPOT is of invaluable importance in building a consistent database.

MATERIALS AND METHODS

The study area is located in the Eastern Italian Alps and includes Pusteresi and Aurine Groups. In the fig. 1, the study area on the Italian Glaciological Committee map, with the code for every glacier located in the area, is shown.

Pusteresi and Aurine glaciers have been chosen because of the availability of long historical recordings both on field and remotely sensed data: these glaciers have been studied for one hundred years by Italian and foreign glaciologists. In this framework, environmental analysis on the basis of hydrological data and the historical studies of snout variations may be performed.

Despite the numerous available sensors for Earth observation, the particular requirements of glacier observation, related to spatial, spectral and temporal resolution, cloud cover and snow conditions and availability of long series of data, lead to choice Landsat images.

Analysis of some Landsat TM images taken at the end of the ablation season highlighted retreat modes in the 1980s on all glaciers in the Breonie, Aurine and Pusteresi groups (Eastern Alps) - an area in which, in the early 1980s, large glaciers were advancing and small ones receding (Serandrei Barbero & *alii*, 1999).

The objective of the work is the analysis of Italian alpine glaciers changes in the last decades using Landsat imagery, acquired from TM sensors. In particular, Aurine and Pusteresi Alps glaciers have been studied and changes during twenty years have been evaluated.

Characteristics of the glaciers, such as glacier extent and terminus elevation, are computed and the analyses of changes are obtained for a twenty-year period from the mid Eighties to the Two-Thousand.

Results obtained by the application of this methodology to the Landsat image of 24th August 2003 are then compared with glaciological data collected during field surveys performed from year 1978 to 2003.

As it is known, Landsat TM images, with a geometrical resolution of 30 m, are taken once every 16 days. However, frequent cloud cover over the alpine sector and the need to restrict observations at the end of the ablation season when the snowline is at its highest elevation, means that only three TM 192/27 images from the past, taken at two-year intervals, could be used. These were taken on 9th September 1985 (Attardo & *alii*, 1989), 13th September 1987 (Serandrei Barbero & *alii*, 1992) and 18th September 1989 (Serandrei Barbero & *alii*, 1999).

The most recent image of summer 2003 is analysed in depth here. Tab. 1 shows the list of acquired satellite images, for the study area, with the indication of the parameters necessary for the image frame identification (path and row).

All the Landsat images have been orthorectified and georeferred using a Digital Elevation Model (DEM) with a grid cell of 20 m. The RMSE (Root Mean Square Error) obtained from the geometric correction procedure is less than one pixel.

Identification of ice and snow cover areas has been achieved through the application of unmixing classification techniques, based on fuzzy set theory.

The multi-temporal analysis has been conducted according to the method of the post-classification comparison

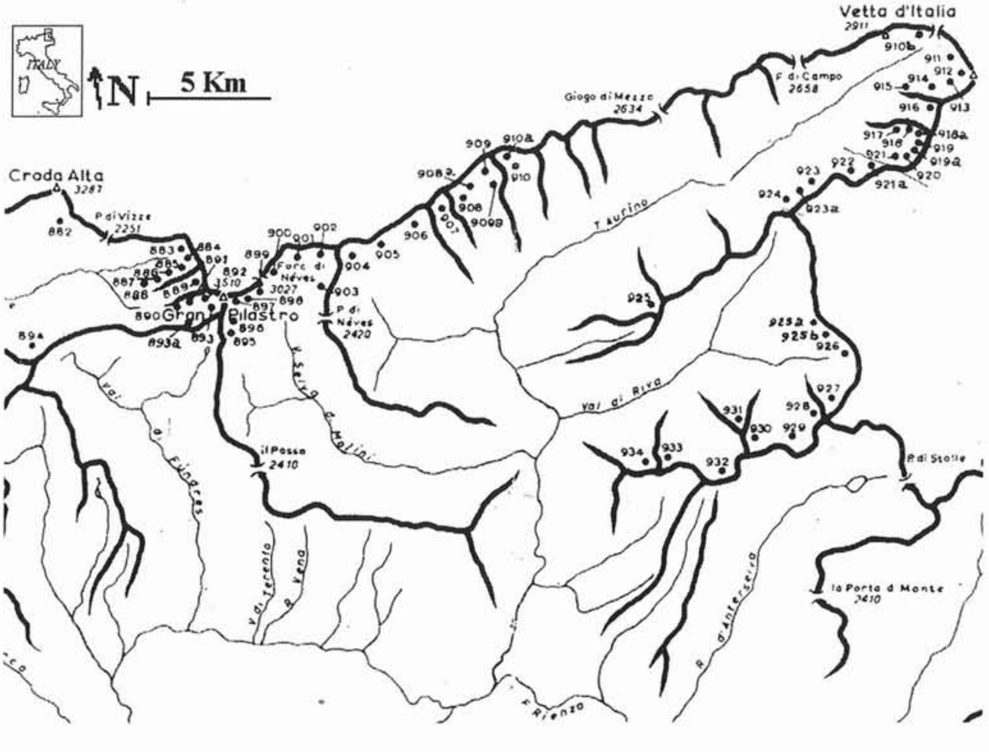


FIG. 1 - The Pusteresi and Aurine glaciers location on the Italian Glaciological Committee map with the CGI-code for each glacier in the area (CNR-CGI, 1962).

TABLE 1 - List of Landsat images (path 192 row 27) for the study area

Satellite	Sensor	Date
Landsat-5	TM	9 September 1985
Landsat-5	TM	13 September 1987
Landsat-5	TM	18 September 1989
Landsat-5	TM	24 august 2003

(Jensen, 1983), which consists in detecting and quantifying cover changes on the results of the classification procedure.

To this aim each image has been classified separately by a supervised fuzzy-statistical classifier (Wang, 1990; Binaghi & Rampini, 1993; Binaghi & *alii*, 1996) to discriminate seven land cover classes: Snow, Ice, Rocks, Pasture, Forest, Water, Clouds.

GLACIER IDENTIFICATION IN THE 2003 LANDSAT IMAGE

Using this approach, partial membership of pixels to classes can be taken into consideration, allowing an accurate classification of mixed pixels, whose presence in terms of mixture between rocks and ice or snow in the boundary of glaciers, may considerable affect the results in the identification of glaciated areas. In figs. 2 and 3 the Aurine and Pusteresi Group in the 2003 and the results of the classification are shown. Seven classes have been selected to well discriminate ice and snow.

Soft error matrix approach has been used to evaluate the accuracy of the seven classes land cover maps (Binaghi & *alii*, 1999). Overall accuracy indices resulted always higher than 90% and the K-coefficient of agreement higher than 0.9.

The whole procedure allowed to identify the most part of the total number of glaciers on the Aurine and Pusteresi Groups: their area extent is reported in tab. 2. The smallest glaciers or totally shadowed have not been classified.

Fig. 4 shows a more detailed representation of a portion of the study area: Vedrette di Ries glaciers. The table on fig. 4 is derived from the Geographic Information System built up on the basis of classification results.

In fig. 5, the Ghiacciaio della Valle del Vento in Pusteresi Alps groups observed during *in situ* measurement on 12[th] September 2003 performed by Italian Glaciological Committee (a), on 2001 orthophoto (b) by courtesy of Provincia

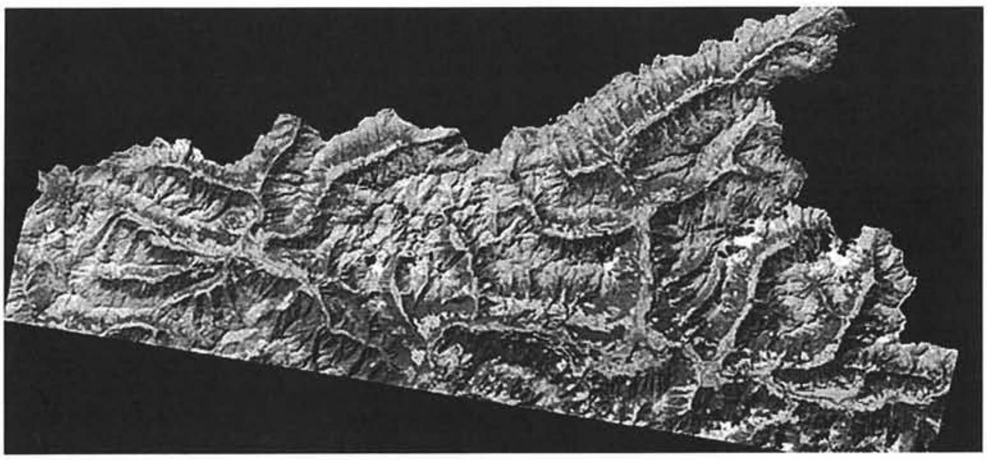


FIG. 2 - False colour composite (RGB: TM5, TM4, TM3) of Landsat image for the year 2003. Due to optical and spectral properties of snow and ice on glaciers, the false colour composite used allows distinguishing snow and ice from the other land covers.

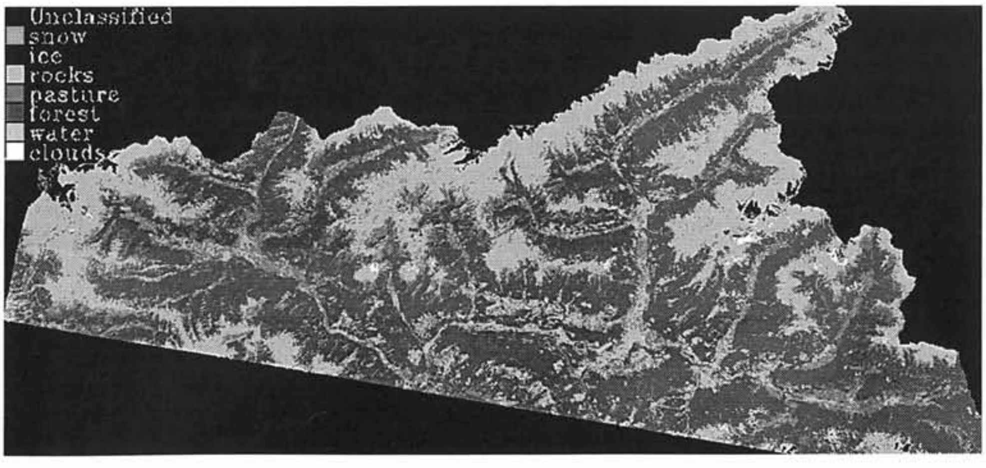


FIG. 3 - The map of classes identified on the image of year 2003.

TABLE 2 - Glaciers in the study area identified using classification of Landsat image of August 2003

GLACIER	COD. CGI	AREA [m²]	PERIMETER [m]	TERMINUS ELEVATION [m slm]	MAX ALTITUDE [m slm]	RANGE [m]	AVERAGE ALTITUDE [m slm]
ORIENTALE DELLA GRAN VEDRETTA	883	132,304	6,561	2,702	3,448	746	3,229
OCCIDENTALE DELLA GRAN VEDRETTA	884	100,402	5,051	2,730	3,430	700	3,188
DI CIMA 3400 + OCC. DI CIMA SOPRAMONTE + OR. DI CIMA SOPRAMONTE	885+886+887	105,156	4,978	3,041	3,396	355	3,231
DELLA QUAIRA BIANCA	889	912,879	12,474	2,598	3,396	798	3,097
ORIENTALE DEL GRAN PILASTRO	892	37,800	1,620	3,076	3,227	151	3,162
DEL GRAN PILASTRO	893	1,576,649	14,758	2,563	3,314	751	2,963
DELLA GUARDIA ALTA	893a	54,900	3,060	2,886	3,017	131	2,943
MERIDIONALE DELLA PUNTA BIANCA	895	148,540	2,535	2,982	3,182	200	3,100
CENTRALE DELLA PUNTA BIANCA	896	47,158	1,825	3,060	3,329	269	3,182
SETTENTRIONALE DELLA PUNTA BIANCA	897	75,600	1,740	2,846	3,021	175	2,962
OCCIDENTALE DI NEVES	900	345,600	4,517	2,913	3,229	316	3,040
CENTRALE DI NEVES	901	149,129	3,249	3,016	3,320	304	3,167
ORIENTALE DI NEVES	902	1,293,629	14,332	2,639	3,309	670	2,980
DI DENTRO	904	328,551	6,575	2,819	3,260	441	3,009
DI RIO MEZZO	905	84,600	3,540	2,605	2,794	189	2,670
DI RIO NERO	906	147,600	5,040	2,637	3,113	476	2,787
DI RIO ROSSO	907	57,600	2,820	2,848	3,192	344	2,963
DI RIOTORBO	908	580,500	6,240	2,555	2,915	360	2,728
SUD OCCIDENTALE DI PUNTA RIOTORBO	908a	144,900	4,680	2,762	3,107	345	2,891
RIOFRANCO (*)	909	198,000	3,180	—	—	—	—
OCCIDENTALE DI PUNTA DEL CONIO (*)	909a	70,200	2,580	—	—	—	—
DI PREDOI	912	514,800	12,840	2,512	3,408	896	2,855
DI LANA	913	684,542	15,636	2,477	3,133	656	2,756
NORDOCCIDENTALE DEL PIE' DI CAVALLO	914	225,000	6,360	2,616	3,016	400	2,818
SUOCCIDENTALE DEL PIE' DI CAVALLO	916	83,700	1,860	2,767	3,021	254	2,867
DELLA VALLE DEL VENTO	919	122,400	3,780	2,598	2,962	364	2,776
ROSSO DESTRO	920	508,050	6,560	2,613	3,229	616	2,899
ROSSO SINISTRO	921	198,900	4,440	2,766	3,364	598	2,959
DI VALLE ROSSA	922	180,900	5,760	2,647	3,047	400	2,823
ORIENTALE DI SASSOLUNGO	925a	162,000	4,740	2,898	3,174	276	3,037
CENTRALE DI SASSOLUNGO	925b	98,100	3,120	2,947	3,181	234	3,066
OCCIDENTALE DI SASSOLUNGO	926	1,009,758	16,412	2,611	3,260	649	2,864
DI COLLALTO	927	511,149	9,046	2,672	3,403	731	2,968
GIGANTE ORIENTALE	928	132,300	4,020	2,656	3,170	514	2,847
GIGANTE CENTRALE	929	577,800	8,520	2,653	3,120	467	2,834
GIGANTE OCCIDENTALE	930	1,923,055	13,777	2,645	3,256	611	2,996
DI MONTE NEVOSO	931,1	306,668	8,475	2,662	3,295	633	3,060
DI VALFREDDA	932	258,862	4,148	2,745	3,017	272	2,868

(*) Glacier parameter not computed due to a lack of elevation data.

di Bolzano (source: http://www.provincia.bz.it) and on Landsat image of 24th August 2003 (c). In the picture, taken in front of the glacier, it is possible to note snow coverage due to a snowfall at the end of the summer that not allow the complete identification of the glacier boundaries.

In the next paragraphs, results of this work are shown with particular attention to glaciological parameters useful to the comprehension of global trends and health of studied glaciers. In tab. 2, all the glaciers identified in the Landsat image of 24th August 2003 are listed; code assigned by Italian Glaciological Committee, computed parameters obtained from image processing like area, perimeter, minimum (frontal) elevation, maximum elevation and range are indicated. Average altitude is the mean of the maximum and minimum ones.

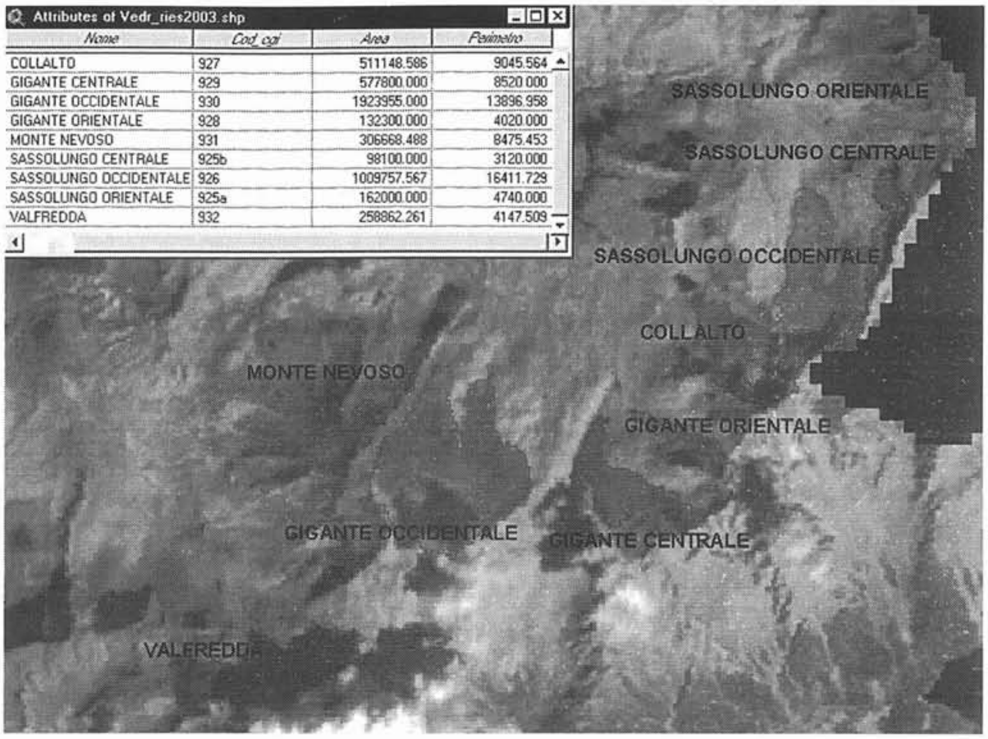
In the fig. 6 it is possible to see the trend of area extent for the entire study area (38 glaciers identified) and for one selected glacier. One big glacier (Orientale di Neves) has been chosen because the decreasing rate depends on exposure, size and altitude. The trends are comparable. General retreat related to ice exposed on analysed glaciers is quantified in 40% of the glaciated area from the '80s to the year 2003.

As already known the studied period is characterized by a retreat of glaciers in the whole Alpine chain; a general agreement is observable in the temporal trend (Maisch, 2000; Haeberli & *alii*, 2002).

ANALYSIS OF THE RESULTS

Generally, information of glaciological interest is derived from data collected during ground surveys or extracted from aerial photographs. Although relatively inexpen-

FIG. 4 - False colour composite (RGB: TM5, TM4, TM3) of Landsat image for the year 2003 for the Ries Group glaciers. In red colour the contours of glaciers identified from classification procedure.



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Nome	Cod_cgi	Area	Perimetro
COLLALTO	927	511148.586	9045.564
GIGANTE CENTRALE	929	577800.000	8520.000
GIGANTE OCCIDENTALE	930	1923955.000	13896.958
GIGANTE ORIENTALE	928	132300.000	4020.000
MONTE NEVOSO	931	306668.488	8475.453
SASSOLUNGO CENTRALE	925b	98100.000	3120.000
SASSOLUNGO OCCIDENTALE	926	1009757.567	16411.729
SASSOLUNGO ORIENTALE	925a	162000.000	4740.000
VALFREDDA	932	258862.261	4147.509

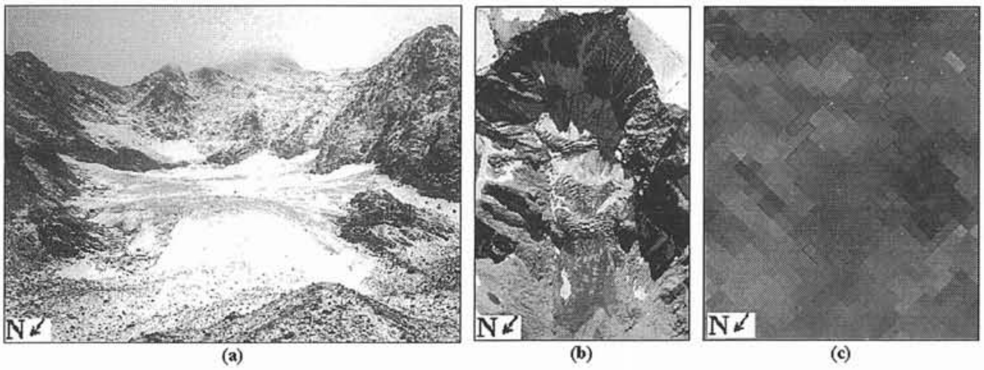

FIG. 5 - The Ghiacciaio della Valle del Vento in Pusteresi Alps. In the pictures the glacier during *in situ* measurements on 12[th] September 2003 (a), on 2001 orthophoto [orthofoto color by Terra Italy products TM CGR S.p.A. Parma] (b), on 24th August 2003 Landsat satellite TM sensor image (RGB composite 543) (c).

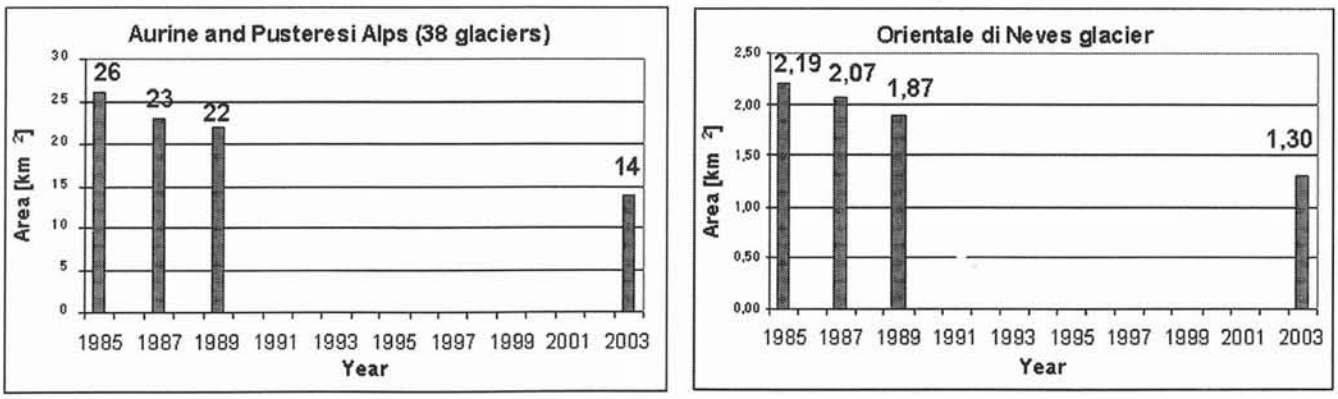

FIG. 6 - Changes in area extent for the Aurine and Pusteresi Alps glaciers.

sive from the economical point of view, ground surveys are subject to severe practical limitations due essentially to the difficulty of monitoring all the glaciated surfaces of interest, in the short time interval during which glaciers have to be observed.

Satellite images provide synoptic information over large territories and particularly on all the smallest glaciers generally not observed. Satellite measurements, therefore, are a valid tool to measure and to extend information about ground truth of these glaciated areas. The study of remote data with images processing techniques plays a basic role to an archive detailed and global of alpine glaciers.

Usually area extents of the glaciers are extracted from visual interpretation of aerial photographs. However aerial surveys are very expensive and systematic coverage of alpine glaciers are rarely programmed.

In the Aurine and Pusteresi Groups ground data are obtained annually by measuring frontal retreat and elevation. Among the characteristics of a glacier, the area extent is probably the most relevant, while the altitude of snow line (only recently monitored) and the glacier terminus elevation are the parameters most easily and often surveyed by traditional ground campaigns. The latter parameter is taken here in consideration comparing surveyed *in situ* and forecasted theoretic data and remotely sensed data.

In order to compare remote sensed results with ground data, due to the lack of 2003 data, an estimation of 2003 terminus elevation, starting from *in situ* measurements, has been performed.

In fig. 7, terminus elevation data derived from field surveys of CGI for five selected representative glaciers in the twenty years from 1981 to 2002 are shown.

The general increasing of this altitude is evident. It is possible to note the irregular trend of the elevation if the whole period is considered. Even if some particular fast changes can be attributed to a not constant slope of the bedrock, it is possible to note an abrupt change between 1990 and 1995. So, for some particular glaciers, linear trend can be assumed only for the latter period. Therefore, using the long series of *in situ* measurements from 1981 to 2002 performed by Italian Glaciological Committee it has been possible to estimate the terminus elevation for year 2003 for glaciers where last data available were almost complete (9 *apparatus*). Lack of data and errors have been considered in the computing of the elevation: linear trend has been assumed in the most recent period and where data are complete.

Then, this result has been compared with elevation data derived by satellite image of 24th August 2003. The altitude of glacier terminus, analysing satellite images, was derived from the integration between glacier boundaries vectors and the Digital Elevation Model: the elevation of the lowest pixel is considered as terminus elevation. Errors in the estimation are due to the geometrical resolution of the Digital Elevation Model used to derive the altitude of the glacier terminus from the image classification. It is necessary to remember that a Digital Elevation Model is a map of pixels with three coordinates (x, y and z) that approximate the elevation of one point with a square with the same mean altitude. Moreover, *in situ* elevation measurements are often carried out by using barometric altimeters that generate additional estimation errors; topographic analysis are performed only for some particular *apparatus*.

In September 2003 glacier terminus elevation was 2,485 m for Ghiacciaio della Valle del Vento and 2,545 m for Ghiacciaio Rosso Destro (Serandrei Barbero, 2004). These values are very near to the forecasted values from past series (respectively, 2,482 and 2,555 m) but not with the

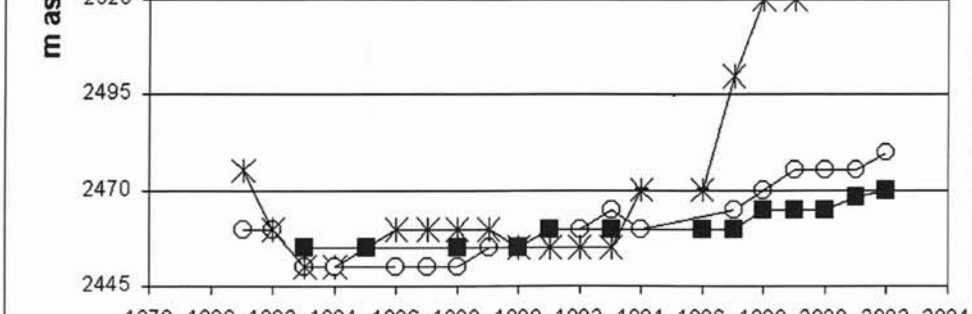

FIG. 7 - Terminus elevation for five selected glaciers in twenty years from 1981 to 2001 derived from field surveys of CGI.

Landsat data (respectively, 2,598 and 2,613 m) due to the specified problems with elevation data and orthorectification procedure.

In table 3, it is possible to analyse the comparison between the result of forecasting procedure and satellite image classification for front elevations of the year 2003. It is evident that there is a high overestimation of this altitude using optical images due to difficulty in discriminating debris covered glacier fronts without the help of radar data and microwave channels information. The difference is more evident for Valle del Vento glacier where *in situ* surveys confirm that the frontal area is buried by abundant debris coverage.

In the scatterogram of fig. 8, the line represents the ideal correlation (bisecting line) between the two kinds of data. It is clear that the elevation resulting from satellite images processing is overestimated. It is possible to attribute this fact, in addition to elevation data problems, to the widespread rock debris coverage on retreating frontal areas: an increasing phenomenon in the last years.

Since data collected by Italian Glaciological Committee are generally linear frontal measurements and there are no areal data (except for some particular scattered aerial surveys), to compare data available both *in situ* and remotely sensed, it has been assumed that a glacier that decrease in area extent has a proportional frontal retreat. This is possible only with the hypothesis of constant slope of the bedrock.

Field measurements allow the accuracy of the results from remotely sensed data to be verified. In 2003 (Serandrei Barbero, 2004) the measured mean yearly frontal retreat was 14.5 m for the Ghiacciaio di Lana, 27.5 m for the Ghiacciaio della Valle del Vento and 22 m for the Ghiacciaio Rosso Destro. These are the most relevant yearly retreats after the advancing between the Seventies and the early Eighties.

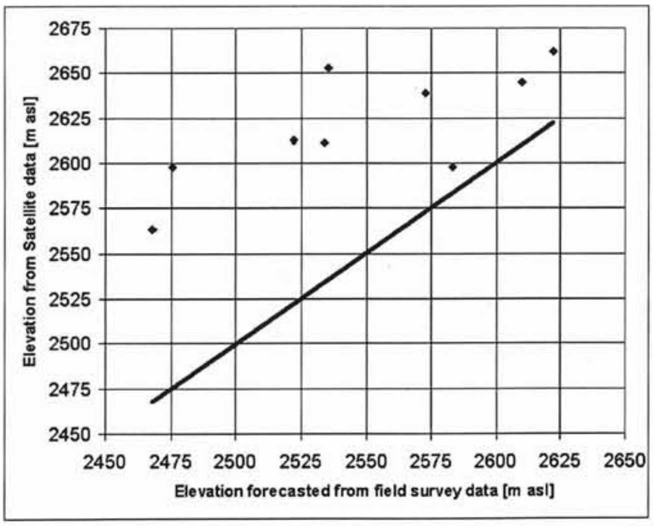

FIG. 8 - Comparison between terminus elevations in 2003 derived by remotely sensed data (ordinate) and forecasted data from the trend of the field survey (*abscissae*) for the nine selected glaciers of tab. 3. The solid line represents the perfect agreement.

TABLE 3 - Terminus elevation on 2003 for 9 selected glaciers on the study area forecasted using long series of field data performed by CGI and result of classification of Landsat image of August 2003. The last column shows the computed difference between the two data

COD CGI	GLACIER	Forecasted value for 2003 from 1981-2002 data [m asl]	TM 2003 [m asl]	Δ [m]
889	DELLA QUAIRA BIANCA	2,583	2,598	15
893	GRAN PILASTRO	2,471	2,563	95
902	ORIENTALE DI NEVES	2,586	2,639	66
919	DELLA VALLE DEL VENTO	2,482	2,598	122
920	ROSSO DESTRO	2,555	2,613	91
926	OCCIDENTALE DI SASSOLUNGO	2,541	2,611	77
929	GIGANTE CENTRALE	2,535	2,653	117
930	GIGANTE OCCIDENTALE (DI M. COVONI)	2,610	2,645	35
931,1	OCCIDENTALE DI MONTE NEVOSO	2,622	2,662	40

TABLE 4 - Correlation between glacier terminus changes from field surveys and area changes estimated by satellite imagery for ten selected apparatus for each annual variation (1987-1985, 1989-1987, 2003-1989). Moreover total glacier area on 2003 for every apparatus is indicated and only changes between 1989 and 2003 is showed.

CGI - ID	GLACIER	TERMINUS POSITION LINEAR CHANGES 2003-1989 [m]	TM AREA CHANGES 2003-1989 [km^2]	TM AREA 2003 [km^2]	r^2
893	GRAN PILASTRO	-224	-0.78	1.57	0.942
902	ORIENTALE DI NEVES	-224	-0.58	1.29	0.994
913	LANA	-86.5	-0.78	0.68	0.854
919	DELLA VALLE DEL VENTO	-125	-0.07	0.12	0.225
920	ROSSO DESTRO	-153	-0.36	0.51	0.989
926	OCCIDENTALE DI SASSOLUNGO	-79.5	-0.40	1.018	0.618
927	COLLALTO	-120.5	-0.14	0.51	0.763
929	GIGANTE CENTRALE	-223.5	-0.74	0.58	0.900
930	GIGANTE OCCIDENTALE (DI M. COVONI)	-67.5	-0.55	1.92	0.937
931	OCCIDENTALE DI MONTE NEVOSO	-39	-0.23	0.31	0.988

Then, data on linear frontal retreat of glaciers, collected during the field surveys from 1978 to 2003, has been compared with the data of area derived from remote sensing imagery of 1985, 1987, 1989 and 2003 years for each glacier where data are contemporary available (10 *apparatus*).

In tab. 4, the results of the correlation between frontal variations and area changes for each *apparatus* for each annual variation (1987-1985, 1989-1987, 2003-1989) are shown. Low correlation for the Ghiacciaio della Valle del Vento is due to problems related to the comparison between areal and frontal variations. In fact, this glacier has an areal decrease bigger than the frontal retreat from the year 1989 to 2003 as the front is placed on a flat zone and answers with some delay to climate variations. Moreover, the frontal zone is characterized by an abundant debris

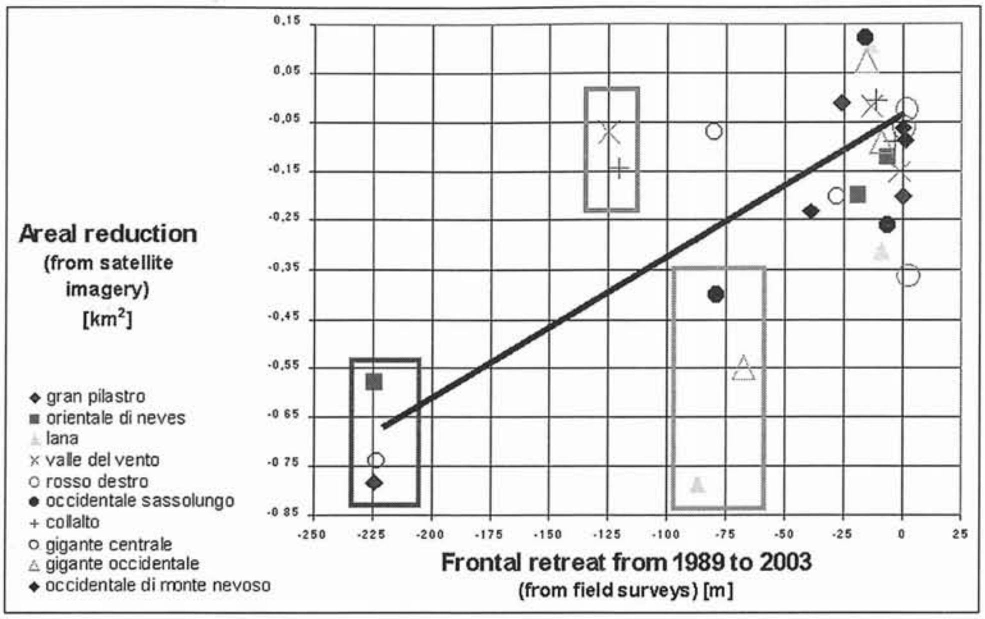

FIG. 9 - Changes in the area extent (from satellite data) vs terminal retreats (from forecasted in situ data) of the glaciers of table 4 and for all years (1985, 1987, 1989, 2003).

coverage that masks the actual position of the front and influences the retreat or advancing modes related to climate.

The scatterogram of fig. 9 presents all the data of variation, measured and estimated, in a unique graph for the four years. A linear regression between field measured linear variations values (independent variable) and area changes remotely sensed estimated (dependent variable) gave a global correlation coefficient of 0.771 (see the black colour trend line).

From the graph on fig. 9, we can extrapolate some other interesting information. It is quite evident the correlation between some values. In the first column, for instance, the red rectangle shows three glaciers (Orientale di Neves, Gigante Centrale, Gran Pilastro) which present a similar frontal retreat from the year 1989 to the year 2003: they are located in a similar elevation range (between 2,600 and 3,300 m a.s.l.). In the second one (grey color) Valle del Vento and Collalto glaciers have the same variation from the year 1989 to the year 2003 again. In the third one (green rectangle) a similar frontal retreat is shown for other three glaciers (Occidentale di Sassolungo, Gigante Occidentale, Lana) again for the same interval of years. These two last clusters of glaciers have almost the same exposure (North).

CONCLUSIONS

Satellite remote sensing accompanied by suitable processing techniques can contribute to establish a national inventory of glacier from space and document ongoing changes of Alpine glaciers.

The performed techniques allow to check areal and frontal changes in glaciers with an area over 1 km^2 not completely shadowed. The data are comparable with *in situ* measurements when the glacial morphology is not too complex or particular.

Classification of satellite image presents drawbacks. To take advantage of the enormous potential of satellite imagery in monitoring the cryosphere, a systematic collection strategy is required. However, it contains some unique challenge: the relatively short time window when snow and ice conditions on glaciers offer maximum amount of glaciological information, the pervasive presence of clouds above mountains region and so the difficulty in automated discrimination between cloud and snow (Bindschadler, 2001). Then, as already mentioned alpine glaciers are very different in size, shape and exposure and discrimination is not always easy.

Moreover, many of the errors in satellite products are of a quasi-systematic nature, which implies that suitable *in situ* measurements can be used to reduce such errors (Oerlemans, 2001).

The present work, that analysed data from 1985 to 2003, confirms results from other researches concerning with the general decreasing trend of glacier surfaces during the last twenty years (Maisch, 2000; Haeberli & *alii*, 2002).

The measured retreat of glaciers from the first Eighties is of 40% but the recent abundant debris coverage in some frontal zones may mask the actual position of the front giving an overestimation of the retreat.

Although some frontal elevation and retreat data are overestimated, the results of satellite images analysis agree with field data from *in situ* measurements. Further efforts are foreseen to improve the techniques used to extract information from satellite data. The availability of images from the ASTER sensor, with 15 m of geometrical resolution, onboard the platform Terra will contribute to increase the accuracy in the estimation of glaciological parameters also on small and shadowed glaciers.

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