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Melting of italian glaciers: analysis of the phenomenon in GIS environment

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Italian glaciers began to melt in the second half of the 19th century. The quantification of melting over time has been described in Glaciers Inventories. The present research aims to contribute to the understanding of the dynamics governing glacier melting as a function of different glacier types and geomorphological parameters analysed in GIS environment. The extent variation of 13 Italian glaciers from 1958 was evaluated by means of automatic classification of aerial images in the Free and Open-Source software GRASS GIS. On-site inspections were carried out too, to identify portions of the glaciers not identifiable by image classification, as well as any peculiarities and boundary conditions. Moreover, the influence of geomorphological parameters and boundary conditions were investigated, extending the analysis to 15 additional glaciers. The results showed that glaciers have undergone different area reductions, which can be correlated with different geographical and geomorphological features. A higher tendency to melt was found in those glacial masses that had an initial size less than 1 km², located in the western sector of the Alps, at medium-low altitudes and facing south. Moreover, the lack of feeding from the surrounding slopes and from glacial masses located at higher altitudes, the lack of snow cover or thick debris during the summer season and a dark geological bedrock increase the phenomenon.

***Keywords**: glaciers, melting, GIS GRASS, image classification.*

1. Introduction

According to the last survey conducted in 2016 (Smiraglia and Diolaiuti, 2015), 903 glaciers are present on the Italian territory, mainly along the Alpine arc, except for the Calderone Glacier, located in Abruzzo, with a total surface area of 368 km^2. They are characterized by different sizes, elevation, slope and exposure, and also by different geology and feeding methods.

Glaciers are exploited for numerous human activities, both indirectly, through water supply, reservoir feeding and irrigation, and directly, through sports-recreational activities and tourism. Therefore, glaciers are a resource to be conserved and protected.

Italian glaciers began to melt due to natural causes in the second half of the 19th century, at the end of the "Little Ice Age" (Lamb, 1972; Mann, 2003; Carturan *et al.*, 2016). Over the last century, and in particular from the 1980s, the melting rate has increased significantly, mainly due to global warming caused by the enormous emissions of greenhouse gases. Also, the glacier darkening (Fugazza *et al.*, 2019), caused by the deposit of polluting dark particles carried by the atmosphere on the surface of glaciers, and the formation of unicellular reddish algae *Ancylonema nordenskioeldii* (Di Mauro *et al.*, 2020) increased the melting. In fact, both these two factors reduce the albedo of the frozen surface, increasing the absorbed solar radiation and, therefore, accelerating its melting.

The quantification of melting over time has been described in Glaciers Inventories. The first Italian one, compiled by the Italian Glaciological Committee (CGI), was published in 1959-1962 (CNR and CGI, 1962). Thereafter, the World Glacier Inventory (WGI) was published in 1989 (Haeberli *et al.*, 1989), with full details at the dedicated web page hosted by the World Glacier Monitoring Service. The Italian data entered in the WGI derived from aerial photo analysis, but in some cases the used images proved to be affected by a not negligible snow coverage. Anyway, a decrease in glacier area was observed between the CGI and the WGI inventories (Ajassa *et al.*, 1997; Diolaiuti *et al.*, 2012).

In 2016, a new Italian Glacier Inventory was published (Smiraglia and Diolaiuti, 2016), exploiting high-quality and high-resolution orthophotos derived by flights between 1999 and 2011. Orthophotos were characterized by low or absent cloud coverage and were acquired in late summer, when glaciers show minimum snow cover and, therefore, their boundaries appear clearer and are more detectable. Few exceptions occur in case of debris covered glaciers (Smiraglia and Diolaiuti, 2011), making more difficult and uncertain to detect and map the glacier outlines. Orthophotos planimetric resolution varies between 0.5 and 1 m, the planimetric accuracy stated by the manufacturers varies between 1 m and 2 m, depending on the performed flight (Smiraglia and Diolaiuti, 2016). Instead, the planimetric accuracy of the oldest data (1958-1989) was estimated equal to 5 m (Ajassa *et al.*, 1997).

The present research aims to contribute to the understanding of the dynamics governing glacier melting as a function of different glacier types and geomorphological parameters, analysed in GIS environment.

Thirteen glacial systems were chosen to represent the different features and including the most significant and particularly interesting ones (red dots in Figure 1). Automatic image classification was applied to the orthophotos of such glaciers, so to evaluate their spatial variation over time. Moreover, on-site inspections were carried out to identify portions of the glacier covered by debris, hence not identifiable by image classification, as well as any peculiarities and boundary conditions. Then, the results of image classification were integrated with the data already present in the CGI (1959-1962) inventory, in the WGI and in the New Italian Glacier Inventory (2016), to highlight the amount of glaciers area reductions. Hence, the influence of geomorphological parameters and boundary conditions were investigated. In order to assess the influence of some parameters, the morphological analysis was extended to 15 additional glaciers (orange dots in Figure 1). Conclusions summarize the results and mention criticalities, that can occur both in the short term in form of sudden events, and in the long term, as a result of a trend that has persisted for many years.

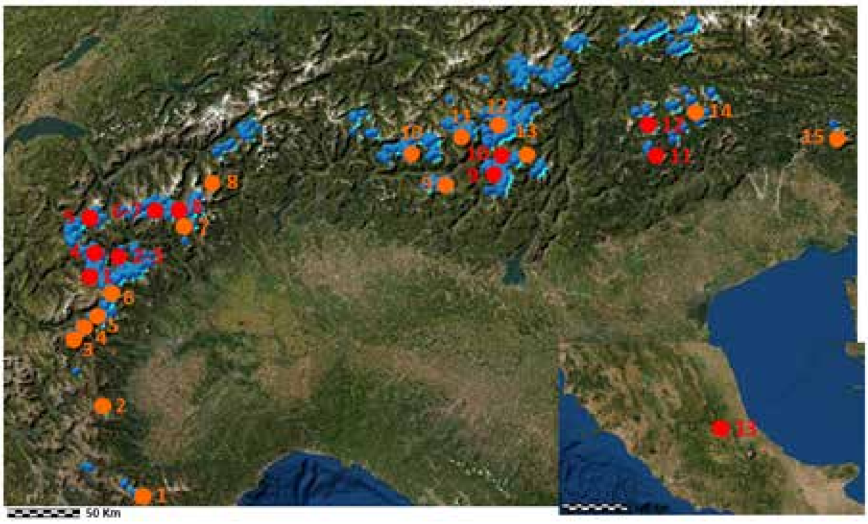

Fig. 1 – Geographical position of the Italian glaciers (in blue). The 13 ones analysed by image classification (red points): 1) Goletta; 2) Grivola; 3) Trajo; 4) Rutor; 5) Planpincieux; 6) Vofrede; 7) Mont Blanc du Creton; 8) Tzere; 9) Adamello; 10) Presena; 11) Fradusta; 12) Marmolada; 13) Calderone. The 15 ones analysed from the morphological point of view (orange points): 1) Clapier; 2) Vallanta; 3) Galambra; 4) Vallonetto; 5) Bard; 6) Carro; 7) Gran Tournalin; 8) Camposecco; 9) Trobio; 10) Sissone; 11) Occidentale di Val Viola; 12) Forà; 13) Corni di Venezia; 14) Occidentale del Sorapis; 15) Occidentale Canin.

2. Analysis of the phenomenon in GIS environment

The workflow in GIS environment can be divided into two phases. The first one consisted in the automatic classification of the aerial photos for the identification of glacier mass boundaries. Possible classification errors highlighted by on-site inspections were corrected before calculating the glacial surfaces and evaluating their temporal evolution. In the second phase, the average morphological characteristics of each glacier, such as elevation, slope and exposure, were extracted from the available Digital Terrain Models (DTMs) and then analysed, together with site-specific features, in order to highlight correlations between each parameter and the melting intensity.

Supervised classification of the images was performed using the Sequential Maximum A Posteriori (SMAP) algorithm (Bouman and Shapiro, 1992 and 1994) in the Free and Open-Source software GRASS GIS. SMAP exploits the fact that nearby pixels in an image are likely to have the same class. The algorithm works by segmenting the image at various scales or resolutions and using the coarse scale segmentations to guide the finer scale segmentations. This allows SMAP to produce segmentations with connected regions larger than a fixed class, reducing the number of classification errors. This is particularly useful in the present case, where it is not necessary to identify individual objects.

The classes are defined by the operator thanks to a training map, from which the spectral signatures are extracted. A spectral class Gaussian mixture distribution model improves the segmentation performance by modelling each information class as a probabilistic mixture with a variety of subclasses, identified by clustering.

In the present research, no more than three or four classes were indicated by the operator in the training maps, depending on each site: glacier and rocky area are always present, sometimes also lakes, vegetations or shadows (Figure 2).

Then, the spectral average values and the variance and covariance matrix relative to the three visible spectral bands (red, green and blue), calculated for each class and the relative subclasses, were used

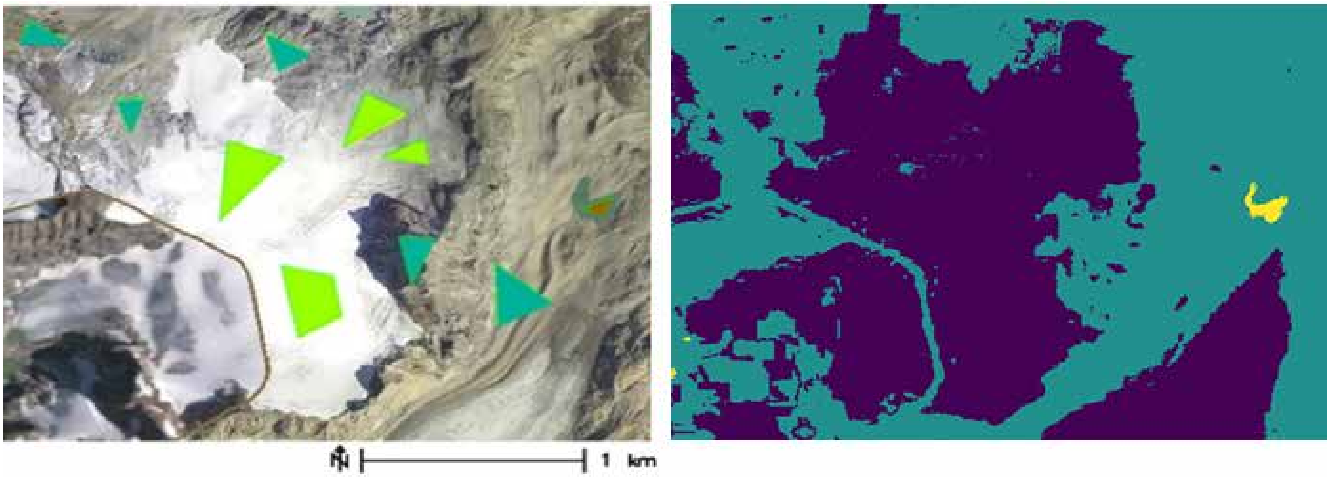

Fig. 2 – Training areas for supervised classification (on the left), related to the Goletta Glacier in 2012: glacier (green), rocky area (dark green) and lake (brown). Classified map of the Goletta Glacier (on the right): glacier (dark blue), rocks (light blue) and lake (yellow).

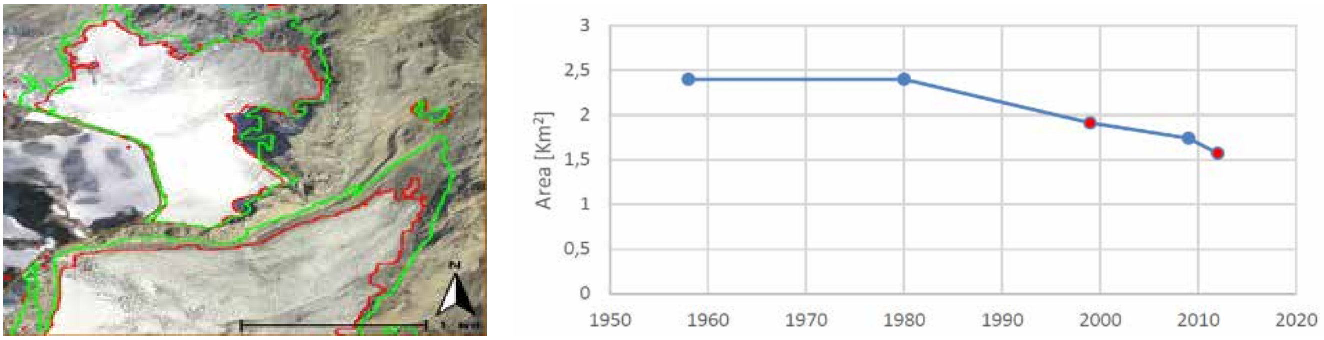

Fig. 3 – Boundaries of the Goletta Glacier in 1999 (green) and in 2012 (red), identified by image classification (on the left). Trend of the spatial variation over time (on the right) coming from the Glaciers Inventories (blue) and the present elaboration (red).

by SMAP algorithm to classify the images. If necessary, the results of the classification were corrected manually, either to insert areas covered by debris inside the glacial boundary that were classified as rocks, and to exclude areas covered by snow that had fallen into the class of glacial masses. Hence, the surface extension of the glacial apparatuses was computed and compared with previous measurements coming from the Glaciers Inventories (Smiraglia and Diolaiuti, 2016; CNR and CGI, 1962; Haeberli *et al.*, 1989), to evaluate the spatial variation over time (fig. 3). Fig. 4 shows images demonstrating the spatial reduction of Goletta Glacier, taken as example.

During the second phase of the GIS analysis, the average or characteristic values of different parameters and boundary conditions influencing the melting process were identified for each site by analysing technical and thematic cartography. From the Digital Ter-

Fig. 4 – Goletta Glacier in 1998 (above) and in 2019 (below).

rain Model (DTM) of each site, the slope and aspect maps of glaciers were created, from which average values were extracted for comparison over time, to study if and how the melting rate is related to the inclination and exposure of the glacier masses. To assess the influence of geographic location on Italian glaciers, 15 glacial apparatuses were identified, 8 belonging to the western sector and 7 to the eastern sector, having comparable characteristics in terms of size, exposure and average altitude. In the following section the influence of such parameters is analysed.

3. Results

Glaciers exhibit very different area variations (tab. 1), due to their different morphology and boundary conditions. Ten of the thirteen glacial systems, analysed by automatic image classification, have undergone areal reductions: on average, the relative surface loss was 37.1% between 1958 and 2016.

The glaciers that underwent the greatest relative reductions between 1954 and the last decade were the Fradusta (-93.8%), Tzere (-81%), Presena (-68.3%), Vofrede (-62.9%) and Calderone (-51.9%) Glaciers. Instead, Planpincieux

Tab. 1 – Percentage variation of the analysed glaciers compared to 1958: values derived by the present work (in bold) and by the Glacier Inventories. Surface compared to 1958 [%].

Glacier	1958	1964	1973	1980	1982	1994	1999	2000	2006	2007	2009	2011	2012	2015	2016
Goletta	100	-	-	100	-	-	79.6	-	-	-	72.5	-	**65.4**	-	-
Grivola	100	-	-	129.2	-	-	124.3	-	-	-	97.9	-	**104.6**	-	-
Trajo	100	-	-	111.7	-	-	105.5	-	-	-	100.5	-	**101**	-	-
Rutor	100	-	-	-	-	-	-	93.9	-	-	88.6	-	-	-	-
Planpincieux	100	-	-	-	-	-	95.7	-	-	-	93.9	-	**77.4**	-	-
Vofrede	100	-	-	74.2	-	-	-	-	51.6	-	**41.3**	-	-	-	**37.1**
Mont Blanc	100	-	-	160	-	-	-	-	80	-	**114**	-	-	-	**114**
Tzere	100	-	-	-	-	-	50.6	-	34.6	-	-	-	**25.5**	-	**19**
Adamello	100	-	-	-	-	-	-	-	-	**74.3**	-	-	-	-	-
Presena	100	-	**95.1**	-	-	**65.9**	-	-	39	-	-	-	-	**31.7**	-
Fradusta	100	-	**55.4**	-	-	**30.8**	-	-	15.4	-	-	10.8	-	**6.2**	-
Marmolada	100	95.4	-	-	78.2	-	-	67.5	55.6	-	-	50.2	-	-	-
Calderone	100	-	-	83.3	-	-	-	-	-	66.7	-	-	-	48.1	-

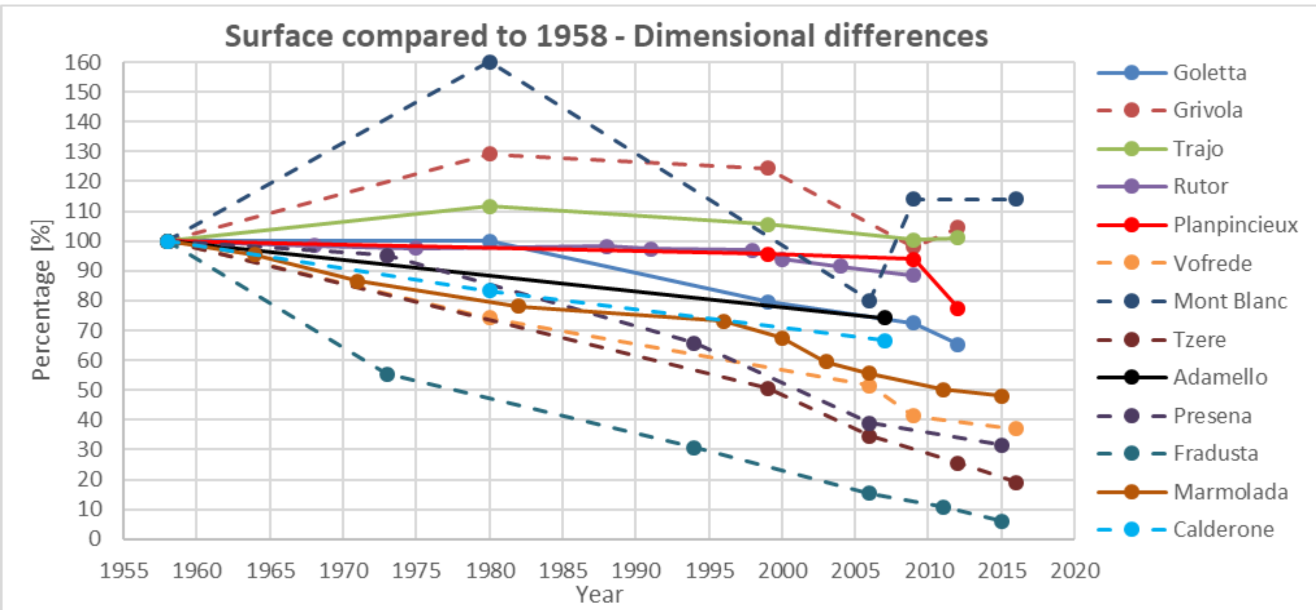

Fig. 5 – Influence of glacier initial area on melting: glaciers with initial area > 1 km^2 (continuous line) and with initial area < 1 km^2 (broken line).

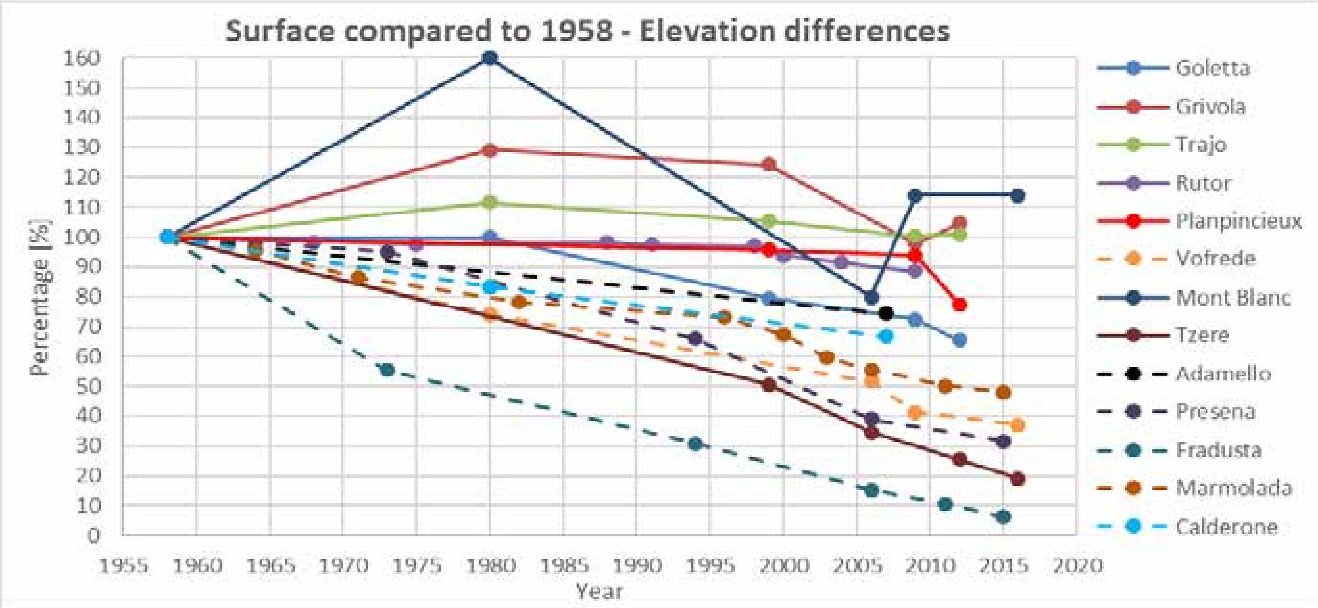

Fig. 6 – Influence of glacier elevation on melting: glaciers located at altitude > 3000 m (continuous line) and at altitude < 3000 m (broken line).

and Rutor Glaciers have undergone minor surface reductions, –22.6% and –11.4%, respectively. Finally, some apparatuses show slight positive areal variations, such as the Trajo (+ 1.0%), Grivola (+ 4.6%) and Mont Blanc du Creton (+ 14.0%) Glaciers.

From the dimensional point of view, smaller glaciers, with an initial area lower than 1 km^2 (broken line in Figure 5), had on average a higher percentage areal variation.

A similar behavior was observed on glaciers located at mean altitudes below 3000 m (broken line in Figure 6). Note that the Fradusta glacier, characterized by initial area lower than 1 km^2 and a mean altitude below 3000 m, underwent the greatest areal reduction and it is now close to disappear.

The analysis of minimum and maximum elevation of each glacier highlights that minimum glacier elevations increased on average from 1958 to the recent years, due to increased melting of the lower elevations (fig. 7). On the other hand, there is no trend in the maximum elevations, as they are influenced by other factors.

Higher melting rates was also

Tab. 2 – Geographical differences of 15 glaciers belonging to different Alpine sectors.

Glacier	Geographical location	Average height [m]	Exposure	1958 area [km^2]	2006 area [km^2]	Residual area [%]
Clapier	Piemonte, Valle Gesso	2775	north	0.3	0.04	13.3
Vallanta	Piemonte, Monviso	2925	north-west	0.15	0.06	40
Galambra	Piemonte, Val di Susa	2950	north-west	0.5	extinct	0
Vallonetto	Piemonte, Val di Susa	3050	north-west	0.14	extinct	0
Bard	Piemonte, Val di Susa	3050	north-west	0.41	extinct	0
Carro	Piemonte, Valle Orco	2769	north	0.34	0.18	52.9
Gran Tournalin	Valle d'Aosta, Valtournanche	3075	north-west	0.12	extinct	0
Camposecco	Piemonte, Valle Antrona	2890	north-east	0.3	extinct	0
Trobio	Lombardia, Val Seriana	2614	north-west	0.19	0.09	47.4
Sissone	Lombardia, Val Marenco	2878	east	0.6	0.54	90
Occ. Di Val Viola	Lombardia, Val Viola	2970	north	0.19	0.1	52.6
Forà	Lombardia, Val Zebrù	2980	north	0.5	0.45	90
Corni di Venezia	Trentino, Val di Bon	2636	north-east	0.32	0.17	53.1
Occ. Del Sorapis	Veneto, Dolomiti	2538	north	0.25	0.18	72
Occ. Canin	Friuli, Alpi Giulie	2387	north	0.09	0.06	66.7

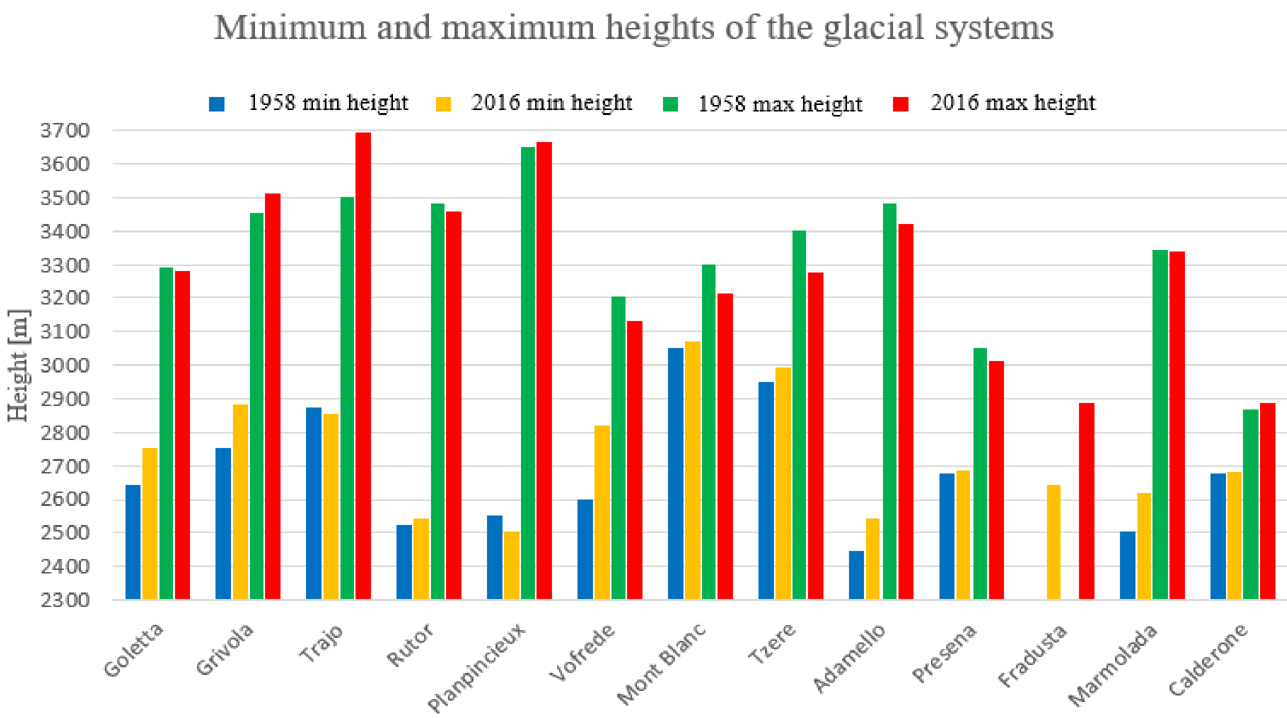

Fig. 7 – Minimum (blue and orange) and maximum (green and red) glaciers elevation [m] in 1958 and 2016, respectively.

observed in those glaciers which are geographically located along the western Alpine sector (fig. 1 and Tab. 2). This could be related to the lower snowfall rate during the winter season in the western sector with respect to the easter one. Hence, glaciers in the western sector have less supply and less protection from solar radiation during the summer months.

Furthermore, the highest melting rate was found in south-facing glacial systems, as Tzere and Vofrede Glaciers, due to the higher solar radiation reaching these surfaces. This aspect is particularly relevant in the Valle d'Aosta region, where many glacial systems exposed to the south are present, due to the orographic conformation and the high altitudes.

In terms of feeding, glaciers can be divided into three types (fig. 8):

- glaciers that are fed exclusively by snowfall;
- glaciers that receive additional input from adjacent slopes (in the form of snowmelt discharge) or from upstream glacier mass flow;
- glaciers that once belonged to the former type, but now are separated from the main glacial mass and no longer receive these additional contributions.

On average, the glacial masses belonging to the third type have the greatest area reductions, while those belonging to the second type have the lowest area losses because summer melting is partially com-

Fig. 8 – Examples of glaciers with different feedings systems: the Goletta Glacier (left) is fed exclusively by snowfall because it is located on a plateau; Planpincieux Glacier (center) is fed by snow discharges from the adjacent steep slopes; the lower Fradusta Glacier (right) was detached from the upper portion that no longer feds it.

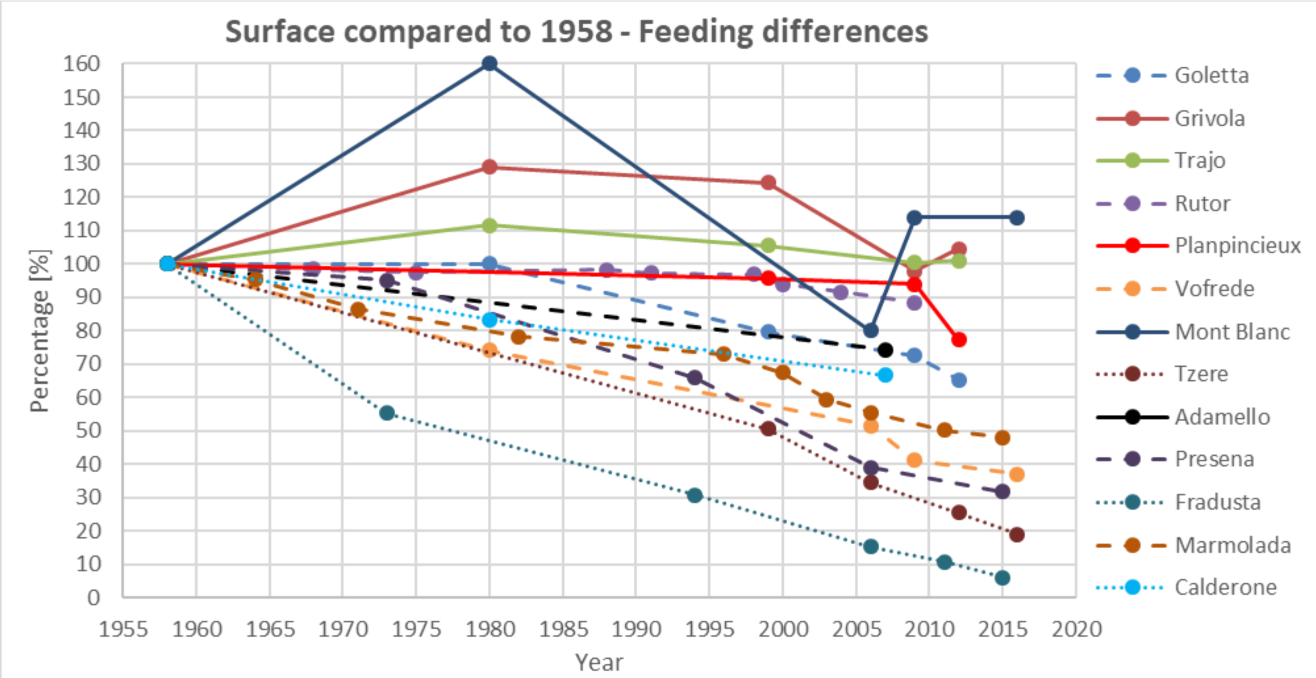

Fig. 9 – Influence of feeding differences on areal reduction: glaciers that feed exclusively with snowfall (broken line), glaciers that also receive snow discharges from the surrounding slopes (continuous line), fragmented glaciers that were once also fed by discharges from the surrounding slopes (dotted line).

pensated for by additional snow contributions (fig. 9).

Another important parameter that influences the melting rate is the coverage of glaciers with snow or debris. The snow cover was analysed on the basis of snow measuring stations, and the debris cover by means of on-site inspections.

With regard to snow cover, the thicker it is, the more protection it gives to the underlying glacier during summer. The greatest coverage was recorded along the eastern Alpine sector and in glaciers located at the base of steep slopes, from which they received snow drifts. Concerning debris cover, a double effect was found, depending on its thickness:

- in case of a moderately thick debris cover, e.g., Fradusta Glacier (Figs. 10-11), the underlying glacier experienced higher melt rates because the thin debris layer is unable to protect the glacier from solar radiation, and also causes a reduction in the albedo factor with a consequent increase in absorbed radiation;
- in presence of considerable debris cover, as in Calderone Glacier (Figs. 10-11), the melting rate was lower, because the debris protected the underlying glacier from solar radiation.

The geological composition of the bedrock was also a significant parameter in defining the melting dynamics. In case of a dark-coloured bedrock, e.g., Vofrede Glacier (fig. 12), the glacier experienced higher melt rates due to the low albedo values of the surrounding rock and the consequent higher amounts of absorbed radiation, causing an increase in temperature. Instead, the light-coloured bedrock produces higher albedo, hence lower surface temperatures of the surrounding rock and less glacier melting, as in Mont Blanc du Creton Glacier (fig. 12).

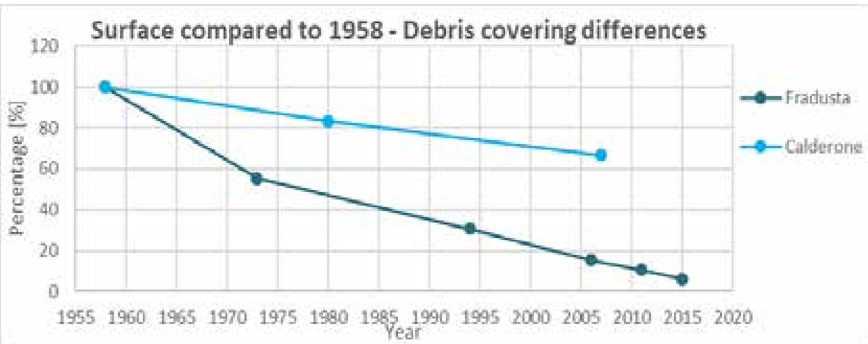

Fig. 10 – Debris covering differences: modest debris cover of Fradusta Glacier (dark blue) and considerable debris cover of , while Calderone Glacier (light blue).

4. Conclusions

Italian glaciers are undergoing a significant areal reduction, caused not only by a natural trend, but

Fig. 11 – Lower portion of Fradusta Glacier (left) covered by a modest debris layer and Calderone Glacier (right) covered by a considerable debris layer.

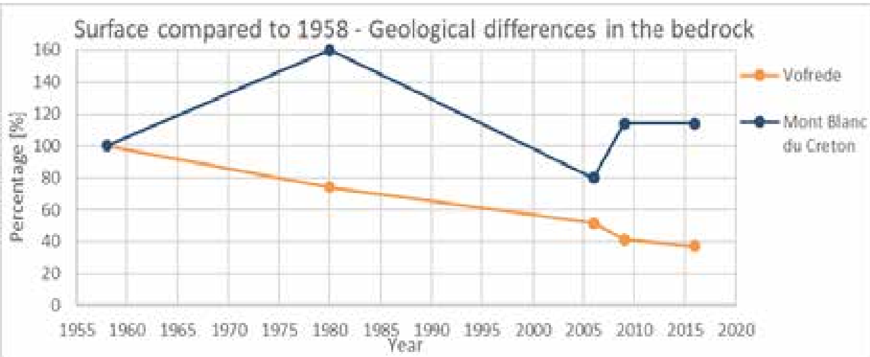

Fig. 12 – Geological differences in the bedrock: Vofrede Glacier (yellow line) is located on a bedrock consisting of dark-coloured paragneiss, Mont Blanc du Creton Glacier (blue line) is located on bedrock consisting of light-coloured marbles, dolomitic marbles and dolomites.

also by the global warming and the darkening of their surfaces.

Supervised contextual classification of aerial images showed that ten of the thirteen analysed glacier systems experienced areal reductions, and the relative area lost between 1958 and 2007-2016 was 37.2% on average.

In addition, a GIS analysis of the main characteristics of Italian glaciers showed a greater tendency to melt in glaciers smaller than 1 km^2, located in the Western Alps, at low to medium altitudes, facing south. Moreover, the lack of feeding from the surrounding slopes and from glacial masses located at higher altitudes, the lack of snow cover or thick debris during the summer season and a dark geological bedrock increase the phenomenon.

The general trend of glacier melting is generating several criticalities on the territory and on numerous anthropogenic activities (born in the past thanks to the presence of glacial systems), that will become increasingly marked if this trend is not halted. Criticality can occur both in the short term, in the form of sudden events, and in the long term, as a result of a trend that has persisted for many years. They can affect areas close to glaciers as well as those far away but in the same drainage basin. The repercussions on the territory in the short term were of greater intensity but easier to manage and control, also thanks to geomatics monitoring techniques. On the contrary, the criticalities linked to long-term trends are more complex to manage and more impacting from a socio-economic and environmental point of view.

Short-term criticalities include glacial mass detachments, rock fall from slopes, in the form of rockfall or debris flow, depending on the type of material and the degree of fracturing of the rock. In addition, the formation of epiglacial and subglacial lakes is very dangerous for the possible rupture of their glacial perimeter and the generation of a massive flood wave towards the valley.

Long-term trends may generate water scarcity in the summer months, an increase in solid transport due to the release of sediments present in the solid matrix of the glacier with the consequent silting up of water courses and reservoirs (Lindsey and Comiti, 2019), the progressive disappearance of the summer ski area and the reduction of the landscape and environmental value. In order to avoid these problems, at least in part, a better management of water resources will be increasingly important to maintain the current economic and social models even when there is less water. To achieve this goal, structural and management measures will be needed on reservoirs, on the urban water network, with the modernisation of existing networks, and in agriculture, with the use of innovative techniques that allow less water to be wasted.

Finally, a solution to prevent the rapid melting of limited areas of glacier of high economic and landscape value consists in the use of geotextile sheets of white non-woven material (mainly polypropylene and polyester) placed over the ice surface (Senese *et al.*, 2014). This solution allows to increase the albedo of the surface, and therefore to reduce its surface temperature and, consequently, the melting rate of the glacier during the summer months. Among the first examples of this application, there are portions of the Presena Glacier in Italy, covered to preserve the ski slope below, and portions of the Rhone Glacier in Switzerland, to safeguard the ice caves present in its terminal portion.

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