The final countdown? Monitoring the rapid shrinkage of the Maladeta glacier (2010-2020), Southern Pyrenees

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Abstract

Small glaciers are one of the best indicators of climatic variations and their short-term effects. Located in the Spanish Pyrenees, the Maladeta is one of these glaciers. Its systematic observation began in the 1980s, being one of the few Pyrenean glaciers with a tongue-shaped front. This study presents the evolution of the Maladeta glacial tongue over a decade (2010-2020) through multiple geomatic techniques. Surveys have ranged from Total Stations and Global Navigation Satellite Systems devices to massive data capture techniques such as Terrestrial Laser Scanners or Unmanned Aerial Vehicles photogrammetry. The aim is to analyse in detail the loss of surface area and thickness of the glacier and its transition from being a glacier with a tongue partially determined by climate to a topoclimatically determined cirque glacier. The results reveal a tongue retreat of over 5 m/yr and area losses of over 0.2 ha/yr, along with ice thickness and volume losses of -1.7 m/yr and over -21 x10^3 m^3/yr, respectively. If this trend continues, the tongue, and possibly the Maladeta glacier, could disappear by the end of the 2030s.

Keywords

Glaciology, Global Change, Monitoring, Geomatics, Terrestrial Laser Scanning (TLS), Photogrammetry, Unmanned Aerial Vehicle (UAV), Pyrenees

1. Introduction

Mountain glaciers are considered one of the best indicators of climate and environmental changes, and small glaciers (surface area less than < 0.5 km^2) are particularly appropriate for understanding short-term climatic variations and their effects (Fischer, 2018). Nevertheless, the involved processes and the relationships among glacier size, climatic and topoclimatic factors are not always straightforward in smaller glaciers, as the local topography is highly influential (Colucci, 2016; Fischer, 2018; Gachev, 2022; López-Moreno et al., 2019; Sommer et al., 2020).

The glaciers of the Pyrenees are all small, dominantly cirque glaciers and they are located at high elevation (González-Trueba et al., 2008; Rico et al., 2017; Serrano, 2022; Vidaller et al., 2021). During the Little Ice Age (LIA), there were over a hundred glaciers, of which 83% have now disappeared (González-Trueba et al., 2008; Oliva et al., 2018; Serrano & Martín-Moreno, 2018). The maximum glacial expansion during the LIA is not well known, although previous studies point to a maximum extension between the end of the 17th and the middle of the 18th century (1680-1750), coinciding with the Maunder minimum (Serrano and Martín, 2018; Oliva et al., 2018), when the most extensive glacier was the Aneto with 236 ha (González-Trueba et al., 2008).

The retreat and disappearance of small glaciers shows diverse processes involving basal fusion, collapses, gradual covering by clasts, and relict glacier ice conserved for long periods on the glacial cirques. Topographic factors may delay their disappearance since remaining ice bodies are located in glacial cirques sheltered from high solar radiation, fed by avalanches, and often covered by debris that protects them from insolation (González-Trueba et al., 2008; Rico, 2019; Vidaller et al., 2021). During the later stages of degradation the changes in the surface of Pyrenean glaciers have been small because of the influence of local topoclimatic factors (Carturan et al., 2013; Fischer, 2018; Huss & Fischer, 2016; López-Moreno et al., 2006; Rico, 2019).

In the Pyrenees, temperature increases have been estimated between 0.9 ºC and 1.2ºC since the LIA (Feuillet & Mercier, 2012; Serrano et al., 2002; OPCC, 2022), corresponding to an increment of approximately 0.02°/yr between 1951 and 2010 (Deaux et al., 2014). The air warming leads to the rise in the Equilibrium Line Altitude (ELA), which in the Maladeta massif, where the highest peaks reach between 3100 and 3400 m a.s.l., is above 3150 m a.s.l. (WGMS, 2015). The annual losses in thickness reveal the imbalance of Pyrenean glaciers under current climatic conditions (Chueca et al., 2007; Del Rio et al., 2014; López-Moreno et al., 2019; Moreno, 2016; René, 2013; Rico et al., 2014; Vidaller et al., 2021). Climate models estimate a temperature increase of over 1ºC by 2050 (Amblar et al., 2017) and point to the disappearance of a large proportion of European glaciers by the middle of the 21st century, including those of the Pyrenees due to their small size, southern location and unfavourable climatic factors, such as the decrease in snowfall and the increase in temperatures and summer radiation (Bonsoms et al., 2022; Del Rio et al., 2014; López-Moreno et al., 2019; Marti et al., 2015).

During the final stages of degradation, climatic factors are less critical than topoclimatic factors in the evolution of the ice body (López-Moreno et al., 2006) and small glaciers can persist under conditions of climate imbalance, not responding directly to regional climatic changes (DeBeer & Sharp, 2009; Grunewald & Scheithauer, 2010; Hughes, 2009). Some authors point to faster variations of the smallest glaciers when the climatic factors are dominant (DeBeer & Sharp, 2009; Fischer, 2018; Fischer et al., 2016; Vidaller et al., 2021). Therefore, it becomes crucial to know the processes of degradation and disappearance of small glaciers and their geomorphological and environmental responses to climate change.

The application of geomatic techniques in studies related to the cryosphere is common, revealing their advantages and limitations (Colucci & Guglielmin, 2015; Fischer, 2018; Fischer et al., 2016; López-Moreno et al., 2016, 2019; Rico et al., 2017; Martínez-Fernández et al., 2019, 2022). Models from classical and more recent techniques can be combined to generate valuable information on cryospheric processes. These records can cover a broad time range and complement recent high-resolution geometric data. In the case of the Maladeta glacier, its mass balance has been studied for decades using traditional methods (Eduardo Martínez de Pisón & Arenillas, 1988), but it is with the introduction of geomatic techniques that it has been possible to analyse in detail the evolution of the front.

This study aims to analyse (i) the loss of surface area and thickness of the glacial tongue of the Maladeta between 2010 and 2020, (ii) the transition of a tongue glacier to a cirque glacier, and (iii) to assess the applicability and quality of the used geomatic techniques (Total Stations, Global Navigation Satellite System devices, Terrestrial Laser Scanners and Aerial Photogrammetry using Unmanned Aerial Vehicles (UAV).

2. The Maladeta glacier

The Maladeta glacier (42º39´N, 0º36´E, Figure 1) is located on the N slope of the peak of the same name (3308 m a.s.l.) within the massif of Maladeta, the highest in the Pyrenees (Aneto peak, 3404 m a.s.l.). Glacier is located above 2895 m a.s.l., it has 700 m wide and 610 m long (according to orthomosaics CC-BY 4.0 scne.es 2021), and the surrounding substrate is granite. According to the World Glacier Monitoring Service (WGMS), it is a mountain glacier, simple basin and cirque with tongue.

Its evolution has been monitored since the 1980s (Martínez de Pisón & Arenillas, 1988), and the glacial mass balance measured since 1991 (Arenillas et al., 2008; Cobos et al., 2017; García-García, 1997; Jiménez, 2016; Martínez de Pisón, E Navarro et al., 1997; E Martínez de Pisón et al., 1995; Martínez et al., 1997; Martínez & García, 1994; Mora et al., 2006; Moreno, 2016; WGMS, 2015).

The glacier developed during the LIA, in 1992, it divided into two parts and, at present, has lost around 85% of the LIA maximum area. A very fast retreat in the 1990s was followed by an increased mass loss in the 21st century (Chueca et al., 2003, 2005, 2007). The surface decrease was at a rate between 2.6 ha/yr and 3 ha/yr from from 1993 to 2007 (Chueca et al., 2007; Jiménez, 2016; Rico et al., 2017), and it was accompanied by ice thinning and length shortening.

The losses in thickness between 1994 and 2013 surpass -16 m, with mean losses close to -1 m/yr (Jiménez, 2016; WGMS, 2015), and between 2011 and 2020, the thickness loss was estimated at -0.82 m/yr for a total of -7.4 m (Vidaller et al., 2021).

The mass balance of the glacier varies annually, though mass losses are dominant, between -1.6 m w.e./yr and -2.4 m w.e./yr, whereas the years with a positive balance do not surpass 0.39 m w.e./yr. The glacier loses mass irregularly. It lost -0.45 m w.e./yr between 1991 and 2008; between 2008 and 2020, this rate doubled with estimates for the period 2008-2016 of -0.9 m w.e./yr and -0.7 m w.e./yr between 2011 and 2020 (Jiménez, 2016; Moreno, 2016; Rico, 2019; Vidaller et al., 2021).

The ELA was located over 2950 m a.s.l. in 2004 (Chueca et al., 2005) and in positive balances years, such as in 2013 and 2018, it was above 3060 m (WGMS, 2015) and 3130 m (Rico, 2019), respectively. In the years with negative balances, as in 2014, 2015, 2016, 2017, 2019, 2020 and 2021, the ELA was always above 3150 m a.s.l., and only three of the last 10 years have had a positive mass balance (WGMS, 2015, 2022).

The structure, morphology and dynamics of the glacier reveal two different environments:

i) The cirque: upper sector represents 81% of the surface area of the glacier (2021). The accumulation zone is located over 3090 m a.s.l. elevation and has a moderate slope and transversal crevasses. The mean glacial flow between 1991 and 2011 was 2.9-4.9 m/yr, whereas, in 2016, displacement was 2.4-3 m/yr (Jiménez, 2016). Differences in ice flow rates generate crevasses of metric width across the central part. The glacier in the 1990s reached 50 m thickness (Martínez et al., 1997; Martínez & García, 1994), in 2008 the thickness was 40 m (Jiménez, 2016) and in 2017 it was 26 m (Cobos et al., 2017).

ii) The tongue: it is a small tongue representing 19% of the glacier surface area (2021). The elevation of the front has risen over the years, standing at 2790 m a.s.l. in 1994, 2870 m in 2013 (WGMS, 2015), and 2895 m in 2020. In the 1990s, it had a slope of ≈28º and a length of ≈600 m, which has currently (2022) decreased to less than 250 m while its slope has increased to ≈32º. The ice front has a beveled morphology characteristic of retreating tongues. The tongue has transverse shear crevasses resulting from glacier thrust on stagnation ice, and debris carried by ablation processes partially covers it. A decrease in flow velocity is evident, from mean velocities of 3.7 m/yr between 1991 and 2011, to 1.6 m/yr in 2016 (Moreno, 2016). Cavities due to basal melting are common, causing glacier hollowing and collapse processes. These processes contributed to the loss of thickness of over -34 m (-1.9 m/yr) between 1994 and 2013 (WGMS, 2015).

3. Materials and Methods

The advance of the geomatic techniques and their application in high mountain environments affected measurement strategies. The topographic data recorded in the present study consist of a compendium of nine years of annual measurements on Maladeta, where limitations have been logistical (personnel and equipment), physical (accessibility), temporal (daylight hours) and meteorological. During this period, four techniques or devices were used: Total stations (TS), Global Navigation Satellite System (GNSS) devices, Terrestrial Laser Scanners (TLS) and aerial photogrammetry (AP) using UAVs (Table 1).

Information on the perimeter and surface area of the glacier tongue was extracted from the techniques mentioned above. Each technique had different characteristics regarding range, precision and sampling density (Figure 2). In the first years, GNSS devices were used in defining the perimeter of the front in addition to TS equipment to determine ice surface changes (Rico, 2019). This latter equipment was the most commonly used on Maladeta during the years of monitoring. In 2017, TLS systems were incorporated to monitor the retreat of the front and the loss of thickness. TLS data were georeferenced in the local reference system established for TS surveys in 2010. The incorporation of the TLS and AP in the 2019 measurement campaign led to the abandonment of TS use in 2020. In 2019, GNSS devices were employed with two aims. Firstly, to provide support for the TLS and AP surveys, and secondly, to transform the local reference system to an absolute one for the joint analysis of the measurements collected over the 10 years of monitoring. Detailed information on the equipment used and the data collection process can be found in Appendix 1.

Despite the use of multiple techniques to monitor the geometry of the glacier tongue, the quantification of the retreat and loss in thickness of the surface is presented through the topographic data that can provide more meaningful geometric information about the glacier. In this way, TLS and later AP techniques replaced TS and GNSS devices, although the latter continued to be used to support the surveys.

The glacier tongue degradation processes were quantified using direct measurements and derived products, orthoimages and digital elevation models (DEM) from the topographic surveys. The front retreat was determined by computing distances and surfaces between the perimeters defined by the measurements and orthoimages. Simultaneously, the thickness loss was derived from the subtraction of DEMs generated from different interpolation methods based on the acquired data. A detailed description of the methods used to quantify the retreat and thickness loss of the glacier tongue can be found in Appendix 2.

Due to the influence of survey quality on the quantification of glacier degradation, comparisons were made between perimeters and elevation models obtained from different geomatics techniques (TS, TLS and AP) in a single campaign. In this way, the reliability and drawbacks of the annual losses presented was established. The assessment of the surveys quality and the uncertainty of the quantified glacier tongue losses can be found in Appendix 3. Furthermore, due to the absence of meteorological stations near the Maladeta glacier (the closest one with continuity in data collection is about 50 km to the northwest and at a significantly lower elevation), daily solar radiation was used as a significant factor to explain glacier behaviour and potential changes in mass balances. In this sense, the radiation data obtained by Bonsoms et al. (2022) allowed the detection of anomalous years from the correlation of annual radiation with thickness and surface losses.

4. Results

A summary of the results (Table 2) and events to be described in this section is presented. The ice surface area measured on the Maladeta glacier tongue in 2010 (1.97 ha) disappeared between 2019 and 2020. Furthermore, in six years, between 2010 and 2016, the entire volume of ice present in the 2010 glacial tongue was lost (121 $x10^3$ m^3). While the longitudinal retreat of the glacier between 2010 and 2020 varied between 2.3 and 7.9 m/yr.

4.1. Loss of surface area

The perimeter defined in the seven years of geomatic measurements varied according to the field surveys and techniques used (Table 3, Figure 3). The normalised surface area loss (area loss considering the perimeter ratio measured in the 2010 campaign) between annual surveys presents maximums of -0.37 ha/yr in 2011-2012 and 2018-2019 and minimums of -0.13 ha/yr on average between 2012 and 2017 (Table 3). This surface area loss coincides with maximum mean retreats of the tongue close to 8 m between 2019 and 2020 and minimums of 2.3 m between 2017 and 2018. The evolution of the surface area of the glacier front (taking as a reference the surface of the tongue measured in 2010) shows an approximate loss of 11% per year from 2010 to 2020 (Figure 3.B). Whereas in 2020, 78% of the total surface area of the tongue existing in 2006 had already disappeared (close to 6% of annual loss; Figure 3.A). Between 2010 and 2020, this evolution meant a difference in the elevation of the front of 54 m (Figure 3; 2020 AP DEM as elevation reference).

Table 3 and Figure 3 are based on Figures SM1 and SM2 (Supplementary Material). Detailed information on the loss of surface area with each geomatic technique used for defining the tongue perimeter between 2010 and 2020 can be found in the latter figures.

4.2. Loss of thickness

The surface observed over nine years showed variations in the size of the area analysed and the thickness values (Table 4, Figure 4). As in the case of the perimeter measurements of the glacier tongue, the AP techniques (2019-2020) facilitated the analysis of a greater surface area, covering more than 3.5 ha (Table 4). Whereas in the TLS surveys (2017-2018), the surface studied was smaller, at around 0.7 ha. Despite the reduction in the area analysed, the difference in mean thickness between 2017 and 2018 was -1.3 m. A similar value to the losses detected in other years (Table 4, Figure SM3). In the period studied, the thickness decreases in 2011-2012 stands out at -4.2 m, accompanied by volume losses of -51,547 m^3 (normalised volume, Table 4). The lowest differences in thickness, of -0.3 m, were found in 2012-2013, coinciding with minor snow accumulations on the tongue due to recent precipitations. The loss of -1.3 m/yr of thickness observed from the photogrammetric flights of 2019 and 2020 allowed determining a difference in total ice volume of -46,679 m^3, representing a normalised volume of -16,454 m^3. In 2020, the ice extent of the tongue measured in 2010 had already disappeared, so the normalised volume determined between the 2010 tongue and the 2020 outcropping substrate was taken as a reference to determine mean volume loss rates of 17% per year (Figure 4).

The data in Table 4 are derived from Figures SM1 and SM2. Detailed information on annual thickness loss with the different geomatic techniques can be found in them, together with ground elevation differences using terrain profiles in Figure SM3.

5. Discussion

5.1. Loss of surface area and thickness in the glacier tongue

The loss in thickness of the glacial tongue from 2010 presents maximum values of over -25 m (-2.5 m/yr; Figure 4; Figure SM3) with mean values of -17 m over a period of 10 years (-1.7 m/yr; Table 2). These values are consistent with the thickness losses of the glacier, estimated at -1.7 m/yr between 1994 and 2008 (Jiménez, 2016), -1 m/yr between 1994 and 2013 (WGMS, 2015) and -1.55 m/yr between 2008 and 2017 (Cobos et al., 2017). Moreover, the -1.7 m/yr of mean thickness lost in the tongue (Table 4) reveals a moderate increase in the rate of loss concerning the -1.56 m/yr in the period 2010-2014 (Rico, 2019). The increase in the rate of thickness loss between 2010 and 2020 stands out despite small snow accumulations (2012-2013, Table 4) and points to a more significant loss at the front of the glacier than in the higher areas. If it is considered that the portion of the ice measured in 2010 has disappeared, the range between -1.7 m/yr and -2.5 m/yr would fit the losses that occurred in the terminus ramp of the glacier before its final ablation. This thickness loss is in line with the rates recorded in other small glaciers, with changes between -0.5 to -5 m/yr (Fischer, 2018; Sommer et al., 2020). This fact shows the high variability of the changes in small glaciers and the high rates of ablation of the Maladeta glacier, which denotes its imbalance and rapid shrinkage.

The longitudinal retreat between 2010 and 2020 (5.3 m/yr; Table 2), doubled the reported values for the period 1991-2011 (Jiménez, 2016; Moreno, 2016). These rates are in accordance with those reported in Rico (2019), in which retreats of the front was determined of 2.5 m/yr for the period 2010-2014 and of 14 m/yr between 2012 and 2016. The differences have been linked to the method used for determining the distance between the fronts (in this study, mean distances throughout the perimeter of the tongue are presented). The retreat reflects the rapid ablation of the glacier terminus favoured by the increase in temperatures and, therefore, in the ELA, which has lain above the elevation of the glacier the 80% of the years since 2012.

The surface area of the glacier reduced at a rate of -2.6 ha/yr between 1993 and 2000 and by -3.5 ha/yr between 2002 and 2007 (Chueca et al., 2007; Jiménez, 2016; Rico et al., 2017). Nevertheless, the results from monitoring the tongue between 2010 and 2020 reveal a normalised loss rate between -0.2 and -0.3 ha/yr (Table 2). In order to evaluate the rates of glacier loss presented in other studies (1993-2000 and 2002-2007) and the rates of loss of the tongue presented in this study (2010-2020), the loss of surface area in the whole glacier and in the tongue was correlated. The perimeter of the entire glacier front was extracted using an orthomosaic (0.5 m/pix) from 2006 (date chosen because of the absence of snow; Figure 3.A). Given the rate of loss of the glacier tongue and a perimeter of about 2350 m obtained from the orthomosaic, the area lost on the entire glacier would amount to -0.9 ha/yr, far from the -3.5 ha/yr reported for the 2002-2007 period. These results would indicate a slower disappearance of the glacial tongue than the periphery of the upper part of the glacier.

The retreat of the entire glacier may point to the importance of topoclimatic factors, as previously proposed for temperate mountains (Colucci & Guglielmin, 2015; Fischer, 2018; Gachev, 2022) and in the Pyrenees (Rico et al., 2017; Vidaller et al., 2021). This fact corroborates that small glaciers housed in shaded sites, without avalanche input and at moderate elevation (< 3000 m a.s.l.), such as the Maladeta glacier, present very rapid shrinkages with a tendency towards their disappearance. These contrast with those that have avalanche inputs and are located at a higher elevation, where the dominant topoclimatic factors favour the permanence of glaciers (DeBeer & Sharp, 2009).

The analysis of the evolution of the surface area and volume of the Maladeta glacier tongue since 2010 notes that volume loss is 1.7 times faster than the disappearance of surface area (Figure 3; Figure 4). This fact show how the small glaciers degradation is characterised by a more significant loss of thickness than surface area (Rico et al., 2015, 2017; Vidaller et al., 2021). The analysis seems to confirm that thickness loss will affect not only cirque glaciers with sizes less than 10 ha but also small glaciers of larger extent.

High-resolution digital elevation models (5.8 cm/pix) have revealed the current position of the front of the glacier at 2895 m a.s.l. (2020; Figure 3.B), 25 m above that estimated in 2013 (WGMS, 2015). The 2015 elevation estimated by the WGMS has been rejected, as it has no concordance either with prior or posterior data. While between 1994 and 2010, an ascent of 3.1 m/yr was estimated (WGMS, 2015), in the following decade, 2010-2020, the mean was 5.3 m/yr (Table 2; Figure 3). A gradual ascent in the front elevation is also observed since it rose by 4.7 m/yr between 2010 and 2017, and 7 m/yr between 2017 and 2020 (Figure 3). Hence, over the last 10 years the elevation shows a clear trend, with some very significant annual rises (e.g. 2019-2020, an ascent of 21 m).

The analysis presented in this study, with the application of several geomatic techniques such as GNSS, TS, TLS or AP, has been useful in the study of the Maladeta glacier tongue as it has been in other studies linked to the cryosphere (Colucci & Guglielmin, 2015; Fischer, 2018; Fischer et al., 2016; López-Moreno et al., 2016, 2019; Martínez-Fernández et al., 2019, 2022; Rico et al., 2017). Moreover, the combined analysis of the elevation models generated in the campaigns of 2019 and 2020 demonstrates that the thickness and volume lost quantification are similar using any of the techniques (Appendix 3). That is mainly due to the geometric characteristics of the surface of the glacier, which favour the generation of similar DEMs despite the different levels of detail of the measurements. According to this study, the elevation models derived from different techniques may affect the volume determined by around ±7% between two surveys. Nevertheless, these same techniques present diverse limitations concerning the extension of the surface surveyed (Tables 3 and 4) or the derivable products (e.g. orthoimages from TLS scans; Appendix 2).

Monitoring the glacier tongue has shown that the values in determining the perimeter should be used cautiously. The variability of the surveys generated from each technique resulting from the sampling distance, the resolution of the products, the accessibility to the study area and the accuracy and properties of the equipment have affected the obtained perimeters (Appendix 2). An error of a subjective nature, resulting from the researcher responsible for defining the perimeter, must be added through direct observations or cartographic products. In the monitoring work on the tongue, it has been shown that these issues may affect around ±80% of the area determined between two consecutive years (2019-2020; Table 3). Nevertheless, this inconsistency in the perimeter definition would only affect ±7% of the surface area loss in the 10 years of study. It is precisely this uncertainty in the perimeter definition that affects the determination of the annual retreat of the tongue (Appendix 3) and thus, the definition of the elevation of the front (Figure 3.B). In some years, no variation appears, while elevation changes are significant in others.

5.2. Transition from a tongued to a cirque glacier

The ablation rates and disappearance of the ice seem to be related to the rate of summer radiation estimated by Bonsoms et al. (2022). High levels (>170 W m^2) bring about a shortening of time the snow cover remains and a longer duration of the period of surface ablation (Bonsoms et al., 2022). In the glacier of the Maladeta, there is a high positive correlation between the high incidence of summer radiation and the high negative mass balances, except for 2014 and 2020, in which high radiation rates correspond to a positive and negative moderate mass balance, respectively (Figure 5, Table 5).

On the glacier tongue, there is also a positive correlation between the loss of thickness and surface area during 2010-2020 period except in the 2014, 2017 and 2020 years (Figure 5). The three years represent an important anomaly with greater loss of surface than thickness that implies a lower correlation. This corroborates the correlation found for the same period between the decrease in area and thickness for the whole glacier between 2011 and 2020 (Vidaller et al., 2021). Nevertheless, once more, there is an exception. The year 2019-2020 did not show any correspondence between a high loss of surface area and thickness (Table 5). Years with notable rises in the front elevation are also reflected, such as the interval of 2012-2017 and 2019-2020 (Figure 3B). The exception recorded in both the climatic behaviour (radiation/mass balance) and the response (thickness/surface area/elevation of the front) permits the affirmation that there are years in which the response of the glacier is not driven by climatic control.

In the Pyrenees, the daily radiation rate has doubled, which has meant that snowmelt, and thus the ablation period, is about one month earlier in the 2000-2020 interval than in 1959-1980 (Bonsoms et al., 2022; López-Moreno et al., 2020). Together with the progressive rise of the ELA and the decrease of the accumulation area, daily radiation is one of the most significant factor in explaining the gradual increase of the glacier ablation with the advancing years. A clear increment can be seen in the retreat rates of the glacier front, and in the equalisation of the loss of surface area and thickness (Cobos et al., 2017; Vidaller et al., 2021), although there is great variability in the mass balances and radiation (Jiménez, 2016; WGMS, 2021). If this trend continues, the loss of the glacier tongue and the transition to a cirque glacier of less than 10 ha will occur in approximately 12 years. Therefore, by the end of the 30s of the 21st century the tongue will no longer exist.

The high degree of variability of the tongue retreat implies a changeable trend. The variability present in the behaviour of the Maladeta glacier is also observed in other small glaciers located in mountains at temperate latitudes, where topoclimatic and climatic factors are involved and the ELA is located above the elevation of the glacier flow (Fischer, 2018; Gachev, 2022; Sommer et al., 2020). The existence of processes such as glacial lake outburst floods (Serrano et al. 2018) or collapses and the coincidence with high rates of glacial retreat point to the high instability of the glacier. These differentiated behaviours of the glacier allow the establishment of two different dynamics in the shrinkage process of the glacier of the Maladeta:

i) Surface ablation: processes associated with high summer radiation that generate high negative balances with substantial losses in thickness but moderate retreats of the front. The main processes are melting and runoff, sublimation and evaporation on the glacier surface. These processes were dominant in 2012, 2015, 2017 and 2019, and an increase in their activity over time has been detected. Nevertheless, they took place every year studied and are one of the main factors causing the shrinkage of the glacier.

ii) Collapses: a process detected under moderate, positive or negative balances of mass that causes small losses in thickness but a pronounced loss in length. These have been detected for the years 2014, 2018 and 2020. This is a process identified in the field, in ice without deformation by flow and with the presence of subglacial water and air circulation. Both water and air favour melting, sublimation and runoff at the base of the ice. Following the snow melt, relatively warmer subglacial air currents initiate ascending or descending air flows along subglacial conducts. They can melt or sublimate the ice at its base, enlarging the hollows of the interior of the glacier (Figure 6). Coinciding with high indices of radiation, water flow and instability, the ceiling of the ice collapses. These processes generate the sudden retreat of the glacier, when the ice blocks falls onto the substrate and the quickly melts after detachment. The retreat processes by collapse occur at intervals of 2 to 4 years and generate sharp retreat sandwiched between periods of gradual retreat, accelerating the glacier shrinkage.

Both processes combined involve great variability in the behaviour of the glacier and the high instability of the system. These are essential characteristics of small glaciers in temperate mountains.

6. Conclusion

The Maladeta glacier is a small one now transitioning from being a glacier moderately influenced by climatic conditions to its dependency on topoclimatic factors. The periodic and detailed monitoring of the glacier tongue for 10 years (2010-2020) has made it possible to determine an annual increase in the rates of loss of ice thickness and surface area, along with the ascent of the front. The present study shows that ablation rates are significant in the glacier tongue. This fast loss of the tongue implies the transformation of the glacier into a cirque glacier over approximately a decade. Despite this trend, it has been found that the reduction of the glacier surface area is faster in the cirque than in the tongue, which points to the gradual disappearance of the entire ice body throughout its length and at any elevation. Such behaviour could lead to the extinction of the glacier in a period close to that of the tongue.

The glacier front is dominated by a substantial decrease in ice thickness and the disappearance of about 80% (2020) of the existing tongue in 2006. The glacier tongue denotes the absence of deformation, with relict folds, shear faults and subglacial ablation. It is a dominant process in which subglacial ablation with the generation of large cavities is followed by collapse processes and the disappearance of large portions of the glacier, such that periods of intense and moderate retreat alternate. These are largely related to years with high summer radiation and high negative mass balances throughout the glacier, which in the front are manifested as collapse processes rather than part of the internal dynamic of the ice. The variability in the ablation and retreat rates of the glacier and the diversity of processes involved in the disappearance of the glacier tongue, such as collapses, glacial lake outburst flood, and supraglacial and subglacial runoff, point to its high instability.

The technologies applied facilitated the periodic observation over 10 years, which has helped to deepen knowledge of the glacier evolution and, above all, of the change rates during the ice ablation and shrinkage. Nevertheless, the technological changes, from TS to TLS and finally AP, show the suitability of the most recent techniques, with optimal precision and resolution for continuously monitoring the evolution of medium-sized and very small glaciers. Aerial photogrammetry using UAVs provides extensive models of high precision and resolution that avoid errors arising from the spatial interpolation of points on the glacier surface while reducing laborious fieldwork, often subject to unforeseen and potentially dangerous events.

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