

Preliminary observation of Marmolada glacier collapse of July 2022 with space-based cameras

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On 3 July 2022, a section of the Marmolada glacier (Marmolada Group, Fassa Dolomites, Southern Limestone Alps) collapsed, causing an ice avalanche resulting in the death of eleven alpinists. Before the event, there were no clear signs of any potential collapse, and no warning notices were broadcasted; due to the velocity of the avalanche, no escape was possible for the involved persons. In this work, a preliminary analysis of the Marmolada glacier collapse is performed with four optical channels space imaging provided by Planet Labs, with resolution of 3 m per pixel. Pre- and post-event satellite observations are employed to assess the areas involved in the event: multispectral images can be compared to identify the collapse area and the debris conoid. A first estimation suggests a collapse area of about 4800 m² and a collapse volume of about 96,000 m³. In addition, historical data from the Planet Labs optical pictures database can be employed to compare the status of the detached glacier and the evolution of the crevasses on its surface.

Keywords: Space imaging; glacier; observations

1. Introduction

Among the various applications of satellite imaging, the detection of artificial and natural disaster showed a continuous growth in the past decades [Voigt, 2016]. Advanced optical and radar imagery of seas and lands is provided at increasing high-frequency intervals and data from different satellite systems can be integrated to further improve disaster analysis and management [Higuchi, 2021]. In addition, space observations can be employed for an accurate mapping of potentially dangerous areas for the continuous monitoring of critical systems and the forecasting of hazardous events [Pallister, 2019] [Sarker, 2020]. Limitations in ground observability (e.g.: due to cloud coverage or passages repetition cycles) are mitigated by the growing number of satellites dedicated to Earth observation [Wang, 2020], the simplification in data access and dissemination

[Gomes, 2020], and the integration with high-definition SAR (**Synthetic-Aperture Radar**) data [Torres, 2019]. As reference, spacecraft imaging was employed to monitor, analyse, and reconstruct landslide events [Roman-Gonzalez, 2017][Quin, 2021][Bovenga, 2017][Shugar, 2021], floods [Notti, 2018][Schumann, 2018][An, 2022], glaciers collapses [Kääb, 2018][Huggel, 2005][Paul, 2019] and rock/ice avalanches [Zhao, 2022].

The Marmolada glacier is currently the largest glacier in of the Dolomites, in the North-East of Italy, lying on the northern slopes of the Marmolada massif; in 2014, the ice thickness was on average about 13 m, reaching a maximum value of 50 m on specific locations [Santin, 2019]. The glacier was subjected to a dramatic shrinking in the last years, with a front retreat up to 30 m per year and a reduction of its area by about 66% from 1888 to 2015; it is currently divided in several sectors separated by rocky outcrops [Santin, 2019]. Surveys have been employed to study its historical evolution and models predict that before 2050 the glacier will likely disappear [Santin, 2019]. Mountaineering routes cross the glacier to reach the Marmolada main peaks, Punta Penia (3343 m) and Punta Rocca (3301 m), the latter served by a cable car and partially anthropized with downhill skiing facilities. Despite subjected to larger winter avalanches (e.g., in 1916 [Brugnara, 2017] and in 2020), to the knowledge of the authors no large ice collapse was registered before July 2022.

In this context, this work investigates the Marmolada glacier collapse event of **3 July** 2022. At about 13.45, a large section of the glacier detached from an altitude of about 3200 m (Figure 1, left) and generated a large avalanche of ice and rocks. The debris slid on the lower section of the glacier and on the rock bed, stopping to less steep slopes at about 2600 m (Figure 1, right), sweeping over and killing eleven alpinists along its course and depositing a large conoid.



Figure 1: On the left, (a) collapsed area of the Marmolada glacier (credits: Italian Alpine Rescue Services). On the right, pictures of the glacier before (b) and after (c) the incident, with red circles highlighting the collapse area and blue circles the debris deposit (credits: Panoramix GmbH, Arabba-Porta Vescovo Webcam).

In the next section, temperature data from a meteorological station close to the collapse area are introduced to show the anomaly of summer 2022. In the following section, space observations before and after the incident are compared to show the event magnitude and the terrain transformation before and after the collapse; image comparison allows the detection of the collapse area and of the debris deposit. In addition, historical images of the area involved in the detachment are shown highlighting the evolution of the main crevasse crossing it.

2. Meteorological data

In the weeks prior to the event, the temperatures in the area were well above the period average. Figure 2 shows the temperature trend for the meteorological station of Punta Rocca, slightly above (few tens of meters) and close (at a distance of about 260 m) to the collapse area: solid lines report respectively the maximum (red), average (green) and minimum (blue) temperature [Punta Rocca meteorological data – last 60 days, 2022] for

the last 60 days, compared to the average month temperature [Punta Rocca meteorological data – years 1994-2021, 2022][24] for the period 1994-2021. It can be noted that the measured temperature is always well above the period average, with only one day (June 9th) showing an average temperature below it. In addition, while for the 2020-2021 winter season snow precipitations were above the average with respect to the previous years, the 2021-22 was well below average, with long periods with no precipitation at all [Winter seasons snow and meteorological reports, 2022]. Under these circumstances, the snow deposit on the glacier mostly melted, exposing the ice below it with a large **anticipation** with respect to previous years: conditions on the glacier were comparable to late summer ones. Despite that, no warning was declared nor a survey performed few days before the event [Marmolada: on flight above the glacier that is disappearing, 2022] suggested that a large collapse could have affected any section of the glacier; scientist concerns were mostly related to the possibility that its disappearing would be faster than expected.

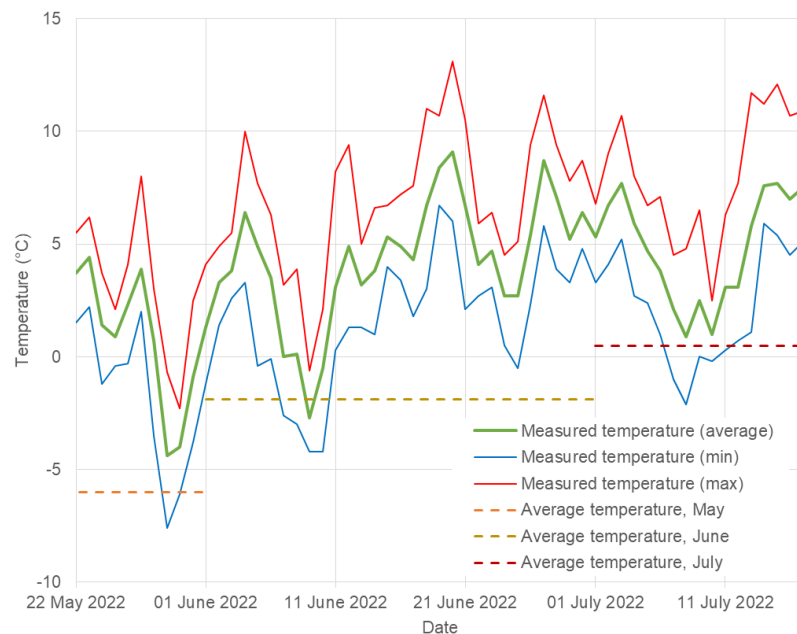


Figure 2: Temperature trend of Punta Rocca meteorological station (3250 m) **in 2022** (solid lines, [Punta Rocca meteorological data – last 60 days, 2022][23]), compared to

average data for the period 1994-2021 (dashed lines, [Punta Rocca meteorological data – years 1994-2021, 2022]).

3. Observation data

Images of the north slopes of Marmolada massif were provided by Planet Labs and can be seen in Figure 3. They have a resolution of 3 m per pixel and consist in 4-channels georeferenced images (red, green, blue, and near-infrared). In the pictures the residual glacier with traces of snow can be seen on the bottom, while the large shape of the Fedaia artificial lake is clearly recognizable on the top. The first picture, before the glacier collapse, dates to **26 June**; while partial cloud coverage can be seen in the bottom right part of the image, the area involved in the event (highlighted with a red box) is clearly visible. The position of the Punta Rocca meteorological station is also indicated. The second picture, from **6 July** (three days after the collapse) was taken with clear sky; again, the area interested by the event is highlighted. Other images closer to the event, available from Planet Labs, were affected by clouds and are not employed in this work.

From the comparison of the two pictures, it is already possible to recognize the collapse area (the white surface of clean ice, appearing at the bottom of the box on the **6 July** image) and the debris conoid (darker areas in the centre and on the top of the box): the large amount of material transported by the avalanche, including ice blocks and boulders, is clearly visible.

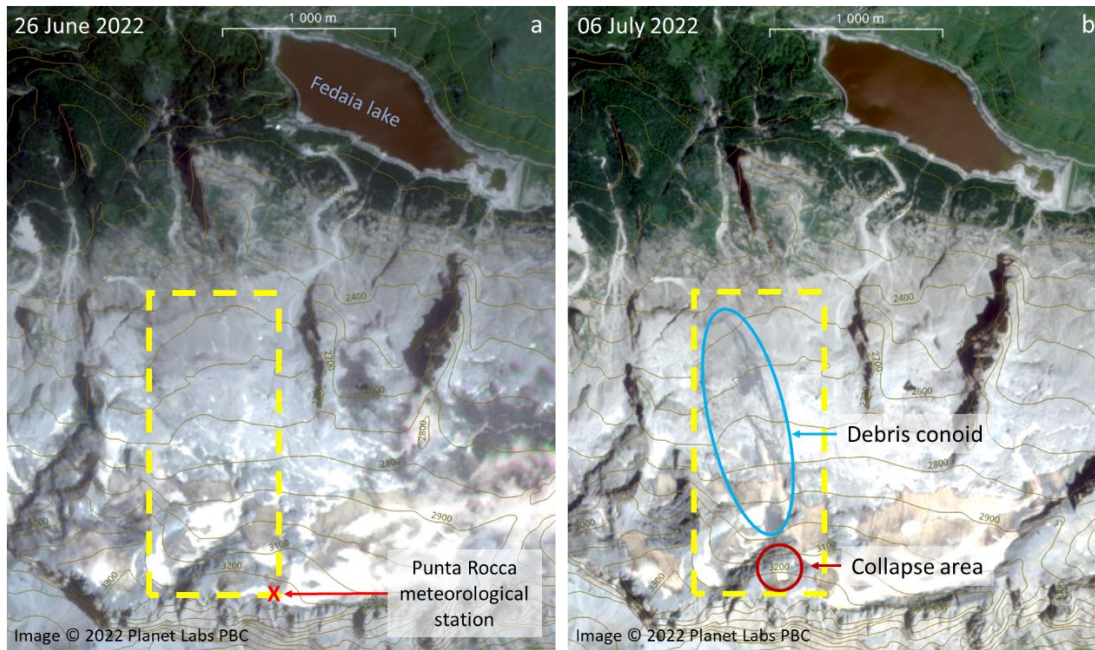


Figure 3: Overview of the Marmolada north slopes and glacier, with highlighted (yellow) the area involved in the event, the collapse (red) and the debris conoid (blue). On the left (a), picture from 26 June; on the right (b), the same area on 6 July.

A more detailed image, cropped from 6 July data, can be seen in Figure 4 (left). In this case the course of the avalanche can be clearly observed as the darker area in the centre and the top of the picture. A simple image elaboration, described in the following lines, allows to highlight the collapse area (in red, Figure 4, centre) and the debris deposit (in blue, Figure 4, right).

The collapse area has been determined by subtracting the red monochrome channel images before and after the event and defining a threshold level, as in this band a higher contrast exists between the darker surface of the glacier and the clean area exposed by the detachment; for this work, employing GeoTIFF pictures with 16 bit per channel, a threshold value of -2000 on pixel DN (Digital Number) has been selected. Few other surfaces are similarly detected by this approach (small red areas in Figure 4, centre), due to the excessive luminance of snow deposits directly illuminated by the Sun in the 6 July

picture.

In a similar fashion, the conoid area has been determined from red monochrome images subtraction and threshold definition (threshold value of +1000). In this case, spurious data affect the left side of Figure 4, right, due to the melting of surface snow in the few days between pictures collection. It shall be noted that the threshold values were selected with a trial and error method and the performance of this algorithm shall be tested with other test cases; despite that, this analysis helps determining the areas directly affected by the avalanche. In fact, this simple and quick method, together with airborne surveys, can potentially support the organization and deployment of ground rescue teams.

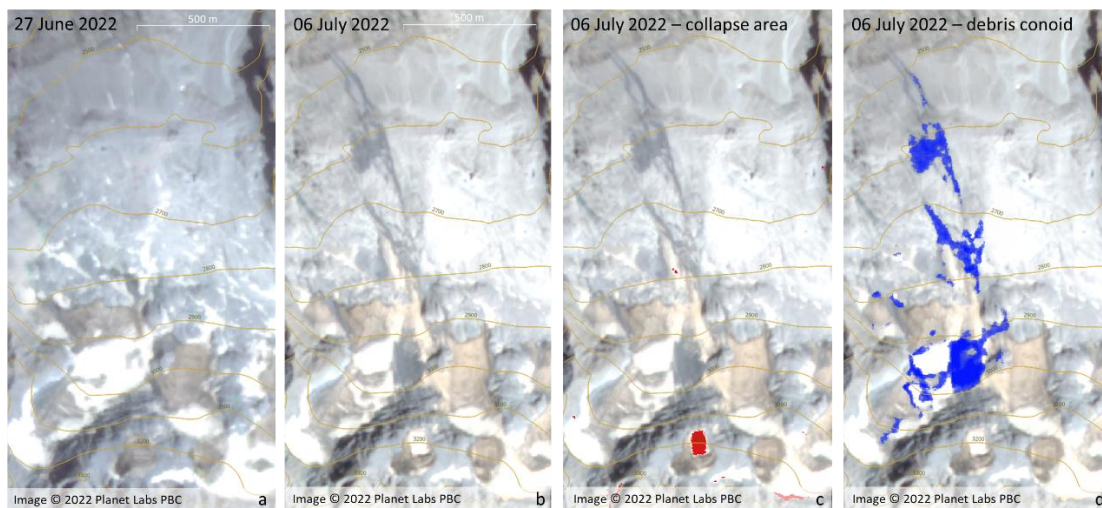


Figure 4: From left to right, zoom of the area involved in the collapse and consequent avalanche (pictures from **27 June, a**, and **6 July, b**), reconstruction (**c**) of the collapse area (filled in red), and determination (**d**) of the debris conoid (filled in blue) from comparison with **26 June** image.

4. Time series of collapse area crevasse

In this section, the time evolution of the collapse area is reported by comparing images collected from August 2021 to July 2022 from Planet Labs database; all pictures have a

resolution of 3 m per pixel. Figure 5 shows magnified views of the glacier, with red arrows indicating the upper limit of the collapse. It can be seen that the lower part of this area of the glacier (grey half-circle above the arrows) was free of snow on August 10, 2021 (first image, top left); the higher section of the glacier, below the arrows, was still covered by the winter deposit. As previously mentioned, the 2020-2021 winter season snow precipitations were above the average with respect to the previous years; **in contrast**, the 2021-22 was well below average, with long periods with no precipitation at all [Winter seasons snow and meteorological reports (in Italian), ARPA Veneto, 2022]. The second image in Figure 5 shows the same area on **18 April** 2022; in this case the snow is not covering the whole glacier, with a larger fraction of the area above the arrows (lower part) already exposed. Both the first and the second picture do not clearly show the presence of a crevasse at the location indicated by the arrows; however, the straight boundary that can be observed in both pictures between the higher and the lower parts of the glacier suggest that in this location the surface was already affected by cracks. Pictures from **18 June** to **2 July** clearly show the crevasse affecting the whole longitudinal section of the glacier; the snow cover is mostly melted also on the upper part (below the red arrows) on **18 June**. Pictures from **6 July** and **9 July** show the glacier after the collapse; the area involved in the detachment is clearly visible due to the higher brightness of the exposed ice. The affected area is highlighted in green in the last picture (bottom left) and is determined by subtracting the red monochrome channel images before and after the event, as reported in the previous section; this analysis allows determining a detachment surface of about 5140 m². The shape of the collapsed area is roughly rectangular, with a longitudinal section (i.e.: in the direction of the crevasse) of about 60 m and a length of about 80 m. In a first approximation, considering an average ice thickness of 20 m, the collapsed volume of ice can be estimated of about 96,000 m³. This result is in line with

the fast-response data elaborated by the French CESBIO (Centre d'Etudes Spatiales de la Biosphère) from the digital elevation model of the Pléiades stereo images, estimating a collapse volume of $65,000 \pm 10,000 \text{ m}^3$ [Estimation of Marmolada glacier collapse volume using Pléiades imagery, 2022][21]. Further analysis with calibrated data and ground measurements shall be performed in the next months to improve the volume estimation.

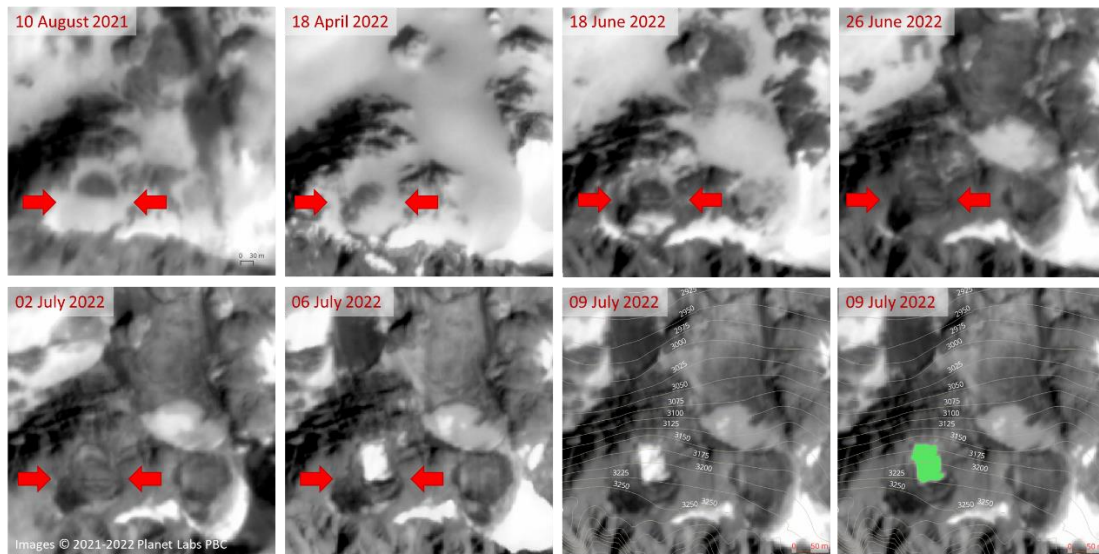


Figure 5: Time series of the glacier evolution from August 2021 to July 2022 from Planet Lab database. The crevasse (detectable since **18 June**) is highlighted with red arrows; the extension of the collapsed area is filled in green in the last frame.

In conclusion, the detachment event was hardly predictable with the information available to the incident date; space imaging does not suggest any particular evolution of this section of the glacier between **18 June** and **02 July**. However, satellite data suggest that the crevasse (or at least some surface cracks) was already present one year ago, as highlighted in Figure 5; the differential snow cover distribution detected on August 2021 further suggests it. In addition, thanks to pictures comparison, it was possible to evaluate the area affected by the collapse.

5. Conclusions

In this work a preliminary analysis of satellites images of the Marmolada glacier before and after the 3 July event was presented. Results show that space imaging can be employed in reconstructing the areas involved in the event; in particular, the collapse area and the debris conoid can be clearly observed and evaluated by image analysis.

The observation of historical images of the section of the glacier subjected to the collapse suggests that a crevasse or some cracks were already appearing from August 2021; while the event was hardly forecastable, space imaging would have allowed its identification and mapping with a good advance. Image analysis allowed determining the surface and the shape of the collapse area (a rectangle of about 4800 m²); additional data, such as high-resolution SAR, would also provide the thickness of the ice, allowing the determination of the volume of the collapse.

In conclusion, space imaging could provide rapid information on the areas affected by the event and on its evolution before and after the collapse. Satellites pictures can help scientists and researchers to better understand the mechanisms behind collapse and to determine the areas that might be affected by future collapses. Fast response analysis can also help determining the areas directly affected by the avalanche and therefore, together with airborne surveys, can support the organization and deployment of ground rescue teams.

Data statement:

The data that support the findings of this study are available from the corresponding author, LO, upon reasonable request.

Funding: This research received no external funding.

Acknowledgments: Image data services were provided by Planet team (2017), Planet Application Program Interface: in Space for Life on Earth, San Francisco, Ca. <https://api.planet.com>

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