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USING LANDSAT IMAGES AND GIS TO ASSESS THE CHANGES OF MER DE GLACE AND MARMOLADA GLACIERS, IN THE LAST THREE DECADES

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ABSTRACT. - Using Landsat Images and GIS to Assess the Changes of Mer de Glace and Marmolada Glaciers, in the Last Three Decades. We have demonstrated that Mer de Glace Glacier (GL) and Marmolada GL are in continuous retreat. The changes in size and status of terminus points were estimated in various time intervals by satellite images (SIs) and Geographic Information Systems (GIS) techniques, during the last three decades. The aim of the research was to found the value of the ice melting areas of Mer de Glace GL and Marmolada GL and to calculate the decline rate for both GLs. A large number of GLs have lost ice mass all over the world. Often glaciologists monitor the GLs movements under climate changes and they express their opinions about the ocean level rise, ecosystem challenges and the future implications of GLs decline. The analysed information to quantify the Mer de Glace GL and Marmolada GL areas derived from SIs. By manual vectorization we obtained the outlines of GLs in different years. For 1984, 1999, 2013 we defined the limits for Mer de Glace GL and for 1986, 1999, 2013 we defined the limits for Marmolada GL. These vector layers were compared in order to observe the melting area and to establish the withdrawal rate. The first results indicate that Mer de Glace GL area declined by 2.365 km^2 between 1984 and 2013 and a mean melting rate of 0.082 km^2/year was obtained. Marmolada GL decreased by 1.035 km^2 between 1986 and 2013 and a mean melting rate of 0.038 km^2/year was calculated. We believe that these results represent significant quantitative data about GLs movements regarding two different areas in the Alps Range and may provide knowledge for hydrology, geomorphology and environmental sciences.

Keywords: *satellite images, GIS, climate change, glacier, Mer de Glace, Marmolada.*

1. INTRODUCTION

The climate change may be easily noticed through measurements of GLs, which are the most sensitive indicators of climate warming (Dong et al., 2013; Kargel et al., 2005; Haeberli et al., 1999). The melting of GLs creates a glacierized face of alpine landscape (O'Neel et al., 2014; Theurillat and Guisan, 2001). In general, the GLs are affected by global warming (Oerlemans, 2005) and many studies demonstrated that GLs from the entire world diminished in mass due to global warming (Painter at al., 2013; Kennedy at al., 2006; Shahgedanova et al., 2005).

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The assessment of areas covered by GLs gives substantial information about how the climate evolves. Remote sensing with Landsat images and GIS techniques have been used to assess the changes of Mer de Glace and Marmolada GLs in the Alps.

The objective of this work is to calculate the square area in various time intervals for Mer de Glace and Marmolada GLs, between 1984/1986 and 2013. The research was made on Mer de Glace and Marmolada GLs, for two reasons: first, because both GLs are located in tourism areas and human activities can accelerate the melting of ice. Secondly, each one represents an important GL for two different sectors of Alps – Mer de Glace GL for the Western Alps and Marmolada GL for the Southern Alps – and we wanted to see where there is a bigger retreat of GLs.

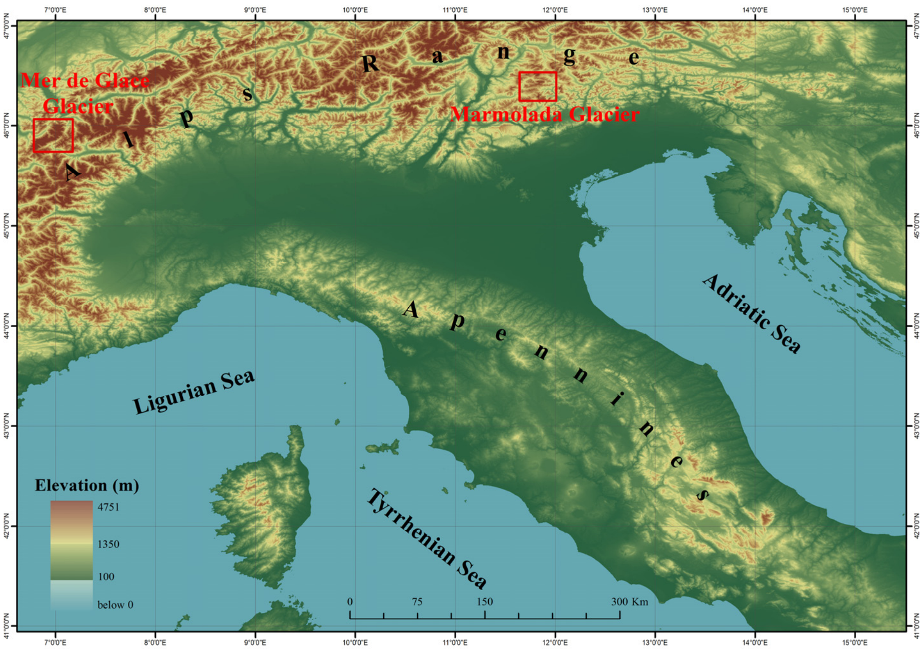

Fig. 1. Location of the Mer de Glace and Marmolada Glaciers on the Northern Italy map

The characteristics of current climate at worldwide level show a continuous increase of temperatures and a reduction of precipitation by 10% for the next five decades (Stavig et al., 2005). These scenarios are alarming for the melting of ice mass, rise in sea level and advancement of shorelines (Khalsa et al., 2004). An increase of mean temperatures by 1.0–3.5° Celsius is predicted for the 21st century (Houghton et al. 1995). The increase of CO_2 and greenhouse gas emissions has direct effects on global warming and on the ecosystems (Cox et al., 2000; Shaver et al. 2000). In this context of climate change, the first results indicate a greater retreat of Mer de Glace GL during 1984-2013, in comparison with Marmolada GL. Thus, the decrease of both GLs brings forward modifications of landscape (Nistor, 2013) and changes in the hydrologic balance. Our findings related to Mer de Glace and Marmolada GLs provide additional support to previous studies and may be useful for environmental sciences.

The paper is structured in five sections which approach the studied GLs in the current climate change situation. The first section of the work relates the impact of global warming on GLs. Section 2 provides information about the study area and its surroundings. Section 3 outlines our methods for assessing GLs challenges. In Section 4 the results obtained from applied methodology are presented and the possible effects of GLs retreat on natural systems are discussed. Our conclusions are provided in the final section.

2. STUDY AREA

The investigated GLs are positioned in the south-central part of Europe, in the Alps (fig. 1). Due to their geographical position and arched shape, the Alps have territories with "oceanic, continental, polar, Mediterranean and, on occasion, Saharan influences" (Beniston, 2006). A rise in temperatures by 2° C during 20^{th} century in the Alps was provided by Haeberli and Beniston (1998). Mer de Glace and Marmolada GLs are located over 1000 m above sea level (asl) and are classified as mountain GLs. Both GLs register a decline in ice mass area and volume, too.

2.1. Geographical setting of Mer de Glace GL

Mer de Glace (fig. 2) is the largest GL from Western Alps and is a compound valley GL. The GL is located in Savoy Alps in the East of France and has the coordinates 6°56' E – 45°53' N. It has a significant impact on tourism, alpinism and research in the north-western part of Mont Blanc. For its size, Mer de Glace is one of the most popular GL in the entire Chamonix Valley. Mer de Glace GL resulted as the confluence of Tacul GL and Léschaux GL. Some decades ago, the Telèfre GL was tributary of Mer de Glace GL, and together with Tacul GL and Léschaux GL, all four GLs cover around 32 km^2 (Kuhn, 2007). The tongue of Mer de Glace GL registers about 5 km in length. The maximum thickness is 400 m and was found at Tacul GL (Vivian, 2001). The lowest altitude of this GL is around 1832 m asl and is in the ablation zone, near Montenvers railway station (fig. 2). The accumulation area extends over 3500 m asl. Mer de Glace GL has the direction of flow to N-NW. The oldest data about the extension of GL dates from 1645s, when the tongue advanced to the Chamonix Valley, near the village, until 1720s (Mougin, 1912, mentioned by Kuhn, 2007). In 2001 the terminus of Mer de Glace ended at about 1467 m asl (Kuhn, 2007). According to the Köppen-Geiger climate classification, the GL is positioned in an area with microthermal climates (Dfc), characterized as fully humid (Kottek et al., 2006).

2.2. Geographical setting of Marmolada GL

Marmolada (fig. 3) is the largest GL in Dolomites Mountains and is a hanging GL. The GL is located on the northern flank of Marmolada Massif in Belluno Province, Italy, and has the coordinates 11°51' E – 46°26' N. The Dolomites were included in UNESCO World Heritage List in 2009 and represent an important tourist attraction.

Marmolada GL is approximately 3 km wide and about 1 km long in maximal sector. It is a small GL, with an area of 1.665 km^2. At Marmolada GL the tongue is missing. The GL lies between 2635 - 2935 m asl. In 2009 the maximum thickness was 52 m (Crepaz et al. 2010). Marmolada GL has the flow direction to the N.

Fig. 2. View of Mer de Glace Glacier from Montenvers Station at 1913 m, South-looking ground photograph

Fig. 3. View of Marmolada Glacier from Sella Pass 2240 m, South-East-looking ground photograph

The studies about GLs in the Dolomites provide the oldest data about the extension of Marmolada GL dating from 1888, belonging to Richter and later to Marinelli. As mentioned by Crepaz et al. (2010), Richter calculated in 1888 an area of 4.95 km^2 for Marmolada GL and in 1910, Marinelli reported an area of 3.35 km^2 for Main Marmolada and 0.57 km^2 for Western Marmolada. According to the data collected by Crepaz et al. (2010), in 1982 the Main Marmolada and Western Marmolada GLs had an extension of 2.98 km^2. Considering the Köppen-Geiger climate classification, the GL is positioned in an area with alpine climate (ET), characterized by a climate similar to tundra, where the warmest month has an average temperature between between 0 – 10° Celsius (Kottek et al., 2006).

3. Methods

3.1. General approach

To highlight the advantages of the used procedures, fig. 4 shows the steps and combination of remote sensing and GIS techniques carried out for the results of the present work. The methods are based on SIs and GIS, and this methodology was chosen because it is fast and easy to integrate for GLs study. Apart from these reasons, the applied methods enable us to acquire the best results at local scale. In order to validate the results, we appealed at field research and interpretation of the references about Mer de Glace and Marmolada GLs.

First of all, we collected the SIs and created a GIS database with the outlines of studied GLs, for 1984, 1999 and 2013. It was then possible to obtain the square area of each GL, in three years, with an appropriate interval of time: 13 – 15 years. The data collection by remote sensing for GLs was characterized by Gao and Liu (2001) as an efficient method. The field research was essential to check the limits of the GLs. Mer de Glace is covered at terminus by terminal moraines while medial and lateral moraines are present along the tongue. For a higher accuracy, we have taken the GLs limits using field data and SIs.

3.2. Remote sensing

We used remote sensing backed by field investigation to obtain the outlines of GLs and their size. Remote sensing was used to collect data from SIs courtesy by United States Geological Survey's Earth Resources Observation website (2014). The SIs belong to Landsat 4 and are images in visible spectrum. SIs from 1984 (TM sensor), 1999 (ETM sensor), and 2013 (OLI sensor) were used for observations regarding the fluctuations of Mer de Glace GL. SIs from 1986 (TM sensor), 1999 (ETM sensor), and 2013 (OLI sensor) were used for Marmolada GL. Remote sensing was applied only for images taken in autumn (Northern Hemisphere) to avoid the influence of snow. We used Landsat images because they are georeferenced and have full resolution. Another reason is that these images are easy to integrate in GIS (Holobâcă 2013). Thus, the implementation data were made in WGS 1984 Web Mercator.

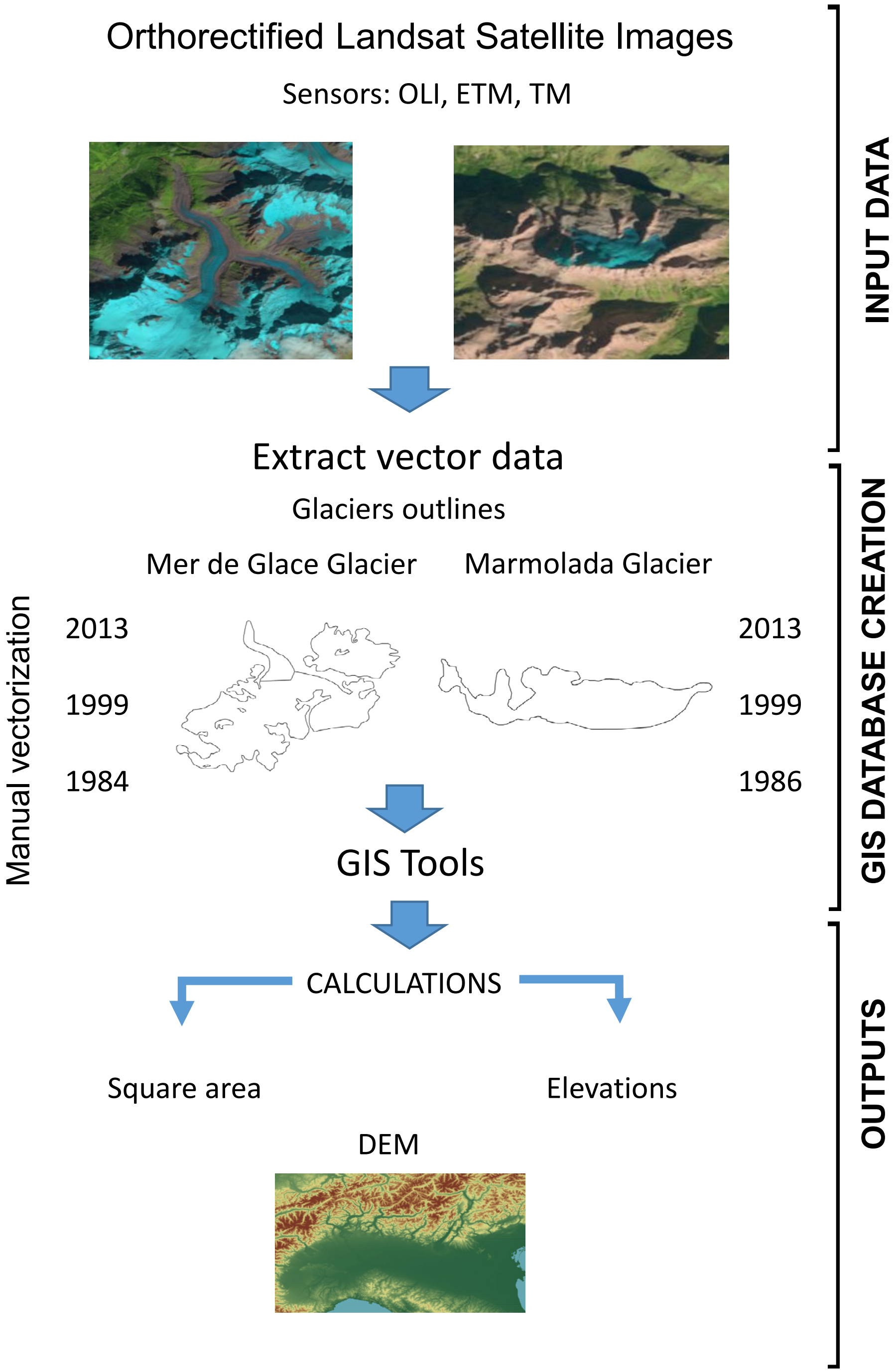

Fig. 4. General framework of the applied methodology

3.3. Vector data extraction

We extracted vector data by manual vectorization using GIS software. The manual vectorization is used by many experts in different fields of study (Elshehaby and Taha 2009; Fuller and Aboudarham, 2004; Wilson et al., 1999), even if is tedious (Hadeel et al. 2010). Raup et al. (2007) appreciate this procedure as a highly accurate method to extract the outlines of GLs. The vector data resulted after digitization of GLs in various years were compared to assess the changes.

In attempt to estimate the area of GLs, we used 'Calculate Geometry' tool from GIS Attribute Table applied for the polygons created in chosen years and then the average retreat rates were calculated. The advantage of this method is that through manual vectorization one can more precisely estimate areas with data analysis, than raster analysis.

4. RESULTS AND DISCUSSION

A total of 2.365 km^2 in area of Mer de Glace GL and 1.035 km^2 in area of Marmolada GL (table 1) were lost between 1984 and 2013 and between 1986 and 2013 respectively. As a response to increasing temperatures due to recent climate changes, both studied GLs diminished significantly (fig. 5, 6). The changes in covered area by Mer de Glace and Marmolada GLs were identified using remote sensing with SIs. Making the difference between the initial area (1984 at Mer de Glace GL and 1986 at Marmolada GL) and their area in 2013, it was possible to assess the decrease of each GL. Using GIS tools, the terminus position was checked at Mer de Glace and the part with major retreat was detected in the case of Marmolada GL.

Table 1.

Assessment area of glaciers

Year	Mer de Glace Glacier area* (km^2)	Year	Marmolada Glacier area (km^2)
1984	6.861	1986	2.699
1999	5.944	1999	2.233
2013	4.495	2013	1.665
Total	2.365	Total	1.035

*The values represent only Mer de Glace size, without tributaries

Fluctuation in area and length were identified at Mer de Glace GL from the analysis of the vector data obtained by manual vectorization. Between 1984 and 1999 this GL decreased by 0.917 km^2 and recorded a 881.73 m of retreat at terminus. In the second half period of data observations, Mer de Glace GL diminished by 1.449 km^2 in area and retreated at terminus by 996.8 m. The comparison of the changes of Mer de Glace GL in the two periods showed that the decrease was higher (fig. 7) between 1999 and 2013. Thus, in the first period a withdrawal rate of 0.061 km^2/year was obtained while in the second period the withdrawal rate was 0.104 km^2/year.

Marmolada GL diminished by 0.466 km^2 between 1986 and 1999 and the largest decline was noticed in its western part. For the same period a mean annual withdrawal rate of 0.036 km^2/year was obtained. It is interesting to note that Marmolada GL in this period decreased in area but some ice-lobes advanced, probably due to more water in the ice mass. Between 1999 and 2013 Marmolada GL reduced its area by 0.568 km^2 and a ratio of 0.041 km^2/year was found (fig. 8).

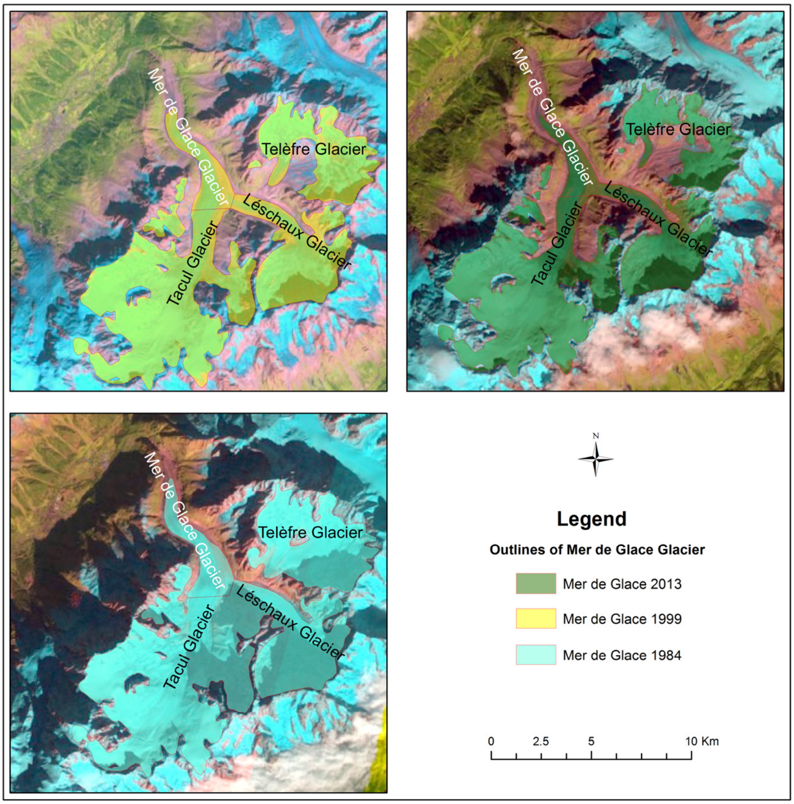

Fig. 5. Landsat full resolution mosaic images of Mer de Glace Glacier, outlines in 1984, 1999, 2013. Landsat images courtesy of the U.S. Geological Survey

Results for Mer de Glace GL were expected, because the tongue of the GL is spread at lower altitude compared to Marmolada GL. Unexpectedly, between 1986 and 2013, Marmolada GL decreased to half and in some portions of the western part of the GL the slip plane was uncovered.

Our findings would seem to suggest that Mer de Glace and Marmolada GLs decreased in area under recent global warming. At the same time, tourism in Chamonix-Mont Blanc area and in Marmolada Mountains contributes to the melting of both GLs. We are aware that our research may have some limitations. In this paper we analysed only the area and length, without computing the volume of melting ice and we did not indicate where the lowest thickness points are. Other limitation is that field surveys were not performed in the 1980s and 1990s, but only in the last three years.

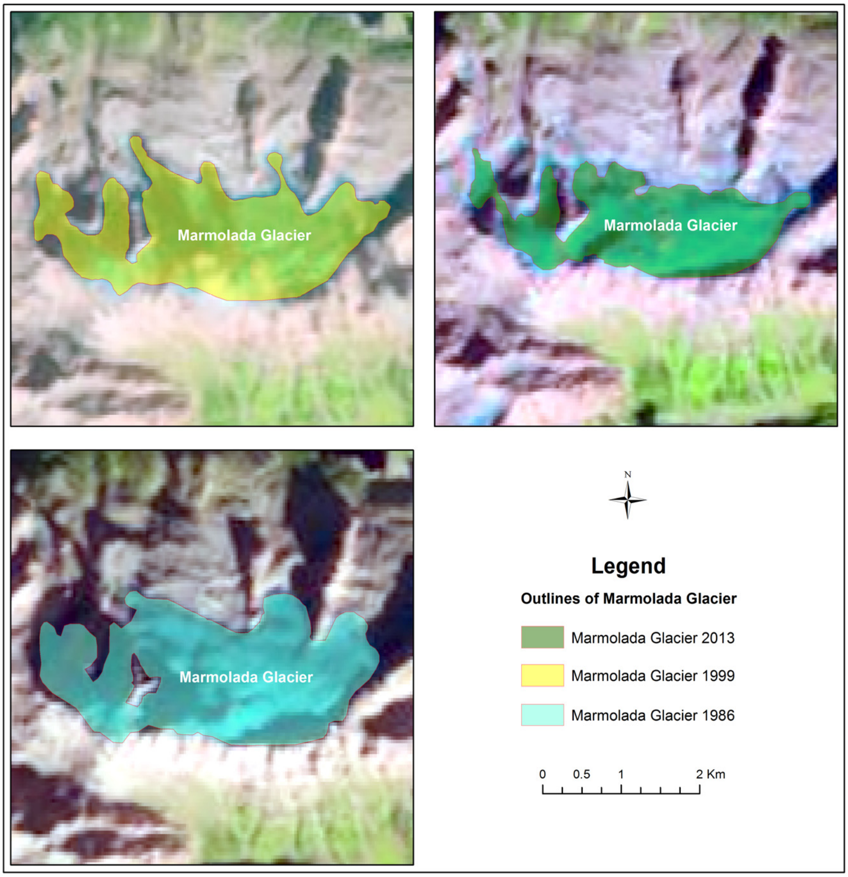

Fig. 6. Landsat full resolution mosaic images of Marmolada Glacier, outlines in 1986, 1999, 2013. Landsat images courtesy of the U.S. Geological Survey

One of the main goals of this research was to assess the GLs changes using SIs and GIS, during the last three decades. The overall direction of results showed trends that could be helpful to understand how climate influences the retreat of two GLs located in different sites of Alps, but at close latitude. The retreat of Mer de Glace and Marmolada GLs does not affect directly the human settlements and the sea level, but together with climate warming, the melting of GLs could induce changes in the natural systems (Campos et al., 2013). Thus, the reducing of Mer de Glace GL contributes to the increased flow discharge of Torrent del Drus and L'Arveyron Creeks. With the withdrawal of the GL, the lateral walls are exposed at rock falls and this could be problematic for tourism activities.

Kuhn (2007) illustrated in his work the fluctuations of Mer de Glace for more than 400 years including historical data for the reconstruction the GL situation, before the Little Ice Age. Kuhn offered information about population complaints from

Chamonix that suggest a great advancement of Mer de Glace GL before 1500. In 1932, mentioned by Kuhn (2007), Kinzl stated that in 1605 the GL created destructions as a result of floods. He found documents and archives from the 18th century belonging to De Saussure and Bourrit and other studies focused on glaciology dating from the 19th century. Studying the moraines material and historical documents, Kuhn (2007) discovered that during the 1820s and 1850s the Mer De Glace GL had a considerable extension for the 19th century. The large decrease in volume was demonstrated by Kuhn (2007) for the 1939 – 2001 period. For the same period, he estimated a retreat ratio of 30 cm/year.

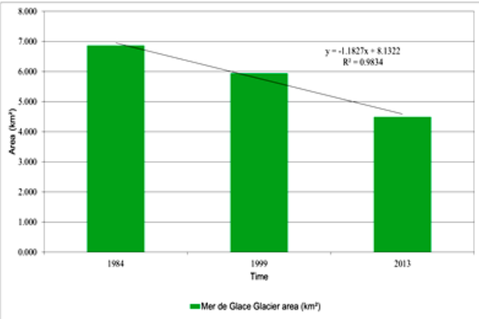

Fig. 7. The area coverage of Mer de Glace GL evaluated by analysis of satellite images and GIS (1984-2013)

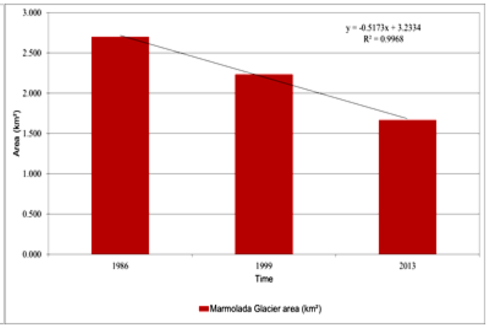

Fig. 8. The area coverage of Marmolada GL evaluated by analysis of satellite images and GIS (1986-2013)

Looking at the fluctuations of GLs in the Dolomites Mountains, Crepaz et al. (2010) confirmed a decrease of GLs by more than 50% during the last century. The largest ice mass melted during the last 30 years. In their investigation on Marmolada GL, Crepaz et al. (2010) showed that the volume of the GL reduced by 9337741 m^3 between 2004 and 2009. He noted that Marmolada GL reduced its area by 52%, in the last three decades. Our results bear a close resemblance to the findings of Crepaz et al. (2010). On the other hand, Marmolada is the largest GL in the Dolomites Mountains of the Southern Alps and its melting represents an important loss. For this reason it was monitored and in 2013 the geologist Dr. Mirco Poletto underlined that the reduction of Marmolada GL was stopped: "This year the weather has brought snow layers that have prevented it from melting." (Ice Age Now website, 2013).

5. CONCLUSIONS

This paper provides an account of two GLs situated in different locations in the European Alps. The evidence of this study implies that Landsat images and GIS have a major importance for the studies concerning area covered by GLs. The results suggest that Mer de Glace and Marmolada GLs reduced their area, above all in the last two decades. We have been able to estimate the area of each inventoried GL in various intervals of time and we succeeded in calculating the retreat ratio of set periods.

Consequently, we observed that the Mer de Glace diminished much more than Marmolada GL, due to its extension at lower elevations. In addition we believe that our findings could be useful for glaciology, climatology, geomorphology, hydrology and other Earth Sciences. We hope that our findings may influence policy planning of the territory flooded with tourists near Mer de Glace and Marmolada GLs, to reduce the negative impact of human activities on these GLs. Future work will entail the refinement of these results and the usage of data from other satellites sensors. At the same time, the adopted methods could be applied to other GLs.

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