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LOCAL VARIABILITY OF SMALL ALPINE GLACIERS: THOULA GLACIER GEODETIC MASS BALANCE RECONSTRUCTION (1991-2020) AND ANALYSIS OF VOLUMETRIC VARIATIONS

Abstract: Mondardini L., Perret P., Frasca M., Gottardelli S. & Troilo F., *Local variability of small Alpine glaciers: Thoula Glacier geodetic mass balance reconstruction (1991-2020) and analysis of volumetric variations.* (IT ISSN 0391-9838, 2021).

High Alpine environments are rapidly changing in response to climate change, and understanding the evolution of small glaciers is a crucial step in the investigation of future water availability for populations that inhabit these areas. With this study, we present a comprehensive analysis of a small glacier's recent mass balance evolution (1991-2020), located on the Italian side of the Mont-Blanc Massif, where very little previous data were available. To do so, we combined historical data (topographic surveys and LiDAR DEMs of the area) with newly acquired satellite stereo imagery and aerophotogrammetric surveys to obtain multi-temporal digital elevation models (DEMs) of the Thoula Glacier (0.52 km^2). The total ice volume estimation was assessed by accomplishing a GPR survey to investigate the ice thickness and the underlying bedrock. The Thoula Glacier shows a significantly lower loss of volume in comparison to other glaciers located in the Aosta Valley region as well as most of the reference glaciers of the Word Glacier Monitoring Service (WGMS) for Central Europe. Particular weather-climatic conditions of the Mont Blanc Massif area, generally characterized by a greater amount of precipitation, could explain the observed differences; however, the present study shows that understanding spatio-temporal local variability of small glaciers can significantly contribute to recognizing different regional and intra-regional patterns of response to climate change.

Key words: Helicopter-borne GPR, Volume variations, Ice thickness, Mass balance, UAV photogrammetry, Digital elevation models (DEMs), Remote sensing.

Riassunto: Mondardini L., Perret P., Frasca M., Gottardelli S. & Troilo F., *Variabilità locale dei piccoli ghiacciai alpini: ricostruzione del bilancio di massa geodetico del ghiacciaio del Thoula (1991-2020) e analisi delle variazioni volumetriche.* (IT ISSN 0391-9838, 2021).

Gli ambienti di alta montagna stanno rapidamente cambiando in risposta ai cambiamenti climatici e comprendere l'evoluzione dei piccoli ghiacciai è un passo cruciale nell'indagine sulla futura disponibilità di acqua, per le popolazioni che abitano in questi luoghi. Con questo studio, presentiamo un'analisi completa della recente evoluzione del bilancio di massa di un piccolo ghiacciaio (1991-2020), situato sul versante italiano del Massiccio del Monte Bianco, di cui si possedeva un numero limitatissimo di dati pregressi. A tale scopo, abbiamo abbinato dati storici (rilievi topografici e dati LiDAR dell'area) ad immagini stereo satellitari di nuova acquisizione e rilievi aerofotogrammetrici per ottenere modelli altimetrici digitali (DEMs) multi-temporali del ghiacciaio del Thoula (0,52 km^2). La stima del volume totale di ghiaccio è stata determinata effettuando un'indagine GPR, che ha permesso di analizzare lo spessore del ghiaccio ed il substrato roccioso sottostante. Il ghiacciaio del Thoula mostra una perdita di volume significativamente inferiore rispetto ad altri ghiacciai situati in Valle d'Aosta, così come rispetto alla maggior parte dei *reference glaciers* del *Word Glacier Monitoring Service* (WGMS) relativi all'Europa centrale. Particolari condizioni meteo-climatiche dell'area del Massiccio del Monte Bianco, generalmente caratterizzata da una maggiore quantità di precipitazioni, potrebbero spiegare le differenze osservate; tuttavia, il presente studio mostra come la comprensione spazio-temporale della variabilità locale dei piccoli ghiacciai possa contribuire in modo significativo a riconoscere diversi modelli regionali e intra-regionali di risposta ai cambiamenti climatici.

Termini chiave: GPR elitrasportato, Variazioni volumetriche, Spessore del ghiaccio, Bilancio di massa, Fotogrammetria UAV, Modelli altimetrici digitali (DEMs), Telerilevamento.

INTRODUCTION

Worldwide glacier mass loss caused by a warming climate is well known and studied (Sayli Atul Tawde & *alii*, 2019; Huss, 2012; IPCC, 2019). The extensive retreat recorded in the last couple of decades is exceeding, in rapidity and volume, previous mass balance loss predictions (Hugonnet & *alii*, 2021). The effects of this rapid retreat have already been observed at both a global and regional scale, with mountain glacier ice loss already contributing to sea level rise (Jacobs & *alii*, 2012; Radić & *alii*, 2011), accounting for an increase in natural hazards (Fischer & *alii*, 2006) and affecting wa-

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ter availability (Georg & *alii*, 2010; Huss & Fischer, 2016). Decreases of glacier water run-offs in mountain areas dominated by small glaciers (here defined as $0.5 \leq x \leq 1$ km^2 accordingly to Huss & Fischer (2016) which defined a very small glacier as ≤ 0.5 km^2) can strongly affect surrounding ecosystems, the biodiversity of glacier-fed rivers, and the ecosystem services that are extremely valuable for the population living in these areas (Brown & *alii*, 2007; Milner & *alii*, 2017; IPCC, 2019). Thus, understanding spatio-temporal local variability of small glaciers and comparing it to modelled evolution predictions, usually focused on large-size glaciers or wide areas, can significantly contribute to recognizing different regional patterns developing in response to climate change (Marti & *alii*, 2015; Debeer & Sharp, 2009).

To accurately study small glaciers' mass balance changes, the use of high-resolution imagery (satellite or airborne) is a proven key factor to obtain precise cost effective results (Abermann & *alii*, 2010; Fischer & *alii*, 2014). For the study of surface displacement and volume reconstruction, UAVs (Unmanned Aerial Vehicles) and satellite data use is rapidly increasing (Giordan & *alii*, 2020; Rankl, Kienholz & Braun, 2014; Fugazza & *alii*, 2015). On the other hand, more expensive radar-based methods are commonly used techniques when ice thickness is investigated (Plewes & Hubbard, 2001). Airborne GPR (Ground-Penetrating Radar) surveys were successfully conducted in different mountain environments (Blindow & *alii*, 2012; Grab & *alii*, 2018; Urbini & *alii*, 2017) allowing the gathering of data on glaciers otherwise inaccessible.

With this study, we present a comprehensive analysis of a small glacier's recent mass balance evolution where very little previous mass balance data were available. By using the latest techniques of DEM reconstruction from UAV and satellite images and airborne GPR data, we aim to precisely assess the remaining ice volume with no field measurement needed.

STUDY SITE

The Thoula Glacier is located on the South-East (SE) side of the Mont-Blanc massif (Western Alps) in Aosta Valley, the Italian region with the largest glaciarized area (Smiraglia & *alii*, 2015). Surrounded by the steep rocky sides of the Aiguilles d'Entrèves and Punta Helbronner, this small-size glacier of 0.52 km^2 develops from an altitude of 3355 m to 2890 m a.s.l., with a linear extension of around 900 m.

In 2012, this glacier was identified as a convenient study site for mass balance measurements for its topographic characteristics. With its lower steepness compared to the surrounding glaciers, limited presence of crevasses and easy accessibility from the valley floor (thanks to a near cable car), the Thoula Glacier was therefore chosen to replace the Pré de Bard Glacier as a reference point for glacier mass balance measurements in the Mont Blanc area. However, after only three years of measurement campaigns the site was abandoned due to the frequent avalanche danger from the steep surrounding mountains that made accessing the glacier a difficult task, especially during the spring season. In addition, the frequent interactions of the study points with avalanches reduced representativeness and increased the loss of ablatometric poles. This added to the already little representativity of the site for regional mass balance estimates because of the climatic peculiarities of the Mont-Blanc massif SE face.

PREVIOUS STUDIES

As mentioned above, prior to this study, Thoula Glacier mass balance was measured only three times, from 2012 to 2015, using the glaciological method. These campaigns, held by Fondazione Montagna sicura in collaboration with ARPA VDA (Agenzia Regionale Protezione Ambientale Valle d'Aosta), were based on three field surveys per year (May, July and September). Maximum and residual snow accumulation was investigated by means of snow thickness surveys and excavations for snow density assessments, as well as the total ablation, using 4 ablatometric poles installed on the glacier in 2012. However, during the three years of measurements, the glacier suffered substantial transformations. Due to subsequent years of strong ablation rates, strongly crevassed sectors appeared, especially in the lower sections. The frontal part of the glacier became inaccessible already in 2014, resulting in the impossibility to measure the glacier's ablation and putting an end to the in-situ monitoring efforts. Data from these three campaigns shows a substantially negative mass balance for the 2011/12 hydrological season, with a net mass balance of -2.56 m w.e., while a positive net mass balance (+0.45 and +0.72 m w.e.) was recorded for the other two seasons.

MATERIALS AND METHODS

Historical mass balance reconstruction

By using the geodetic method of the of the DEM of Difference (DoD) the chosen data were determined by the availability of existing DEMs (Digital Elevation Model) of the area of interest. For the period of 1991 – 2020, four DEMs were available: the 1999 DEM (survey of 1991) of Aosta Valley Region (with spatial resolution of 10 m/pixel and vertical accuracy of ± 1.5 m), the 2008 aerial Laser-Scanner DEM of Aosta Valley Region (with sampling size of 35 cm, spatial resolution of 2 m/pixel and vertical accuracy of ± 30 cm), a 2020 Pléiades DEM (with sampling size of 50 cm, spatial resolution of 2 m/pixel and vertical accuracy ± 1 m - Airbus, 2021), and a 2020 UAV photogrammetric DEM with spatial resolution of 0.25 m/pixel, obtained using a DJI Mavic 2 Pro.

To generate the 2020 Pléiades DEM, a pair of Stereo images of the entire SE side of the Mont-Blanc massif (fig. 1), collected on September 20, 2020, was used. Pléiades high-resolution satellites 1A and 1B provide images with a resolution (ground sampling distance) of 0.5 m/pixel for the panchromatic channel (wavelength in the 480-830 nm range) and 2 m/pixel for the multi-spectral channels (Airbus, 2021). Panchromatic band images are often used in glaciological studies for their capability to enhance flat and textureless regions thanks to their wide radiometric range (Berthier & *alii*, 2014). The 2020 Pléiades DEM was generated using the OrthoEngine module of PCI Geomatica. 13 Ground Control Points (GCPs) were used for the orthorectification process.

Using Agisoft MetaShape Pro, the 2020 UAV photogrammetric DEM was extracted by combining 161 photos taken on september 24, 2020, only 4 days after the Pléiades Stereo pair acquisition. 7 GCPs and 2 checkpoints were available to orthorectify the obtained DEM. The 1991 DEM of the whole Aosta Valley region was extracted from the Regional Numerical Technical Map (CTR - Carta Tecnica Regionale Numerica) at a large scale, using the information of the elevation points, islets, and other significant points for the elevation reconstruction. In addition, glacier outlines for the analysed periods were derived from manual digitization of high-resolution (res. 0.25 to 1 m/pixel) orthophotos and satellite images.

The DoD calculation was performed in the R environment for the intervals of 1991-2008 and 2008-2020 (fig. 3). For each interval, a DEM subtraction was carried out obtaining the total volume change (ΔV), as shown by Denzinger & *alii* (2021), and the averaged glacier areas of two-time intervals (A). Then, the geodetic mass balance (B) was calculated using Eq. 1:

$$B = \frac{\Delta V}{A} \frac{\rho_{glacier}}{\rho_{water}} \tag{1}$$

where ρ_{water} is the density of water (1000 kg m^{-3}) and $\rho_{glacier}$ is the density conversion factor value. $\rho_{glacier}$ was chosen to be 850 ± 60 kg m^{-3} because of Thoula's glacier characteristics and the study duration being greater than 5 years (Huss, 2013; Denzinger & *alii*, 2021). The mass balance obtained was then compared with available data of other glaciers in the region and the Word Glacier Monitoring Service (WGMS) reference glaciers.

Accuracy assessments

To assess the vertical accuracy and precision of the 1991 and 2020 DEMs, 2000 point-type control elements on ice-free terrain were randomly selected, using the 2008 LiDAR DEM as a reference. To describe the error distributions, commonly used statistical measures were calculated, such as Root Mean Square Error (RMSE), standard deviation (σ) and mean (μ), based on the assumption of a normal distribution of the errors (Haala & *alii*, 2010; DeVenecia & *alii*, 2007) (table 1). However, this assumption is quite often incorrect (Mesa-Mingorance and Ariza-López, 2020), and, therefore, robust measures were used, such as the 50% (Median), 68.3% (Q68) and 95% quantiles (Q95) and Normalised Median Absolute Deviation (NMAD). The NMAD is a metric for the dispersion of the data that is not as sensitive to outliers as the standard deviation and is recommended to evaluate DEM precision (Höhle & Höhle, 2009) (table 1). Geodetic mass balance uncertainty over the whole period was calculated by conventional propagation of errors.

TABLE 1 - Statistical accuracy measures of error distributions for the different DEMs used. Statistics are computed on the elevation differences (Z DEM 2008 – Z DEM*) for 2000 random points on the mountainous ice-free terrain around the glacier.

	DEM 1991	DEM 2020 Pléiades	DEM 2020 UAV
RMSE [m]	5.64	4.43	6.08
Mean (μ) [m]	-0.48	1.05	0.84
Standard deviation (σ) [m]	5.62	4.30	6.02
Median (50% quantile) [m]	0.23	0.68	0.18
NMAD [m]	4.42	1.27	3.74
Q68 (68.3% quantile) [m]	2.33	1.29	2.00
Q95 (95% quantile) [m]	6.71	5.73	11.90

Due to the manual mapping of the glacier outlines, the variability was estimated in 1% of the calculated area as the interpretation of glacier limits, debris-covered parts, seasonal snow and dead ice was supported by high quality dataset, previous terrain knowledge and the analysts experience in photo interpretation (Paul & *alii*, 2017).

GPR survey

A helicopter-borne ground-penetrating radar (GPR) survey, with dual polarisation AIRETH system, was performed on July 7, 2020 in collaboration with the ETH Zürich (Eidgenössische Technische Hochschule Zürich) and the company Geosat SA, which handled the navigation and GNSS coordinate data analysis. The chosen system allows recording with two different antenna orientations, roughly parallel and perpendicular to the flight direction. Both orientations were considered for picking the bedrock reflections visible in the individual profiles to avoid the potentially different data quality resulting from the two pairs of bistatic dipole antennas (Langhammer & *alii*, 2017). These measurements were completed as part of a larger study, the aim of which was to better understand Planpincieux Glacier bedrock topography (Dematteis & *alii*, 2021). In total, 1 km of profile data were acquired over the Thoula Glacier, with 1 horizontal profile and 1 longitudinal profile.

GPR data processing and ice volumes calculations

Data processing and analysis was carried out by the ETH Zürich and Geosat SA. Firstly, the GNSS coordinates acquired during the helicopter flight were merged with the GPR data. By using the laser altimeter data and the GNSS data recorded at three corners of the GPR (platform, yaw, pitch and roll angles), the positions at the glacier's surface were computed. Corresponding values were assigned to each GPR trace. Then, the GPR data were processed using the in-house software toolbox GPRglaz (e.g., Grab & *alii*, 2018) (fig. 2).

The AIR-ETH system offers recording with two orthogonal (dual-polarisation) pairs of 25 MHz dipole antennas. Therefore, GPR data from two channels, one parallel and one perpendicular to the flight direction were available for data processing. The procedure included the following steps:

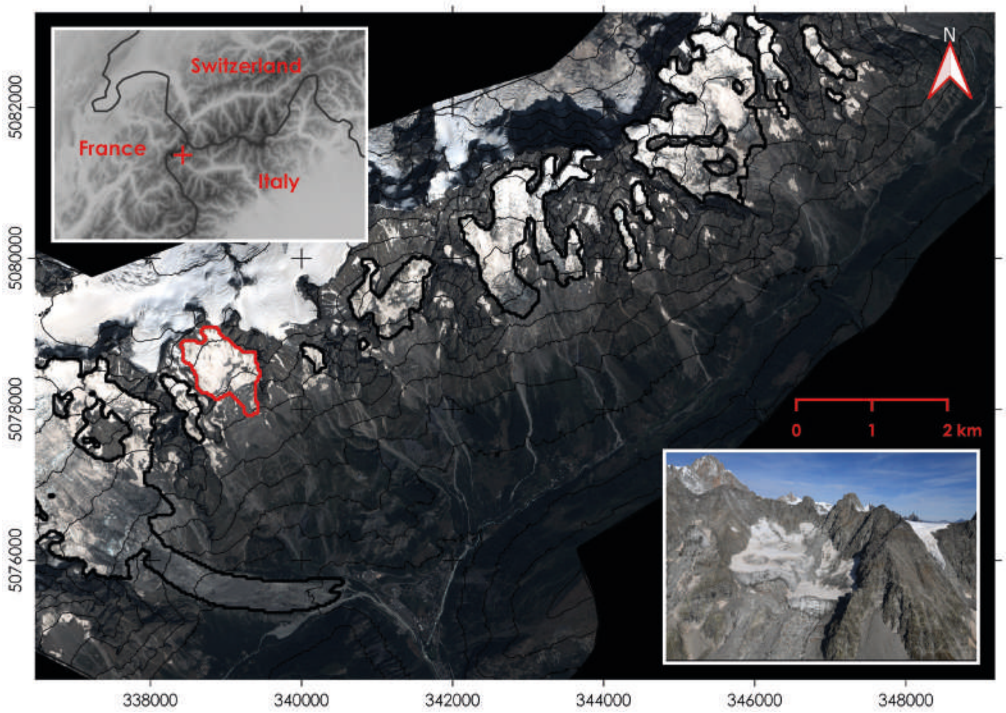

FIG. 1 - 2020 Pléiades Stereo image of the entire SE side of the Mont-Blanc massif, collected on September 20, 2020 (©CNES 2020, Distribution Airbus D & S). Thoula Glacier localisation is highlighted in red.

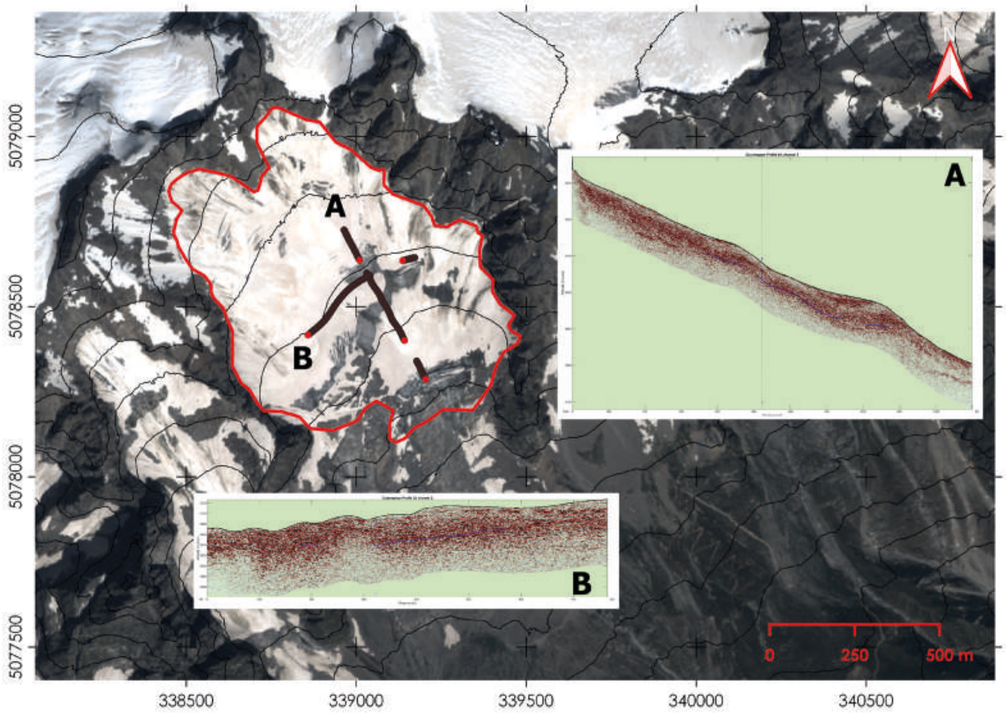

FIG 2 - Processed GPR sections (A and B) and their localisation on Thoula Glacier. Inside the two sections, bedrock limits are highlighted in blue.

TABLE 2 - Thoula Glacier mass balance reconstruction.

Time interval	Cumulative mass balance [m w.e.]	Average annual mass balance [m w.e. a^{-1}]
1991-2008	-5.8 ± 4.0	-0.3 ± 0.2
2008-2020	-7.3 ± 1.3	-0.6 ± 0.1

TABLE 3 - Comparison of Thoula Glacier total net mass balance with those available for the Timorion and Grand Étret glaciers. Errors for the glaciological (*) mass balance are deduced from Berthier & *alii* (2014) and Zemp & *alii* (2010).

Period	Glacier	Glacier cumulative mass balance [m w.e.]	Study method
2005-2020	Thoula	-8.3 ± 1.3	Geodetic
	Timorion	-12.5 ± 0.4*	Glaciological
	Grand Étret	-12.3 ± 0.4*	Glaciological

TABLE 4 - Comparison of Thoula, Timorion and Grand Étret glaciers by elevation, surface area expansion, and slope exposure.

Glacier	Min. elevation [m s.l.m.]	Max. elevation [m s.l.m.]	Glaciated area (2020) [km^2]	Slope exposure
Thoula	2871	3329	0.52	SSE
Timorion	3184	3496	0.45	NO
Grand Étret	2738	3201	0.55	N

- time-zero correction,
- ringing removal (GPR wave interaction between antennas and helicopter),
- bandpass filtering (enhancing signal-to-noise-ratio),
- identification of surface points (using the altimeter attached to the GPR system),
- trace-binning (obtaining a regular sampling along the profile lines),
- image focusing (by applying a Kirchhoff migration),
- identifying bedrock reflection (manual picking),
- ice thicknesses computation.

The identification of bedrock reflections was performed on the image from the antenna pair that provided better data quality.

In the profile images, GPR wave velocity and detection of bedrock reflections can generate uncertainties of glacier bedrock topography and corresponding ice thickness. For this study, the GPR wave velocity was estimated as 0.169 m ns^{-1} with an uncertainty of ± 0.005 m ns^{-1}, slightly smaller than the one identified by Lapazaran & *alii* (2016) of ± 0.008 m ns^{-1}. An uncertainty of ± 5 m was considered because of manually picking the bedrock reflection. Uncertainties due to limited vertical resolution (half a wavelength), and the lack of third dimension during image focusing by 2D migration (Lapazaran & *alii*, 2016) were considered and estimated as 15% of the ice thickness. By assuming that these uncertainties were independent from one another (Lapazaran & *alii*, 2016), and combining their contributions by the root-sum-square, the depth-increasing thickness uncertainty was obtained and ranged from ± 6 m at 10 m of ice thickness, to ± 10 m at 50 m. Subsequently, to obtain a precise bedrock topography of the Thoula Glacier and surrounding areas (approx. 2.45×10^6 km^2), 700 bedrock points (from the GPR data) and 5000 elevation points outside the glacier (from the 2008 LiDAR DEM) were interpolated by using the thin-plate smoothing spline (TPSS) (Duchon, 1977) with implementations in the R environment.

Finally, to validate the results, we compared the obtained thickness values with the GPR data not used in the interpolation process (Cressie, 2015).

RESULTS

Mass balance reconstruction

The geodetic mass balance obtained by the DoD, -13.1 ± 4.2 m w.e. for the entire study period, shows an increasingly negative average annual mass balance with -0.3 ± 0.2 m w.e. for the period of 1991-2008, and -0.6 ± 0.1 m w.e. for the period of 2008-2020 (table 2). For the first time, these newly available data allowed the comparison of the evolution trend of Thoula with other glaciers, in order to assess differences or similarities in small glacier retreats around the Aosta Valley region. For the period of 2005-2020, the Timorion and the Grand Étret glaciers, on which a completed mass balance data series is available from in situ measurements (fig. 4), were chosen for the comparison. These two glaciers, both located in the Valsavarenche valley, around 40 km southeast from the Thoula Glacier location, possess similar altitudinal range and glaciated area extension to the study site (table 4). However, the Thoula Glacier shows a significantly lower loss of mass in comparison to the other two glaciers (fig. 4 and table 3). While comparing glaciological and geodetic mass balance measurements, methodological differences have to be taken into account (Cox & March, 2004; Huss & *alii*, 2009; Thibert & *alii*, 2008). The geodetic method is usually considered better suitable to assess multi-year mass balance variations, as it is less subjected to time-dependent errors (Cox & March, 2004; Thibert & *alii*, 2008). It is also often applied to detect

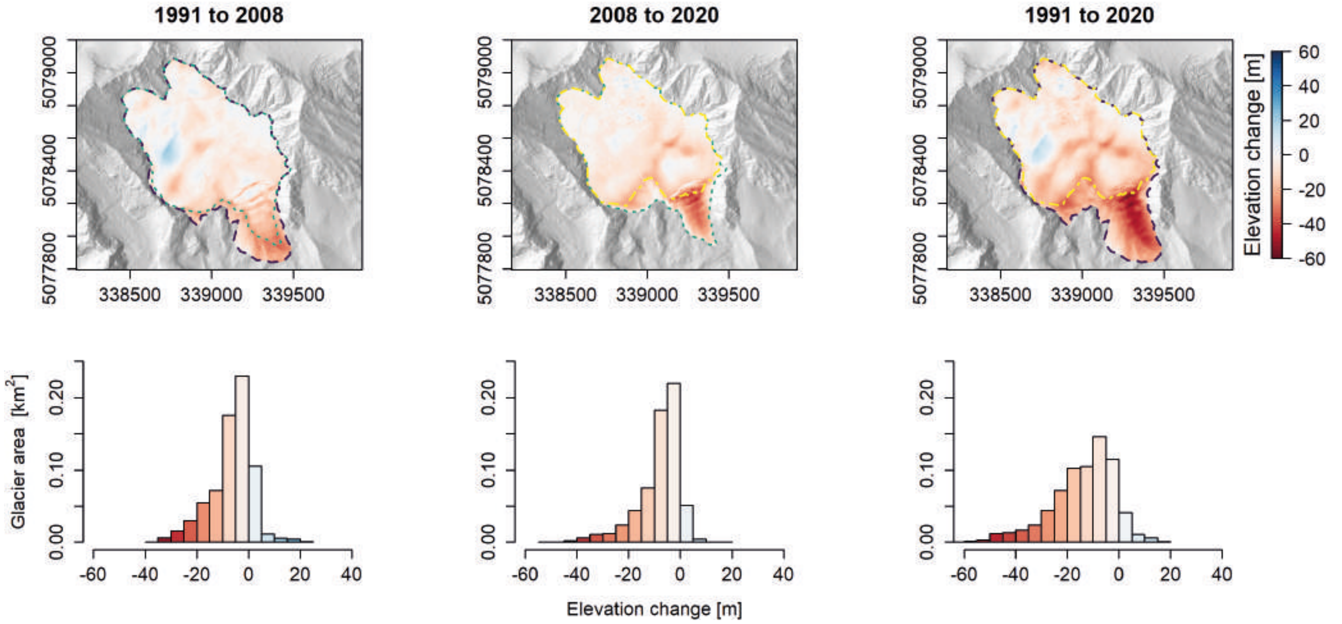

FIG. 3 - Thoula Glacier surface elevation changes for the years 1991, 2008 and 2020 with distribution over the areas. Different glacier areas are highlighted in purple for 1991, green for 2008 and yellow for 2020.

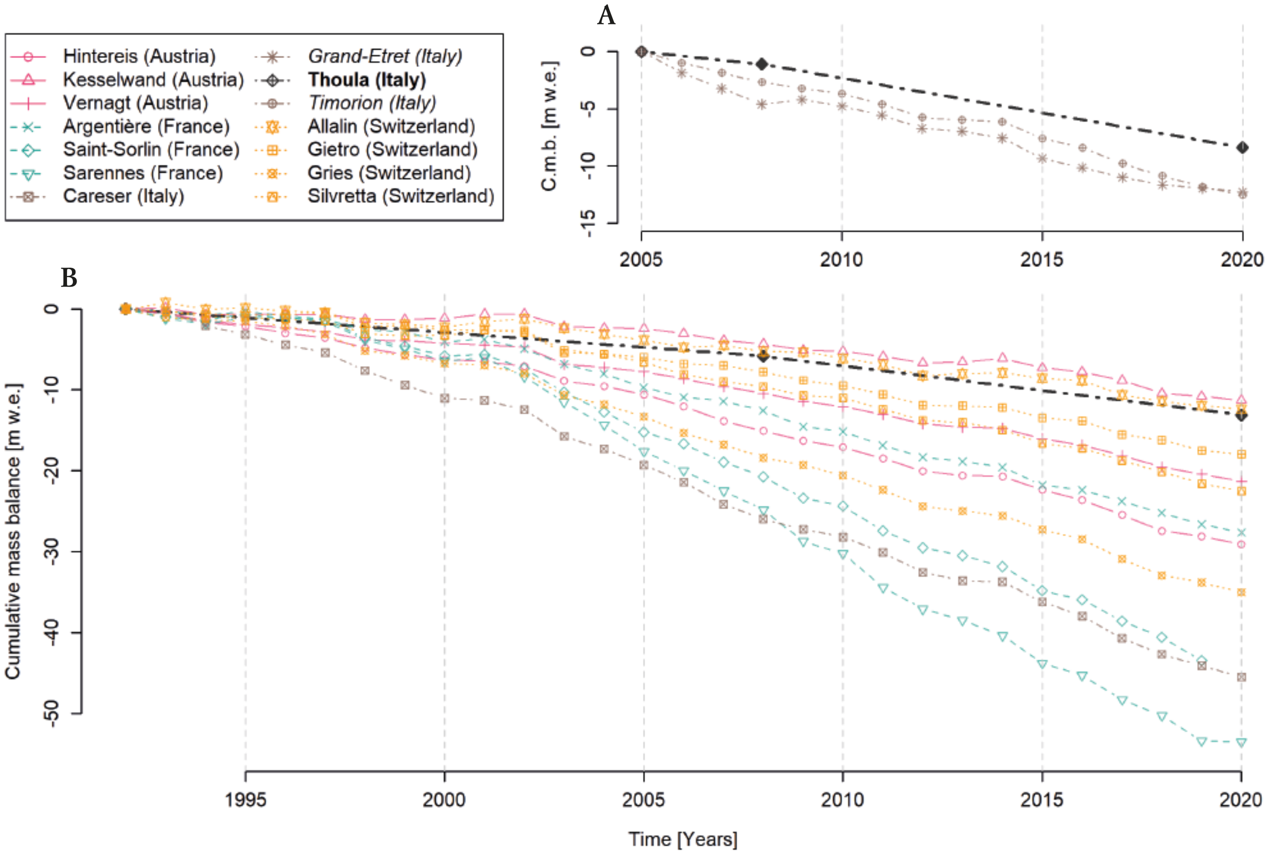

FIG. 4 - Chart A shows the comparison between Thoula Glacier cumulative mass balance and Grand Étret and Timorion glaciers, for the period of 2005-2020. Chart B shows the cumulative mass balance comparison between Thoula and the reference glaciers for Central Europe (data from *Fluctuations of Glaciers browser - accessible at: http://www.wgms.ch/fogbrowser/- World Glacier Monitoring Service*), for the period 1992-2020. Different colours differentiate glaciers from different regions: Austria - pink, France - green, Italy - grey, and Switzerland - yellow. Individual glaciers are differentiated by symbols. Thoula Glacier cumulative mass balance is highlighted in bold.

biases, homogenise and re-analyse the direct glaciological mass balance measurements (Huss & *alii*, 2009; Thibert & *alii*; 2008; Zemp & *alii*, 2009). A homogenization of Timorion and Grand Étret data would have been ideal to thoroughly compare these results, however, at the time of this study, geodetic data for these sites were not yet published, and a separate study would be necessary to investigate such differences. Moreover, even if possible errors due to the different methodologies are considered (general uncertainties for glaciological mass balances usually range between ± 0.4 to ± 0.1 m w.e. a^{-1} – Berthier & *alii*, 2014, Zemp & *alii*, 2010) the decreasing trend of Thoula Glacier would still be the lowest in comparison.

The observed differences could then derive from the different slope exposure, which can potentially influence site specific snow accumulation and ablation patterns (Evans, I. S., 2016; Evans, I. S., 2021). However the Timorion and Grand Étret glaciers, both beeing north/north-west-facing, should be more protected from solar radiation, and generally cooler (Evans, I. S., 2016; Evans, I. S., 2021) compared to the southeast-facing Thoula (table 4). Therefore, it is reasonably conceivable that the Thoula Glacier's less negative mass balance reflects a particular weather-climatic condition of the Mont-Blanc Massif area that is significantly influenced by the local orography and characterised by a generally greater amount of rainfall and snowfall (fig. 5). On average, the Mont-Blanc area receives more than 120 mm of precipitation per month, while in the areas of Timorion and the Grand Étret glaciers values are only around 30 mm per month (fig. 5). This significant diversity in mass balance loss between different glaciers of the same region, enhances the importance of having multiple reference points to estimate glacier ice loss at a regional level. In particular, it shows the necessity of keeping a reference glacier in the Mont-Blanc SE area to not overestimate Aosta Valley regional ice loss and total glacier area retreat.

The Thoula mass balance evolution was also compared, for the period of 1992-2020 (fig. 4), with the cumulative mass balance data of the WGMS reference glaciers for Central Europe. Here again, the Thoula Glacier falls amongst the least negative in reduction trends.

Ice volume calculation and comparison with glacier evolution estimates

To investigate glacier fluctuations over time, a precise calculation of the current volume of ice provides a strong starting point for both past and future evolution studies (Farinotti & *alii*, 2009). At a local scale, especially in mountain regions, following fluctuations in glacier ice volume can provide valuable information on water availability and glacier stability. In fact, droughts are predicted to increase even in the mountain areas (Cremonese & *alii*, 2020) and glaciers stability is a valuable asset being that glaciers are both an important economic resource (as a tourist attraction) as well as a potential cause of natural hazards (Fisher & *alii*, 2011; Troilo & *alii*, 2019; Perret & *alii*, 2020; Villa & *alii*, 2007). Aosta Valley glaciers are well studied (Cerutti, 2013; Vanuzzo 2001), with available long term data on surface changes, which for some glaciers dates back to the beginning of the 19th century (Deline, 1999; Diolaiuti & *alii*, 2012; Villa & *alii*, 2007). Solid data on reference glaciers for mass balance variations are also available (i.e. Rutor and Timorion glaciers) (Diolaiuti & *alii*, 2012). However, estimates of glacier ice fluctuations are often presented as surface reduction or as volumetric variation, which do not include calculations of the whole glacier volume (Diolaiuti & *alii*, 2012; Villa & *alii*, 2007; Vanuzzo & Pelfini, 1999). The main limiting factor in this type of analysis is to obtain precise data of the bedrock morphology underneath the glacier, which requires expensive GPR surveys that are often only employed on glacial environments to assess potential related risks (Dematteis & *alii*, 2021; Viani & *alii*, 2020). In this spectrum, the present study represents a unique opportunity to study the evolution of a glacier where bedrock data are available. The ice thickness derived from the airborne GPR measurements ranges from 20 to 85 m. The 2020 total ice volume of Thoula Glacier was thus estimated to be 18.9 ± 4.1 × 10^6 m^3 (fig. 6). This result was then compared with the modelled glacier ice volume evolution under different Representative Concentration Pathways (RCPs) proposed by Zekollari & *alii* (2019). For the Thoula Glacier, the ice volume expected for the year 2020 under the RCP 2.6 was equal to 6.2 × 10^6 m^3 and to 6.8 × 10^6 m^3 under the RCP 4.5. This wide difference in volume assessment (12 × 10^6 m^3) is very likely derived from the methodology used by Zekollari & *alii* (2019) to assess glacier ice thickness, which provides evident underestimations especially when thicknesses ranges from 30 to 70 m, which is the case for the Thoula Glacier (Huss & Farinotti, 2012). Discrepancies in the final volume calculation are also very likely to result from different input data (i.e. Thoula Glacier total volume and surface estimate) used by Zekollari & *alii* (2019) as starting points for the glacier evolution modelisation. Future work is needed to address these differences, and a better evolution analysis could be provided by modelling the Thoula Glacier evolution using Zekollari & *alii* (2019) methodology with area and volume data provided by this study.

CONCLUSIONS

In the presented research, existing historical sparse data were combined with recently acquired space borne altitudinal data, having potentially global coverage (Hugonnet, 2021), in order to reconstruct several decades of mass balance evolution of a specific Alpine glacier. The geodetic mass balance of the Thoula Glacier for the period of 1991-2020 was calculated to be -13.1 ± 4.2 m w.e., showing an incremented ice loss during the last 12 years, -0.6 ± 0.1 m w.e. a^{-1}, while still falling into the least negative reduction trends compared to regional examples and WGMS reference glaciers. An accurate evaluation of glacier total ice volume for the years 1991, 2008 and 2020 is also provided. As of 2020, the remaining ice volume of Thoula Glacier is estimated to be 18.9 ± 4.1 × 10^6 m^3.

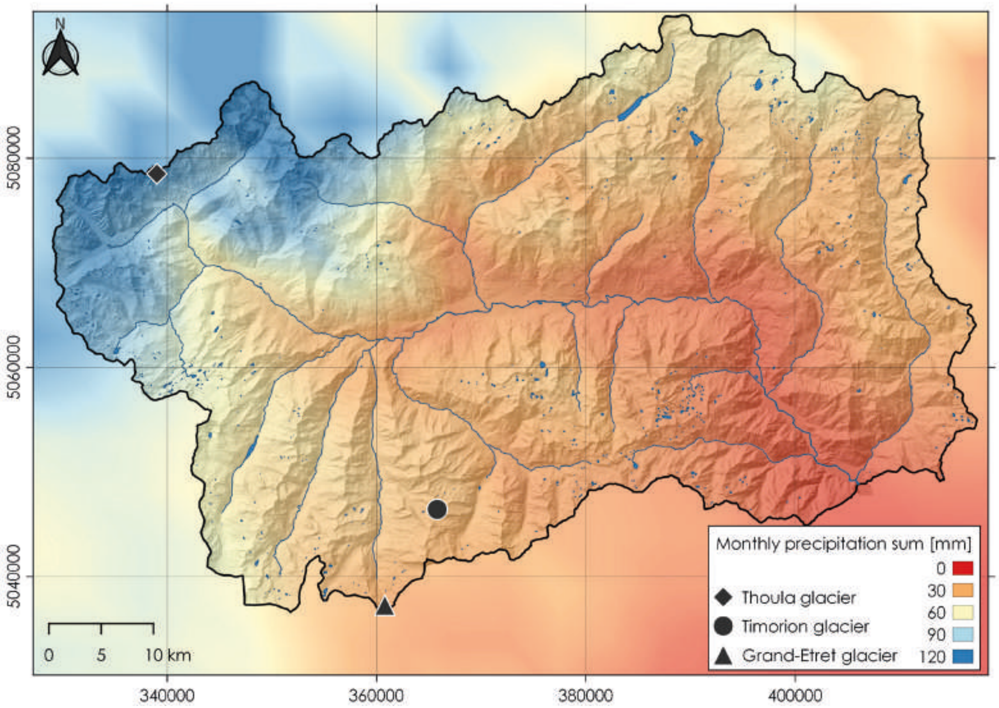

FIG. 5 - Precipitation map of the Aosta Valley region, showing the monthly precipitation sum values for the period of 1901-2019. The Mont-Blanc area shows a greater amount of precipitation compared to any other area of the region. Data source: Copernicus Climate Change Service (C3S) (2021).

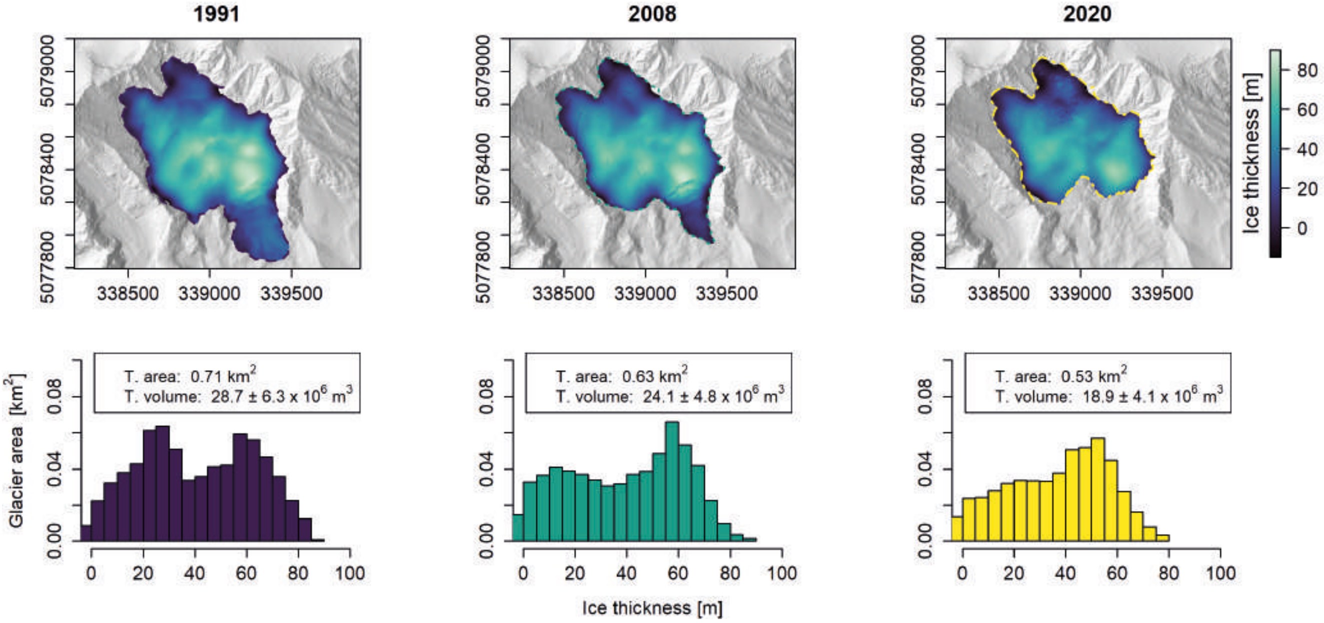

FIG. 6 - Thoula Glacier area and volume reconstructions for the years 1991, 2008 and 2020 with ice thickness distribution over the areas. Different glacier areas are highlighted in purple for 1991, green for 2008 and yellow for 2020.

The typical errors encountered and the actual limits of space borne derived stereoscopic DEMs are analysed in a practical case study, highlighting which elevation changes fall into the range of DEMs errors, giving a guideline to what time spans or what site specific variations can be investigated successfully (multi-year variations) or not (single year mass balance).

The integration of the results with ice thickness models and comparisons with local glacier evolution and global-scale mass balance models (Zekollari & *alii*, 2019), highlighted that the particular weather-climatic conditions of the Mont Blanc Massif area could have played an important role in easing the impacts of the warming climate on local glaciers in recent decades. In addition, results of this study suggest that if an interest is set to a specific site, global models should be combined with site-specific data in order to detect site-specific deviations from global trends. This is particularly evident when comparing the expected volume by Zekollari & *alii* (2019) and Thoula's remaining ice volume provided by this study (12×10^6 m^3 of difference are found). At a supra-regional level, the above-mentioned differences can be negligible however; regional and local ice loss as well as total glacier area retreat could be well overestimated if site-specific data are not considered.

Finally, employing the proposed methodology, can serve as an advantage in obtaining useful data on hardly accessible glaciers, where application of in situ monitoring techniques is often cost-ineffective or dangerous. By showing the type of results and the degree of accuracy that can be achieved by solely using remotely sensed data, the proposed methodology can find applications in various fields such as water resource availability, hydropower plant planning and management of potential glacial risks such as new glacial lake formations and glacier front instabilities.

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