IT ISSN 0391 - 9838

Bollettino del Comitato Glaciologico Italiano - ser. 3

GEOGRAFIA FISICA e DINAMICA QUATERNARIA

An international Journal published under the auspices of the
Rivista internazionale pubblicata sotto gli auspici di

Associazione Italiana di Geografia Fisica e Geomorfologia
and (e) Consiglio Nazionale delle Ricerche (CNR)

recognized by the (*riconosciuta da*)

International Association of Geomorphologists (IAG)

volume 44 (1)
2021

COMITATO GLACIOLOGICO ITALIANO - TORINO
2021

GEOGRAFIA FISICA E DINAMICA QUATERNARIA

A journal published by the Comitato Glaciologico Italiano, under the auspices of the Associazione Italiana di Geografia Fisica e Geomorfologia and the Consiglio Nazionale delle Ricerche of Italy. Founded in 1978, it is the continuation of the «Bollettino del Comitato Glaciologico Italiano». It publishes original papers, short communications, news and book reviews of Physical Geography, Glaciology, Geomorphology and Quaternary Geology. The journal furthermore publishes the annual reports on italian glaciers, the official transactions of the Comitato Glaciologico Italiano and the Newsletters of the Intemational Association of Geomorphologists. Special issues, named «Geografia Fisica e Dinamica Quaternaria - Supplementi», collecting papers on specific themes, proceedings of meetings or symposia, regional studies, are also published, starting from 1988. The language of the journal is English, but papers can be written in other main scientific languages.

Rivista edita dal Comitato Glaciologico Italiano, sotto gli auspici dell'Associazione Italiana di Geografia Fisica e Geomorfologia e del Consiglio Nazionale delle Ricerche. Fondata nel 1978, è la continuazione del «Bollettino del Comitato Glaciologico Italiano». La rivista pubblica memorie e note originali, recensioni, corrispondenze e notiziari di Geografia Fisica, Glaciologia, Geomorfologia e Geologia del Quaternario, oltre agli Atti ufficiali del C.G.I., le Newsletters della I.A.G. e le relazioni delle campagne glaciologiche annuali. Dal 1988 vengono pubblicati anche volumi tematici, che raccolgono lavori su argomenti specifici, atti di congressi e simposi, monografie regionali sotto la denominazione «Geografia Fisica e Dinamica Quaternaria - Supplementi». La lingua usata dalla rivista è l'Inglese, ma gli articoli possono essere scritti anche nelle altre principali lingue scientifiche.

INDEXED/ABSTRACTED IN: Bibliography & Index of Geology (GeoRef); GeoArchive (Geosystem); GEOBASE (Elsevier); *Geographical Abstract*: *Physical Geography* (Elsevier); GeoRef; Geotitles (Geosystem); Hydrotitles and Hydrology Infobase (Geosystem); Referativnyi Zhurnal.
Geografia Fisica e Dinamica Quaternaria has been included in the Thomson ISI database beginning with volume 30 (1) 2007 and now appears in the Web of Science, including the Science Citation Index Expanded (SCIE), as well as the ISI Alerting Services.

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Printed with the financial support from (pubblicazione realizzata con il contributo finanziario di):

– Comitato Glaciologico Italiano
– Associazione Italiana di Geografia Fisica e Geomorfologia
– Ministero dell'Istruzione, Università e Ricerca
– Consiglio Nazionale delle Ricerche
– Club Alpino Italiano

Geogr. Fis. Dinam. Quat.
44 (2021). 13-28, 7 figg., 3 tabb.
DOI 10.4461/ GFDQ.2021.44.2

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THE SULDEN/SOLDA GLACIER (EASTERN ITALIAN ALPS): FLUCTUATIONS, DYNAMICS, AND TOPOGRAPHIC CONTROL OVER THE LAST 200 YEARS

Abstract: Savi S., Dinale R. & Comiti F., *The Sulden/Solda Glacier (Eastern Italian Alps): fluctuations, dynamics, and topographic control over the last 200 years.* (IT ISSN 0391-9839, 2021).

The Sulden/Solda glacier, located in the Ortler/Ortles massif (South Tyrol, Eastern Italian Alps), currently (2017 data) covers an area of ca. 5.2 km^2. The glacier ranges in elevation from about 3500 m to 2440 m a.s.l., and it is largely debris-covered below 2900 m. By combining bibliographic resources, topographic maps and aerial images, we reconstructed the evolution of the Sulden Glacier since the beginning of the 19th century. The result is a detailed history of the glacier variations over the last 200 years, which reveals the complex interactions existing between glacier dynamics and valley morphology. The Sulden Glacier is formed by three ice bodies originating in the uppermost part of the Sulden catchment. In the past, the three glaciers merged to a single valley glacier that flowed northward down to the village of Sulden/Solda, at an elevation of ca. 1900 m a.s.l.. The evolution of these three ice bodies has not been uniform through time, and this heterogeneity drove some of the most impressive dynamics which have characterized the glacier history. In particular, the most prominent advances of the 19th century, including the 1818 surge, were driven by the lateral ice bodies of the Sulden Glacier that advanced and pushed the glacier tongue forward. When retreating, the morphology of the valley floor – characterized by several valley steps, played an important role in fragmenting the glacier, creating very large bodies of dead ice. The last prominent advance of the Sulden Glacier occurred in the 1920s (and lasted until 1927) and, excluding the small advance in the 1980s, the glacier has been retreating since the 1930s. From topographic reconstructions we can estimate the volume of ice lost from 1936 to 2019 in ca. 169 million m^3 (18.7 m w.e.). Out of these, ca. 144 million m^3 (the 85%) have been lost after 1985, highlighting the inexorable impact of recent global warming.

Key words: Glacier fluctuation, Mass budget, Volume reconstruction, Environmental forcing.

Riassunto: Savi S., Dinale R. & Comiti F., *Il ghiacciaio di Solda/Sulden (Alpi orientali italiane): fluttuazioni, dinamiche e controllo topografico negli ultimi 200 anni.* (IT ISSN 0391-9839, 2021).

Il Ghiacciaio di Solda/Sulden, situato nel massiccio dell'Ortles/Ortler (Alto Adige, Alpi italiane orientali), copre attualmente (dati 2017) una superficie di circa 5,2 km^2. Il ghiacciaio si estende da una quota di circa 2.440 m a 3.500 m s.l.m., ed al di sotto dei 2.900 m è in gran parte coperto da detriti. Dall'insieme di risorse bibliografiche, carte topografiche e immagini aeree, abbiamo ricostruito l'evoluzione del Ghiacciaio di Solda dall'inizio del XIX secolo. Il risultato è la storia dettagliata delle fluttuazioni del ghiacciaio negli ultimi 200 anni, che rivela le complesse interazioni esistenti tra la dinamica del ghiacciaio e la morfologia della valle. Il Ghiacciaio di Solda è formato da tre corpi glaciali che hanno origine nella parte più alta del bacino di Solda. In passato (verso l'inizio del XIX secolo), i tre corpi glaciali erano uniti in un unico ghiacciaio vallivo che scorreva verso nord fino al villaggio di Solda/Sulden, arrestandosi ad una quota di circa 1900 m s.l.m. L'evoluzione di questi tre corpi glaciali non è stata uniforme nel tempo, e questa eterogeneità ha guidato alcune delle dinamiche più impressionanti che hanno caratterizzato la storia del ghiacciaio. In particolare, gli avanzamenti più importanti registrati dal Ghiacciaio di Solda nel XIX secolo, compreso il surge del 1818, sono stati innescati dall'avanzata dei corpi glaciali laterali che hanno spinto la lingua del ghiacciaio verso valle. Durante il ritiro, invece, la morfologia del fondovalle - caratterizzata da diversi gradini in roccia - ha giocato un ruolo importante nel frammentare il ghiacciaio, accelerandone il ritiro e creando corpi molto grandi di ghiaccio morto. L'ultima importante avanzata del Ghiacciaio di Solda è avvenuta negli anni '20 (ed è durata fino al 1927), ed escludendo la piccola avanzata degli anni '80, il ghiacciaio si sta da allora ritirando. Dalle ricostruzioni topografiche abbiamo potuto stimare il volume di ghiaccio perso dal 1936 al 2019 in circa 169 milioni di m^3 (18,7 m w.e.). Di questi, circa 144 milioni di m^3 (l'85%) sono stati persi dopo il 1985, evidenziando l'impatto inesorabile del recente riscaldamento globale sull'evoluzione di questo, come di altri, ghiacciai alpini.

Termini chiave: Fluttuazioni glaciali, Bilancio di massa, Ricostruzione del volume, Controllo ambientale.

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This paper has been selected for publication among those presented at the 24th Alpine Glaciological Meeting held in Milano (Italy) from 25th to 26th March 2021 and organized by the University of Milano, the University of Milano-Bicocca, the Italian Glaciological Committee and the Bavarian Academy of Science and Humanities. The Authors would like to acknowledge constructive discussions with many colleagues of the "River Basin Group" of the Free University of Bozen/Bolzano (Italy). A grateful thanks also to the Journal Editor, Carlo Baroni, to an anonymous reviewer, and to Roberto Ranzi for their helpful review. This research was carried out under the auspices of a research grant of Deutsche Forschungsgemeinschaft (DFG) awarded to S. Savi for the project "Effects of climate warming on sediment supply and debris-flow activity in high-mountain regions" (project no. 399435624)

INTRODUCTION

Glaciers are among the most effective indicators of climate change (WGMS, 2020) and their constant loss in size and volume, particularly pronounced in the second half of the 20th century, is considered an undoubtable sign of global warming (e.g., Hock & *alii*, 2019; Zemp & *alii*, 2015). Because of their sensitivity to environmental changes, glaciers are considered the best proxy to study past climatic variability (Orombelli, 2011; Zumbühl & *alii*, 2008). However, the reconstruction of glaciers dynamics in the past is not always straightforward, because geomorphic evidences, such as moraines, may be destroyed by successive glaciers movements, thus allowing to date only the most recent and/or prominent advances (Zasadni, 2007). Systematic and global measurements of glaciers fluctuations started only in 1894 (Allison & *alii*, 2019) with the foundation of the *Commission Internationale des Glaciers* (CIG), born to study and compare glaciers front variations with standardized methods (WGMS, 2020). Its legacy is an almost complete 130-year long series reporting the front variations of many world glaciers with a yearly resolution. Prior to the establishment of the CIG, glaciers variations were studied by individual countries only (mainly European) with a wide lack of information from other mountain regions of the world (i.e., Artic, Himalaya, South America, and others; Allison & *alii*, 2019).

Even within Europe, though, direct measurements of glaciers fluctuations started only at the end of the 19th century (Orombelli, 2011; Zumbühl & *alii*, 2008), whereas prior to this time, reconstructions of glaciers dynamics are generally possible only where other sources of documentation are available (e.g., wood fossils for dendrochronological reconstructions, paintings, popular chronicle or witnesses reports; Baroni & Carton, 1990; Joerin & *alii*, 2006; Orombelli & Pelfini, 1985; Pelfini, 1999; Pelfini & *alii*, 2014; Von Sonklar, 1857; Zumbühl & *alii*, 2008; Zumbühl & Nussbaumer, 2018). As expected going back in time, data are generally more fragmented, less accurate, and reporting only the most prominent changes (e.g., Orombelli, 2011; Zumbühl & *alii*, 2008; Zumbühl & Nussbaumer, 2018). Nevertheless, even the presence of few, high-valuable data (e.g., fossil wood or paleosoils; Orombelli & Pelfini, 1985; Pelfini & *alii*, 2014) may be very useful for the reconstruction of past climatic conditions and for the determination of size and marginal positions of glaciers (Baroni & Carton, 1990; Joerin & *alii*, 2006; Pelfini, 1999). Joint together, such information led to the historical reconstruction of several European glaciers (e.g., Abermann, 2001; Carturan & *alii*, 2014; Orombelli, 2011; Orombelli & Pelfini, 1985; Pelfini, 1999; Pelfini & *alii*, 2014; Zasadni, 2007; Zemp & *alii*, 2008; Zumbühl & *alii*, 2008) which show a good agreement in terms of timing of the most important phases of glaciers advance and retreat, suggesting an overall similar response to environmental forcing (Hegerl & *alii*, 2019; Neukam & *alii*, 2019; Schurer & *alii*, 2015).

In this paper, we report and interpret the history of the Sulden/Solda Glacier (Ortler/Ortles-Cevedale Group), located in South Tyrol/Alto Adige (Eastern Italian Alps) since the beginning of the 19th century. For sake of simplicity, names are reported in both German and Italian only the first time they are mentioned, whereas afterwards only the German version is used.

The Sulden Glacier reconstruction is based on different bibliographic resources (e.g., Desio & *alii*, 1973; Finsterwalder & Legally, 1913; Italian Glaciology Committee - CGI; Payer, 1867; Simony, 1865; Von Sonklar, 1857) that were integrated with old topographic maps and aerial images as well as with the most recent orthophotos and high-resolution DEMs. By integrating all these sources we were able to reconstruct >200 years of the past Sulden Glacier changes, thus providing one of the longest time series of glacier front variations in the Italian Alps (e.g., see Baroni & Carton, 1990; Diolaiuti & Smiraglia, 2010; Orombelli & Porter, 1982; Pelfini, 1999; Strasser & *alii*, 2018). Additionally, we could also analyze the changes occurring along the glacier margins and at its surface.

STUDY SITE

The Sulden Glacier is an important glacier of the Ortler-Cevedale group, located in the western part of the Vinschgau/Venosta valley (South Tirol, Italy, fig. 1). As for many others glaciers in the region (e.g., Carturan & *alii*, 2013; Knoll & *alii*, 2009), the last decades have witnessed a fast reduction of the Sulden Glacier size, with consequent fragmentation of the main glacier into smaller ice bodies (Smiraglia & *alii*, 2015). In 2008, the Sulden Glacier covered an area of ca 5.5 km^2 and comprised 5 ice bodies (Sulden, plus Sulden I to Sulden IV; fig. 1). The largest one, called "Sulden" in Smiraglia & *alii* (2015), covered a surface of ca. 4.27 km^2. Today, the ice fragmentation has proceeded further, increasing the number of smaller ice bodies (up to 10 in 2017) while the glacierized area has decreased (5.2 km^2 in 2017). In the past, all these small ice bodies were merged together to form a single glacier that flowed north in the center of the valley (fig. 1). For sake of clarity, hereafter we will use the term Sulden Glacier or main Sulden when referring to the main ice body since 1945, or to the whole glacier in the past (prior to 1945), when the different ice bodies were unified. For recent conditions (after 2000), we further differentiate between Western Sulden and Central Sulden Glaciers to refer to the two ice bodies that form the main glacier and that are separated by the large medium moraine (fig. 1).

In 2021, the glacier ranges from an elevation of ca. 3500 a.s.l. to 2440 m a.s.l. and it is largely debris-covered below 2900 m. It flows north-east surrounded by some of the highest peaks of the region (e.g., Ortler/Ortles, 3905 m a.s.l., Zebrú/Monte Zebrú, 3737 m a.s.l., and Königspitze/Gran Zebrú, 3856 m a.s.l.). The accumulation zone can be divided into three main areas (Von Sonklar, 1857): i) one comprised between the Ortler and the Königspitze, ii) the circle of the Königspitze, together with the area reaching the Kreilspitze/Punta Graglia and Cedecpass/Passo Cedec, and iii) the area comprised between the Cedecpass and the Suldenspitze/Cima di Solda (fig. 1). These three areas have slightly different topographic characteristics and

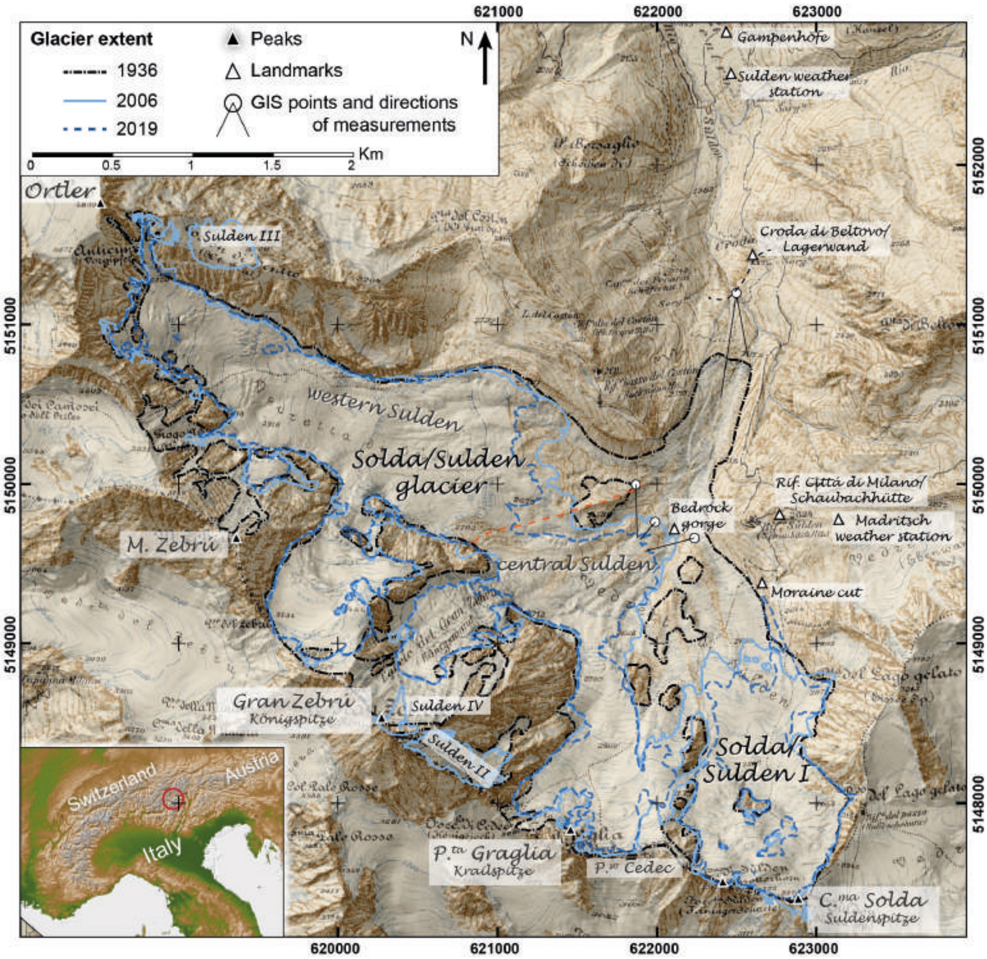

FIG. 1 - The Sulden Glacier, in the Eastern Italian Alps (inset). The figure shows the 2005 DEM (Aut. Prov. Bozen - Bolzano) with superimposed the 1936 topographic map (IGM) and the extent of the glacier in 1936, 2006, and 2019 respectively. The orange dashed line represents the virtual division between Western and Central Sulden, following the large median moraine. To note that in 2006 the Sulden I glacier was still merged to the Sulden Glacier, whereas in 2008 it was already a separate ice body (Smiraglia and Diolaiuti, 2015). Through the text, glacier movements always refer to important landmarks shown here with white triangles (e.g., the *Lagerwand*, or Croda di Beltovo, is a prominent 100 m bedrock step that played an important role in governing the glacier dynamics). Other landmarks are: the weather stations, the cut in the lateral moraine, and the bedrock gorge. The white circles, instead, show the position of the GIS points used for the GIS measurements (see text for explanation).

orientations, and thus receive snowfall and solar radiation with different magnitude (Savi & *alii*, 2021). As such, they feed the glacier at different rates, creating three main ice bodies (i.e., Western Sulden, Central Sulden and Sulden I) – which are separated by median moraines – that flow north/north-east with different dynamics (Finsterwalder & Legally, 1913; Von Sonklar, 1857).

The contrasting topographic features of the different source areas reflect the geology underlying the glacier. The area comprised between the Ortler and the Königspitze is composed of limestones and dolomitic rocks, which impart the classical dolomitical aspect to this part of the Sulden catchment, with impressive relief and very steep walls (fig. 2). In contrast, on the other side of the valley, slopes are gentler, reflecting the underlying metamorphic rocks. This lithological difference is also clearly visible in the moraines structure (Rabanser, 2019) and at the glacier surface, where large amounts of dolomitic and metamorphic debris deposits on the ice (fig. 2).

Two weather stations are located in the Sulden Valley: one in the valley bottom at 1905 m a.s.l. near the village of Sulden/Solda (hereafter called "Sulden"), and one higher up in the basin, at 2825 m a.s.l. (hereafter called "Madritsch", fig. 1). Average climatic conditions for the period 1981-2010 (3PClim database; http://www.3pclim.eu/) indicate a mean annual air temperature (MAAT) of 2.8°C for the Sulden village station, and of -2.4°C for the Madritsch station. Mean annual precipitation (MAP) shows values of 835 mm and 980 mm for Sulden and Madritsch, respectively. The analysis of high resolution climatic data (Crespi & *alii*, 2020, 2021) reveals a general higher warming trend (in average + 2.1 °C for the last decade when referred to the standard reference period 1961-1990) registered in the Alpine region when compared to other European countries (Auer & *alii*, 2007), thus confirming that warming is stronger at higher elevations (Savi & *alii*, 2021). Precipitation shows a more variable pattern and lack any general trend, with the alternation of wetter and drier periods (Savi & *alii*, 2021).

MATERIAL AND METHODS

The reconstruction of the position of the Sulden Glacier active front was carried out using different sources (table 1). Firstly, we looked at existing bibliography dating back to 1857 (Von Sonklar, 1857), which includes studies conducted by different glaciologists (e.g., CGI, annual reports 1927-2019; Desio & *alii*, 1973; Finsterwalder & Legally, 1913; Finsterwalder and Schunk, 1887; Payer, 1867). Secondly, we retrieved old topographic maps for the years 1923 and 1936 elaborated by the Italian Institute of Military Geography

TABLE 1 - Source of information for the reconstruction of the Sulden Glacier history.

	Source	Period
Direct measurements	Historical reports (Sonklar, 1857; Payer, 1867) + German and Austrian Alpine Club journals	1760-1911 (not all years)
	Italian Glaciology Committee reports	1924-2019 (not all years)
Topographic maps	IGM, Aut. Province of Bolzano	1923, 1936, 1989
Aerial images	IGM	1945, 1954, 1959, 1969, 1985
Orthophotos	Aut. Province of Bolzano, Free University of Bolzano	1992, 2003, 2006, 2008, 2014, 2017, 2018, 2019, 2020
DEMs	Bolzano Province, Free University of Bolzano	2005, 2019
Others	ENSRI, Google Earth	2013, 2017

(IGM), as well as aerial images from the period 1945-1985 (IGM). Additional material came from the Autonomous Province of Bozen - Bolzano: a topographic map surveyed in 1989, different orthophotos (from 1992 to 2020) and a high-resolution (2.5 m), ALS-derived Digital Elevation Model (DEM) from 2005. Another, more recent (2019) ALS-derived DEM contracted by the Free University of Bozen - Bolzano was also used. Finally, we used two high resolution images available through ENSRI and Google Earth (for 2013 and 2017).

Merging the measurement series

Compared to others European sites, the reconstruction of the Sulden Glacier history was complicated by the geographic position of the glacier, as South Tyrol was governed by the Austrian-Hungarian Empire until the end of the First World War. As a consequence, measurements and historical reports are fragmented between the two countries and literature exists either in German (prior to 1915) or Italian (after 1920). To our knowledge, the first and only attempt to merge German and Italian data on the Sulden Glacier was carried out by Desio & *alii* (1973), who published a quite detailed report in English that covered the period 1818-1966.

Additional difficulties were encountered in terms of reference positions used to measure the active glacier front. In fact, with the exception of few points marked on the topographic maps of Finsterwalder & Schunk (1887) and few others that we could find in the field, the position of the active front always referred to mobile points, most commonly large boulders, that changed in time accordingly to the advances and retiring phases of the glacier. To overcome this problem, we utilized the detailed map of Finsterwalder and Schunk (1887), as well as the topographic survey of the different glacier front positions carried out by Finsterwalder & Legally (1913). Thanks to the impressive topographic accuracy of these maps, we were able to georeference (by the dedicated tool present in the software ESRI-ArcGIS) the paleoglacier-topography to the present DEM. In doing so, we could determine the positions of the glacier front prior to 1915 and compare it to the 1927 moraines, which are still well visible in more recent topographic maps.

Glacier fluctuations before and after 1974

Following the First World War, the Italian Glaciological Committee started the measurements of frontal variations of Italian glaciers (CGI, 1928-1977). Although glaciological campaigns have been conducted almost every year (with a large gap only in the time period around the Second World War - 1943-1957), bad weather conditions did not allow for a yearly resolution of the observations. The lack of direct observation in the mid-20th century, together with the complex dynamics of the Sulden Glacier, were probably responsible for an erroneous interpretation of the exact position of the active glacier front in the 1970s. In fact, only in 1974 the CGI observed that the main valley bottom was occupied by a large mass of dead ice, and that the whole lower part of the glacier was undergoing a dramatic fragmentation. Because of this, the actual positions of active front of the glacier in the previous years have to be considered unreliable (CGI Bullettin, 1974). The conditions of the glacier in the following years were so difficult to interpret that the glaciologists of the CGI did not perform any measurement. Only since 1978, observing an important advance of the eastern tongue of Sulden Glacier (Sulden I, fig. 1), the CGI started to monitor this glacier front (CGI, 1978-2018; Baroni & *alii*, 2019, 2020).

Such a change in the monitored glacier front implies that different methods are needed to reconstruct the variation of the main Sulden Glacier after 1974. To solve this issue, we selected fixed points based on the available information of the different reports (e.g., point along the Lagerwand), and on the presence of very large boulders visible on aerial photos. These points have been used as reference points to measure the distance of the active glacier front (fig. 1). This method did not allow us to determine a statistical correlation between the GIS-based measurements and the data derived by the measuring campaigns (mean difference of 7 m), but it did permit to quantify the fluctuations of the main Sulden Glacier front in absence of direct field measurements.

For the most recent years (e.g., since 2003), due to the glacier asymmetric retreat, the frontal variations were measured as an average value between the front position and the margin positions observed from the lateral moraines (fig. 1), following the same procedure used by the CGI when measuring very asymmetric ice margins.

FIG. 2 - Panoramic view of the Sulden Glacier and surrounding peaks in 2020. Note the complete separation of the Sulden I and the large debris cover of the Sulden Glacier.

Volume and mass balance calculation

Topographic maps (1936 and 1989) and DEMs (2005 and 2019) have been used to reconstruct the glacier surface and calculate the volume of ice lost in different periods. To reconstruct the glacier topography we first georeferenced the 1936 map and then manually digitized each contour line at 20 m intervals. For the topography outside of the glacier margins, we extracted contour lines from the 2019 DEM, keeping the 20 m interval to match that from the topographic maps. Subsequently, the 1936 DEM was obtained (at 5 m resolution) by utilizing the "topo2raster" function in "ArcGIS" software. The same steps were applied to the 1989 cartography, which nonetheless was already georeferenced. By subtracting the 2019 DEM from the 1936 and 1989 DEMs (i.e., by applying a DEMs of Difference – DoD – analysis, as in Carturan & *alii*, 2013) we could then calculate the volume (m^3) of ice lost between the two time periods. Additionally, we calculated the volume of ice lost between 2005 and 2019 by directly differencing the DEMs (previously aligned) of the respective years. The obtained DoD for this period has a resolution of 2.5 m.

To calculate the mean error associated to this operation, we used the approach proposed by Carturan & *alii* (2013) who calculate the mean value obtained in the subtraction of stable (bedrock) areas. We created 4 classes of different slope (in degrees: 0-15; 15-35; 35-50; 50-80) and calculate the mean error for each class. For the 1936 map, we additionally noted that there were differences in the altitude of the topographic measurements of quoted points (for example, the top of the Ortles is given at 3899 m a.s.l. in the 1936 map, whereas the currently official value is 3905 m a.s.l.). As such, we added a mean error of 2.46 m to the errors obtained from the stable areas analysis. The total error associated with the volume calculation is then given by the sum of each single error, i.e., of each cell of the DoD.

Once obtained the ice volumes, we calculated the glacier mass balance per unit area, M (m w.e. a^{-1}) by using the following equation:

$$M = \frac{\Delta V \times \rho_{ip}}{t \times A \times \rho_w}, \quad (1)$$

where ΔV is the ice volume variations (m^3), ρ_{ip} is the ice-pack density (kg m^{-3}), ρ_w is the density of water (equal to 1000 kg m^{-3}), A is the area of the glacier (m^2) at the beginning of the analyzed period, and t is the time interval (in years) between the analyzed time periods (Fischer, 2011). For the ice-pack density we used the value of 850 kg m^3, suggested when local data of snow-firn density is unknown (Huss, 2013; Carturan & *alii*, 2013). By using the inverse of formula (1) and the data reported in Carturan & *alii* (2013) for the mass budget of the glaciers in the Ortler-Cevedale group (i.e., for the Sulden Glacier a yearly mass loss of 0.7 ± 0.08 m w.e. a^{-1} is there reported, we could additionally calculate the volume of ice lost in the time period 1984-2005. This value has been used to compare the reliability of our results with existing measurements, and to better reconstruct melting rates.

Climatic data

To analyze the relationship between climate and glacier fluctuations, we used the climatic data of the two weather stations located in the catchment mentioned in section 3.1, jointly with two additional nearby stations, which were homogenized over a longer time period. These stations are: i) the Marienberg/Monte Maria station (1323 m a.s.l.), located at ca. 23 km north-west from the Sulden Glacier, which registers data since the 1857 (data gently provided by the Federal Office of Meteorology and Climatology of MeteoSwiss; Isotta & *alii*, 2014); and the Caserer weather station (2600 m a.s.l.), located south-east at ca. 11 km from the glacier, which registers data since 1930 (data freely available from Meteo Trentino website). Following the same approach used by the CGI to evaluate favorable or unfavorable climatic conditions for glaciers, we used monthly data of each year to calculate the average temperature for the ablation season (from June to September) and the average precipitation for the accumulation season (from November to April). Accordingly, low temperatures associated to high precipitation should provide climatic conditions favorable to glacier advance, whereas high temperature and low precipitation should favor glacial melting.

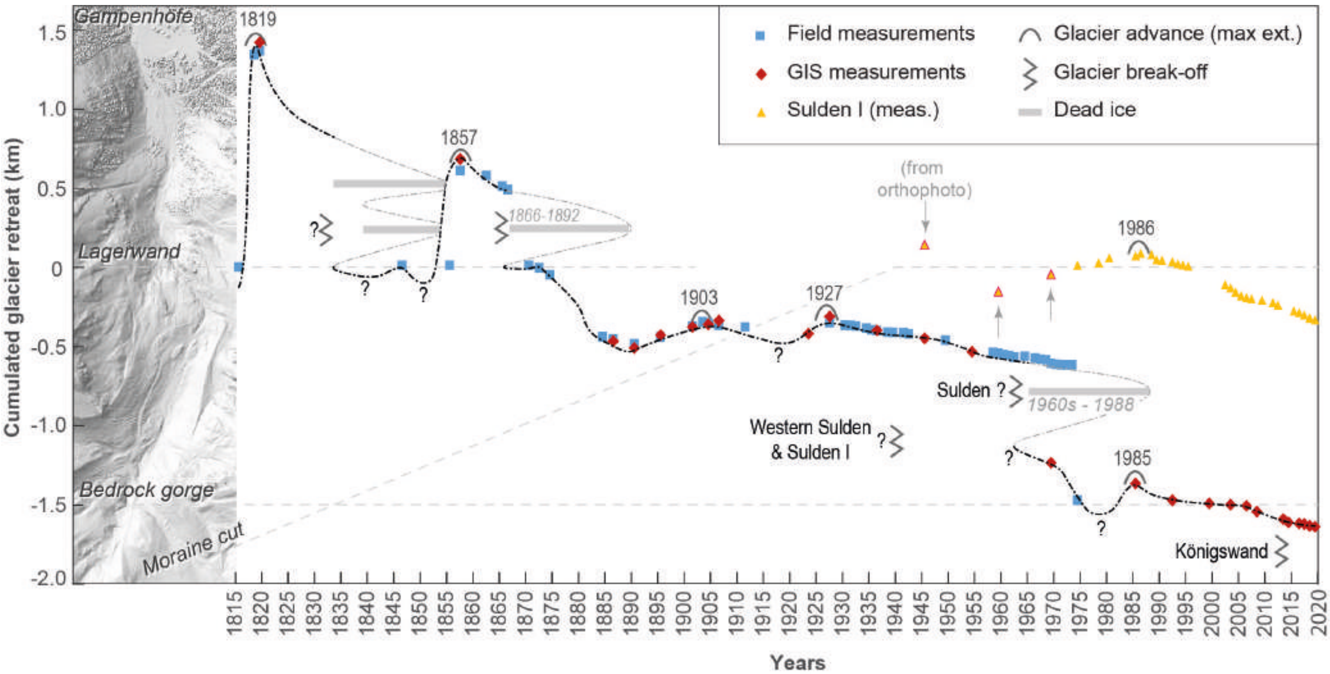

FIG. 3 - Position of the Sulden Glacier front through time (1815-2019) derived from direct- (blue squares) and GIS-measurements (red diamonds). The figure also shows the measurements of the Sulden I front position after 1974 (yellow triangles) and those observed on aerial images prior to this date (yellow triangles with red border). For the Sulden I, the dashed gray reference line represents the cut in the lateral moraine where passes the modern ski-piste (i.e., the initial reference position taken from the GCI when starting measuring this part of the glacier). The dot-dashed black line linking all points shows the inferred glacier variations through time with unknown minimum positions marked by a "?" symbol. Also, by a dot-dashed gray line, the possible variations of dead-ice bodies are shown.

RESULTS

Glacier fluctuations in the period 1760-1911

The first known advance of the Sulden Glacier started around 1760s, in agreement with other glacier advances reported across the European Alps (Finterwalder & Legally, 1913; Von Sonklar, 1857), but the exact position of the glacier front in this period is not known. Based on dendrochronological studies – Arzuffi & Pelfini (2001) hypothesized that the maximum extent of the Sulden Glacier was reached around the 1770s, similarly to what was found for the nearby Madatschferner/Madaccio glacier in the Trafoi valley (Pelfini, 1999). In contrast, Finterwalder & Legally (1913) report that the maximum extent was reached during the surge culminating in 1819. According to these authors, the most impressive advance of the Sulden Glacier started in 1815, when the glacier was still above the Lagerwand (fig. 3). In April 1817 the advance increased, and large ice blocks started to fall down the Lagerwand. By December 1817, the glacier had reached the upper pastures in the valley bottom, and in March 1818 the advance progressed further. By August 1818 the glacier stopped ca. 300 m behind the uppermost houses of the Sulden village (fig. 1 and fig. 3). Therefore, over slightly more than one year (April 1817 - August 1818) the glacier had advanced in a surge-like mode for almost 1300 m, moving at a velocity of about 2m/day. In 1818 the glacier occupied the whole valley bottom and its front was 277 m wide and 57 m high (Von Sonklar, 1857). In the following year the glacier moved forward at a slower pace, advancing only 23 m (Finsterwlder & Legally, 1913). The origin of this surge was attributed to an advance of the Sulden I ice body (Von Sonklar, 1857), probably in relation to the very cold and wet conditions that characterized the years 1815-1818 (Carturan & *alii*, 2014). Soon after, by 1820, the retreat had started and by 1846 the glacier was back above the Lagerwand, although large blocks of dead ice were still visible in the valley bottom (Simony, 1865; Von Sonklar, 1857). Reports about a break-off of the main ice body at the Lagerwand do not exist, but, by looking at the glacier dynamics in the following years, it is likely that a break-off occurred, speeding up the melting of the glacier tongue in the valley bottom. A short advance occurred in 1846, when the glacier reached again the rim of the Lagerwand, but without overpassing it. The glacier retreated again in the following years, while a new phase of advance started around 1855 – reportedly driven by the Western Sulden tongue (Finsterwalder & Legally, 1913) – when ice avalanches fell down the Lagerwand and started to merge with the previously abandoned dead ice (Von Sonklar, 1857; fig. 3). A fast advance occurred in the following year, stopping ca. 750 m behind the 1819 terminal moraine (Finsterwalder & Legally, 1913). The maximum extent of this phase was reached in 1857, but its exact position is unclear (Arzuffi & Pelfini, 2001; Finsterwalder & Legally, 1913; Payer, 1867). In 1865 the glacier was ca. 850 m behind the 1819 terminal moraine, while the following year it had retreated by 22 m when it broke off at the Lagerwand (Finsterwalder & Legally, 1913). A huge

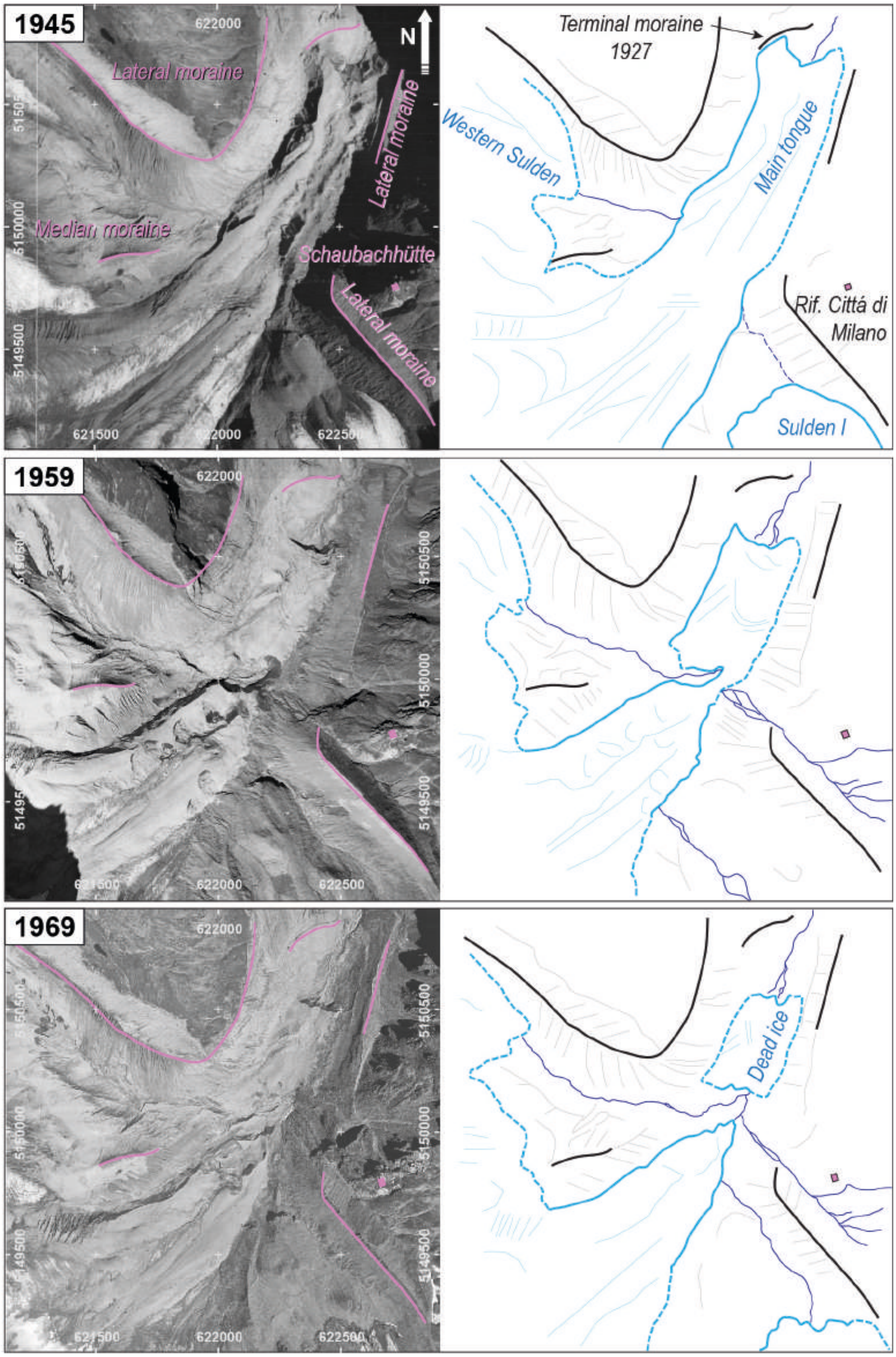

FIG. 4 - The terminus of the Sulden Glacier in 1945, 1959 and 1969, highlighting the dissection of the glacier tongue by the Western Sulden outflow. Right panels: In light blue, the glacier margins; in dark blue, the channel network; in black and light gray, morphological landmarks.

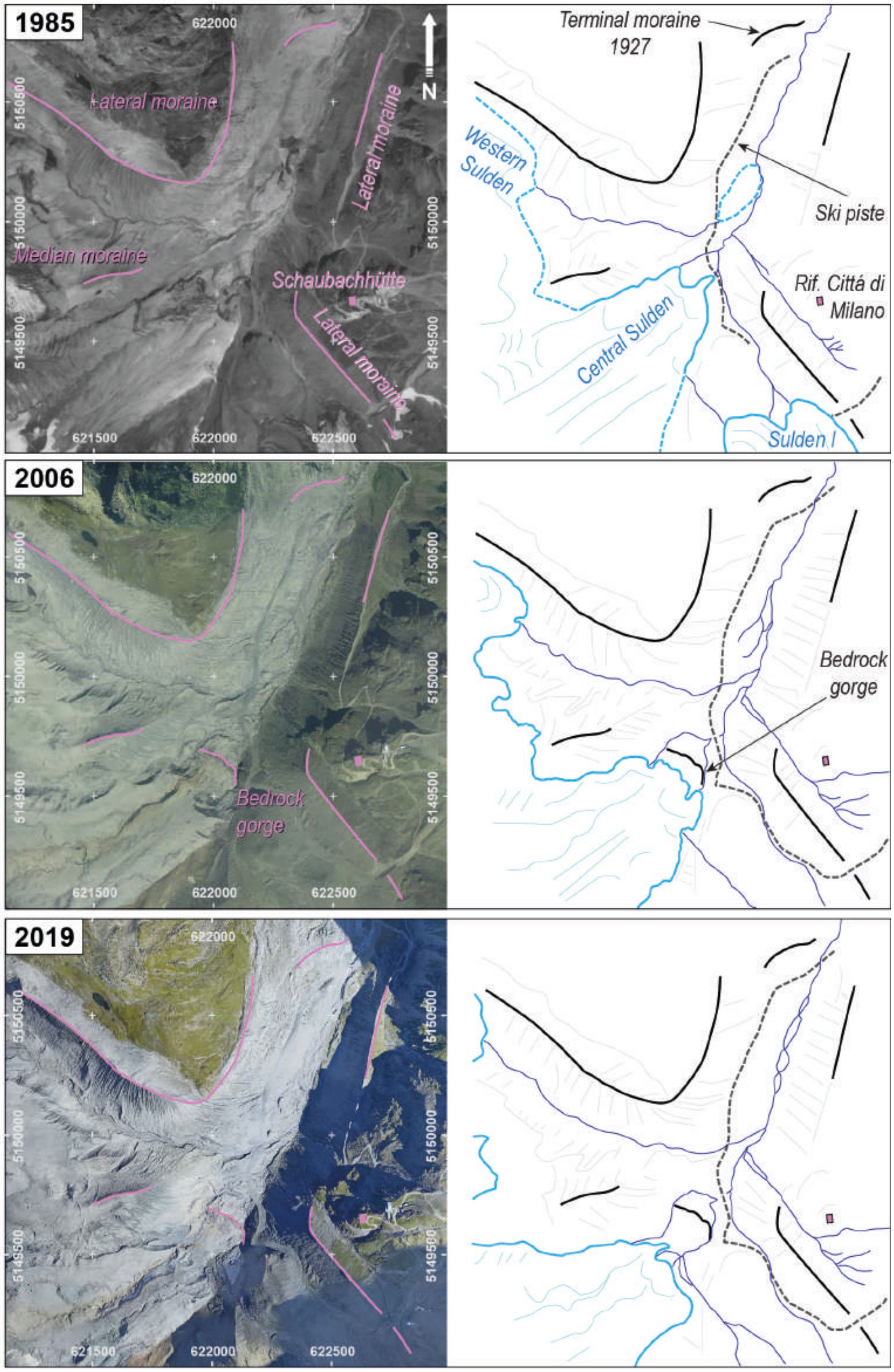

FIG. 5 - The terminus of the Sulden Glacier in 1985, 2006 and 2019. Right panels: In light blue, the margin of the glacier; in dark blue, the channel network; in black and light gray, morphological landmarks.

mass of dead ice was left in the main valley bottom, where a small portion remained until 1892. The new active front above the Lagerwand remained still until 1870, when it started a fast retreating phase that lasted until 1890 before a new advancing phase began (fig. 3).

The fast disintegration phase after the 1850s advance was driven by the rapid retreat of the Western Sulden ice body, which in 1879 was separated by the main tongue and already behind the bending of the left lateral moraine (Finsterwalder & Legally, 1913). This ice body started to rapidly advance in 1883 and by 1886 it had advanced 200 m, filling the gap with the main glacier (see Supplementary material). By 1890, it had advanced another 120 m, and started pushing the glacier forward. By 1895, with an additional push from the Sulden I ice body, the main Sulden Glacier had advanced 41 m (Finsterwalder & Legally, 1913). In 1901 a further advance of 70 m was registered, although the pressure from the Western Sulden was decreasing. Small advances continued until 1903 after which started a retreating phase (fig. 3). Between 1883 and 1901 the Western Sulden had advanced ca. 400 m, with a rate of ca. +22 m a^{-1}, thereby pushing the Sulden Glacier 138 m forward, i.e., about +10 m a^{-1} (Finsterwalder & Legally, 1913).

Glacier fluctuations in the period 1911-2019

The position of the glacier front between 1911 (last year of measurement from Finsterwander and Legally, 1913) and 1923 (year of the first available topographic map) is not known, but in accordance with the variations of other glaciers in the Alps, the retreating phase likely continued until the beginning of the 1920s, when a new phase of advance characterized many European glaciers (Desio & *alii*, 1973; Kuhn & *alii*, 1997). The Sulden Glacier has indeed advanced between 1922 and 1924 (+ 7.5 m; Desio & *alii*, 1973) and the maximum extent of this phase is marked by the well visible 1927 terminal moraine located ca. 315 m above the Lagerwand. After this year, the Sulden Glacier started a retreating phase that lasted at least until the end of the 1970s (CGI, 1978).

From topographic maps and aerial images acquired from the IGM, we could observe that the glacier was still a single ice body at least until 1936 (fig. 1), whereas in 1945 the two lateral tongues (i.e., Western Sulden and Sulden I) had separated from the main Sulden, and their fronts where ca. 430 m and 280 m behind the main ice body respectively (fig. 4). By the end of the 1970s/early 1980s the glacier underwent a short advancing phase that peaked in 1985/86, leaving small (1-2 m high) terminal moraines that are still well visible in the landscape. By this period, the main Sulden front was just above the confluence zone with the two lateral ice bodies (fig. 5), which, although advancing, never merged again with the main glacier. Since 1986 the glacier has been experiencing a rapid disintegration phase, losing both volume and length (CGI. from the 1980s onward). All detailed measurements of the front variations are provided in the supplementary material.

The 1960s glacier dissection

As already mentioned in the Method section, particularly problematic for the direct measurements of the front variations of the Sulden Glacier were the years following the Second World War. Only in 1974 it was recognized that the glacier in the valley bottom was a large body of dead ice and that the active front of the glacier was probably somewhere above the bedrock gorge located in the proximity of the Schaubach/ Città di Milano mountain hut (fig. 1; CGI, 1974). Thanks to the aerial images, in particular those of years 1945, 1954, 1959 and 1969, we were able to identify the dynamics that drove the formation of this large dead ice, and to define the position of the glacier front in the following years. As already mentioned, between 1936 and 1945 the two lateral ice bodies of the Western Sulden and Sulden I separated from the main tongue and continued to retreat at different rates. Already in the 1945 aerial image it is possible to note that the outflow channel from the Western Sulden started to erode the ice of the main Sulden Glacier (fig. 4). The erosion is more evident in the 1954 and 1959 images, where the dissection of the glacier tongue is almost complete. We do not know when the glacier tongue was definitely cut from its upper body, but the separation was complete by 1969 (fig. 4). Although the GCI glaciologists measured the Sulden front variations continuously from 1958 until 1973, we now know that these measurements cannot be considered reliable for the reconstruction of the glacier front position in this period. The dissection occurred sometime in the 1960s and left a large body of dead ice in the valley bottom that remained until 1988 (CGI). The position of the active front in 1969 is not easy to define because open mouths were already visible on the plain above the bedrock gorge that today hosts the terminus of the glacier. The whole tongue was in strong disintegration at least until the end of the 1970s, when a new advancing phase pushed the glacier front below the bedrock gorge (fig. 5). After 1985 the glacier started to retreat again, and it never stopped since then. By 1996, the bedrock gorge was completely free from ice, whereas in 2014 the Königswand glacier (one of the feeding area of the main glacier, hosted in the Königspitze cirque, fig. 1) became separated from the Central Sulden.

Mass balance and rates of change

With the two topographic maps and the available DEMs, we could calculate the volume of ice lost in the time periods 1936-2019, 1989-2019 (fig. 6), and 2005-2019 (table 2, see also the supplementary material).

The rates of glacier fluctuations have been calculated only for those periods that showed a constant advancing or retreating phase. As such, all periods characterized by dead ice bodies have not been considered. In this regard, the values reported by Desio & *alii* (1973) should not be considered as real rates, because these authors did not account for the breaks-off of the glacier tongue nor for the presence of dead ice. Regarding the frontal variations of the glacier terminus, we have considered the beginning and the end of the most continuous fluctuations, whereas to calculate yearly mass

TABLE 2 - Area, volume, and mass balance calculated for different periods.

Time period	Reference Map	Area§ (km^2)	Debris cover area (%)	Volume ± Error (million m^3)	Error (%)	Mass balance (m w.e.)	Mean annual mass balance (m w.e. a^{-1})
1819-1886*	1819	10.4	Unknown	45		3.7	-0.05
1936-2019	1936	7.7	12	169 ± 21	13	18.7 ± 2.35	-0.22
1984-2005**	1987	6.5	Unknown	112 ± 13	12	14.7 ± 1.68	-0.70
1989-2019	1989	6.6	25	144 ± 2	1	18.6 ± 0.27	-0.62
2005-2019	2006	5.7	42	61 ± 0.5	1	9.1 ± 0.08	-0.65
	2019	4.8	41				

* from Finsterwalder & Legally, 1913. This value only refers to the volume of ice lost in the glacier tongue.
** from Carturan & *alii*, 2013; the value is averaged by considering the uncertainty in the yearly mass balance rate.
§ For the whole Sulden glacier (sensu latu).

TABLE 3 - Rates of change in glacier front position and mass balance for the different periods. Note that the periods are different for the three ice bodies.

Front position variations					
Sulden Glacier (or Central Sulden)		Western Sulden		Sulden I	
Time period	Rate of change (m a^{-1})	Time period	Rate of change (m a^{-1})	Time period	Rate of change (m a^{-1})
1857-1866	-13.5	1945-1959	-8.2	1945-1959	-17.9
1870-1890	-24.7	1959-1969	-7.5	1959-1969	+6.2
1890-1903	+10.6	1969-1985	+1.9	1978-1986	+6.5
1927-1949	-5	1985-2003*	-4.6	1986-2003	-12.1
1985-2003	-7.5	2003-2019*	-22.2	2003-2019	-12.6
2003-2019	-8.7				

Volume change		
Time period	Rate of change (million m^3 a^{-1})	Rate of change (m w.e. a^{-1})
1936-1989	-0.5	-0.05
1989-2005	-5.9	-0.77
2005-2019	-4.3	-0.65

* see discussion

balance rates we used the volume calculation previously reported. Results are shown in table 3. It is worth to note that data relative to changes after 1936 (i.e., 1936-2019 for ice volumes, and 1936-1989 for front position) include also the small glacier advance occurred in the 1980s. Therefore both information should be considered with care, as values are very probably underestimated.

DISCUSSION

Sulden Glacier fluctuations in the context of other Alpine glaciers

The history of the Sulden Glacier reveals a good agreement with the fluctuations of the most prominent glaciers in the European Alps (e.g., Abermann, 2011; Baroni & Carton, 1990; Carturan & *alii*, 2014; Orombelli, 2011; Zemp & *alii*, 2008), but it also shows very distinctive characteristics.

Similarly to other glaciers in Europe (Brönnimann & *alii*, 2019; Carturan & *alii*, 2014; Orombelli, 2011; Orombelli & Porter, 1982; Pelfini, 1999; Zemp & *alii*, 2008; Zumbuhel & *alii*, 2008;), also the Sulden Glacier shows its maximum extent at the beginning of the 1800 (namely in 1819), and not in the middle of the century, as observed for many other European glaciers (Baroni & Carton, 1990; Carturan & *alii*, 2014; Pelfini, 1988; Ranzi & *alii*, 2010; Zumbuhel & *alii*, 2008). The glacier advance registered in the 1850s was certainly very important, but did not match the 1818 surge. The other advancing phases of the glacier are in agreement with the general trend shown by European glaciers, with advancing in 1890-1900, 1920-28, 1980-85 (Abermann, 2011; Baroni & Carton, 1990; Kuhn & *alii*, 1997; Orombelli, 2011; Zemp & *alii*, 2008). Also the retreating rates during the last period of the 20th century, if excluded the time period 1936-1989 that is probably underestimated, are in line with those observed in the Ortles-Cevedale group (Carturan & *alii*, 2013, 2016; Giada & Zanon, 1996; Knoll & Kerschner, 2009; Zanon, 1992;) as well as across the European Alps, with an acceleration of ice loss starting from the 1990s (D'Agata & *alii*, 2014; Gabrielli & *alii*, 2016; Zemp & *alii*, 2015).

The distinctive features of the Sulden Glacier dynamics lie in the morphology of the glacier, both in terms of accumulation zones and of the valley bottom morphology.

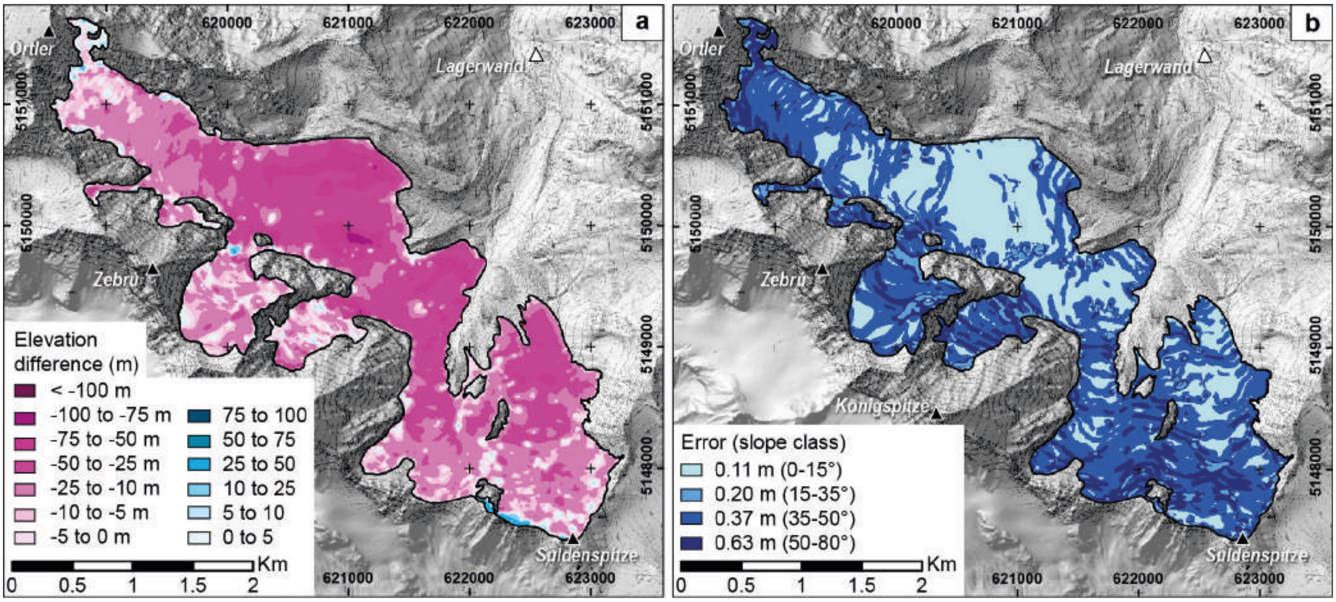

FIG. 6 - Example of the DoD calculation performed for the Sulden Glacier for the period 1989-2019. (a) Elevation difference between 1989 and 2019; (b) Mean errors in elevation difference calculated for different slope classes.

The presence of three different accumulation areas, receiving snowfall and solar radiation at different proportions (Savi & *alii*, 2021), seems to have played a pivotal role in governing both the advancing and retreating dynamics of the glacier. For example, all the advancing and some retreating phases occurred in the mid-19th century have been driven by the advance or retreat of individual lateral ice bodies forming the main glacier (Sulden I and Western Sulden, respectively; Finsterwalder & Legally, 1913; Von Sonklar, 1857). The highly stepped morphology of the valley bottom, instead, has surely impacted the retreating phases, favoring glacier fragmentation and the formation of large dead ice bodies.

Impressive is also the 1960s dissection by the Western Sulden outflow channel. The different speed at which the three ice bodies moved, together with the topography of the valley bottom, are probably responsible for this peculiar event. We could speculate that a similar cut could have occurred at the end of the 1800, when the Western Sulden became separated from the main tongue and it was above the bending of the left lateral moraine (Finsterwalder & Legally, 1913). However, the fast advance occurred since 1883 may have prevented the occurrence of a similar dynamic, while favoring the advance of the whole ice mass. The fact that the outflow of the Sulden I did not have a similar effect on the eastern side of the Sulden tongue is explained by the morphology of the valley floor and by the dynamics of this lateral ice body. The Sulden I outflow is indeed flowing at a higher altitude compared to the Central Sulden and Western Sulden, and its channel may have been less effective in terms of discharge (Engel & *alii*, 2019, 2020). Also, the position of the Sulden I outflow channel changed through time (fig. 5), reducing its ice-melting effects. In most recent years (e.g., after 2000) the position of the Sulden I outflow has been more stable and its effects on the erosion of the Central Sulden has become more important (fig. 5), causing indeed a very asymmetric retreat of the glacier terminus.

The role of supraglacial streams and debris cover in the recent glacier dynamics

The presence of supraglacial streams and different debris cover may be one of the causes of the different rates at which the three ice bodies retreated and fragmented (e.g., Fyffe & *alii*, 2019a, 2019b; Nicholson and Benn, 2006; Nicholson & *alii*, 2018; Nicholson & Stiperski, 2020). Presently, large supraglacial streams are present only on the Western Sulden, whereas few and small streams are present on the Central Sulden and Sulden I. Also, the Sulden I is basically a clean ice glacier, and debris started to accumulate only in the last (6 to 10) years in the terminal part of the glacier. By looking at the different orthophotos, we can see that the retreating dynamics of the Western Sulden are very different from those of the other two ice bodies. Between 1985 and 2003, for example, the terminal part of the Western Sulden showed an important loss of volume along the path of a supraglacial stream, while its terminus position did not retreat much (only 83 m in 18 years). In contrast, the Sulden I showed a uniform loss in both volume and length, with a retreat of 218 m. In a similar time span (2003-2019), the Western Sulden showed an apparent accelerated melting, retreating by 355 m in only 16 years. The Sulden I, instead, maintained a more constant rate and retreated further 201 m in the same period. This difference may be explained by the presence of large supraglacial streams and extensive debris cover on the Western Sulden (Nicholson & Boxall, 2020; Rabanser, 2019). It is indeed known that, depending on debris thickness, the presence of debris cover can change the albedo and the thermal properties of the glacier surface (e.g., Nicholson and Benn, 2006; Nicholson & Stiperski, 2020), favoring a very inhomogeneous melting. Additionally, the presence of supraglacial – as well as of endoglacial streams – may significantly increase local

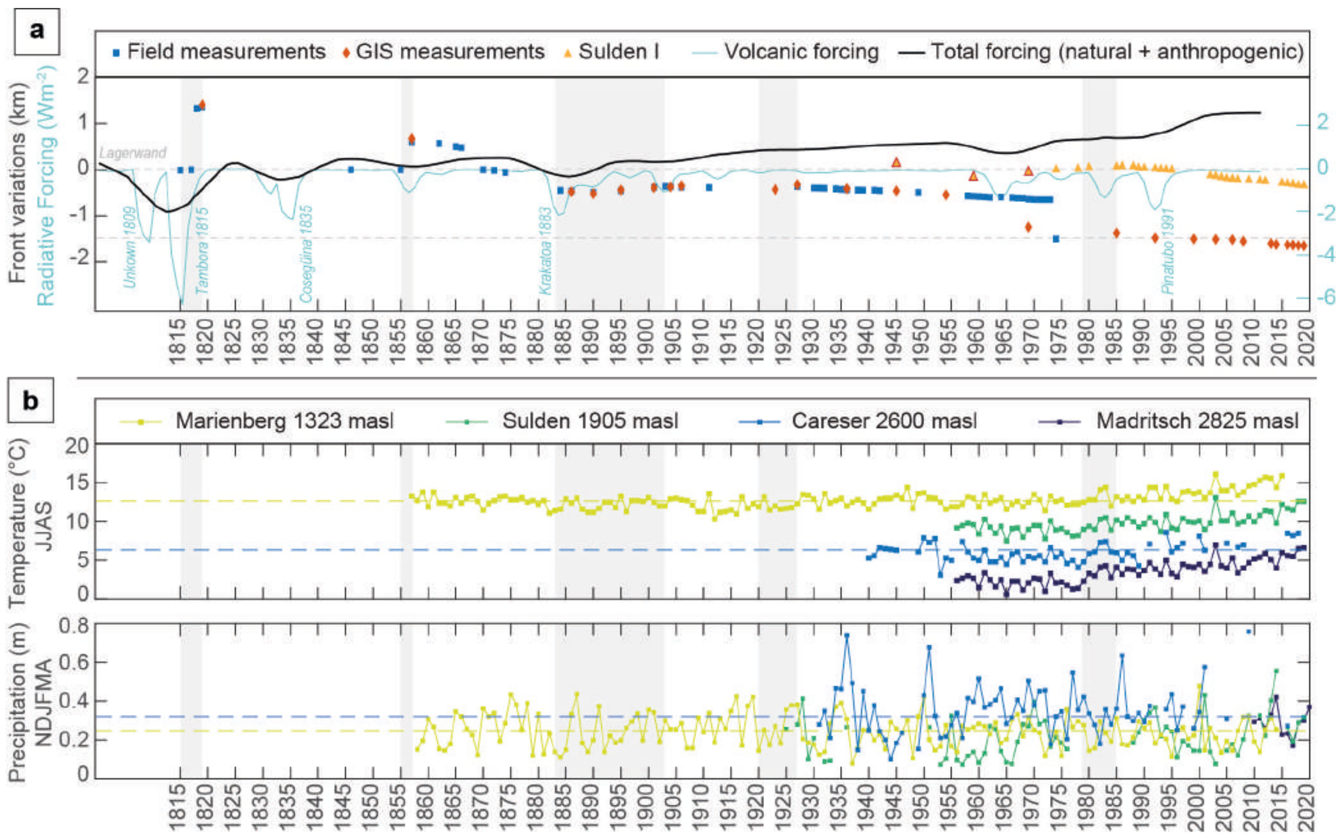

FIG. 7 - a) Sulden Glacier front variations together with radiative forcings from volcanic eruptions and other (natural + anthropogenic) factors (data derived from Hegerl & *alii*, 2019). Light gray bars in the background of the graph show the period of glacier advance. b) Climatic data on mean temperature for the ablation season (upper panel) and on precipitation for the accumulation season (lower panel) of different weather stations in the surrounding of the Sulden Glacier. Dashed lines represent the mean value for the standard reference period 1961-1990 (only calculated for the Marienberg and Caserer weather stations). See text for more details on the data sources.

melting rates (Fyffe & *alii*, 2019a, 2019b). Therefore, the Sulden I ice body, which features smaller supraglacial streams and very limited debris cover, has been overall melting more rapidly and spatially uniformly compared to the Western Sulden.

These dynamics imply that by looking only at the glacier front position one could erroneously conclude that the Western Sulden underwent an accelerated melting after 2000. In fact, this glacier lost ice volumes at rapid rates already during the previous 15 years, but ice losses occurred mostly by glacier thinning rather than by frontal retreat. Similar dynamics have been reported also for the past, in particular for years 1862 and 1911, when the retreating phase started with an important loss of volume followed by a fast retreat of the terminus position (Finsterwalder & Legally, 1913). This suggests that, in order to correctly interpret glacier fluctuations, it is of extreme importance to analyze 3D glacier variations, and not only those occurring at the terminus. This aspect is further emphasized by the important role of the three main ice bodies in driving some of the most impressive dynamics that characterized the Sulden Glacier history (e.g., the 1818 surge, the advance of the 1890, and the cut-off of the 1960s).

Environmental forcing on glacier fluctuations: implications for climate change and future water availability

The very distinctive dynamics of the Sulden Glacier, especially the rapid advances of the 19th century, have long drawn the attention of several glaciologists (e.g., Von Sonklar, 1857; Finsterwalder & Legally, 1913). However, the lack of systematic measurements of climatic parameters, such as temperature and precipitation, during the first half of the 19th century (Kuhn & *alii*, 1997), prevented a clear link to peculiar climatic conditions that favored glacier advance or retreat. However, many investigations examining the interplay between natural and anthropogenic forcing relative to glaciers changes have been recently conducted (e.g., Brönnimann & *alii*, 2019; Hegerl & *alii*, 2019; PAGES 2k Consortium, 2019). According to these studies, the most prominent glaciers advances that occurred in the 19th century in the European Alps may be related to an intense period of volcanic activity that concentrated in the first half of the 1800 (Garrison & *alii*, 2018; Guevara-Murua & *alii*, 2014; Raible & *alii*, 2016). Numerical models have demonstrated that such volcanic activity had a global influence on climate, with a strong negative impact on temperature and radiative forcing over Europe, which resulted in particularly cold summers and wet winters (Brönnimann & *alii*, 2019; Hegerl & *alii*, 2019), i.e., favorable conditions for glaciers advances. Indeed, particularly striking are: i) the correspondence between the Tambora eruption (1815), which in 1816 caused the famous "year without summer" and blocked incoming radiations for the following 3 years (Raible & *alii*, 2016; Brönnimann & *alii*, 2016; and reference therein), and the Sulden surge of 1817-1818; as well as ii) the Krakatoa eruption (1883) and the phase of advance that characterized the Western Sulden, and then the whole glacier, starting exactly on that year (fig. 7). According to these authors, large volcanic eruptions may have been responsible not only for the glacier advancing phase, but also for a fast retreating phase after the cooling caused by the eruption (Brönnimann & *alii*, 2019; PAGES 2k Consortium, 2019; Shurler & *alii*, 2015). This, together with the increasing temperature started at the end of the Little Ice Age, would help explain the fast retreating phases which followed the glacier advances in the 19th century.

Through the 20th century, instead, the lower volcanic activity, together with the increasing temperatures and the simultaneous increase in green-house gases (Hegerl & *alii*, 2019), promoted a phase of general positive radiative forcing that favored glaciers retreat. During this period, glaciers advances of 1920s and 1980s were more likely linked to cold summers and wet winters (Kuhn & *alii*, 1997) that characterized the antecedent (1910-20 and 1975-80) periods (fig. 7). Finally, the rapid temperatures rise (due to anthropic greenhouses gasses) that characterized the whole Earth and very pronouncedly the European Alps from the 1980s (Hegerl & *alii*, 2019; Savi & *alii*, 2021) is undoubtedly responsible for the fast acceleration of glacier ice losses registered in the same period (Citterio & *alii*, 2007; D'Agata & *alii*, 2014; Zemp & *alii*, 2015).

The results of this study indicate that since the beginning of the 19th century the Sulden Glacier has retired over a length of more than 3 km, and since 1936 it has lost ca. 169 million of m^3 of ice (ca. 18.7 m w.e. with an average rate of -0.2 m w.e. a^{-1}). In the last 35 years only (1985-2020) the glacier has lost ca. 144 million m^3 of ice, the 42% of which (61 million m^3) after 2005, i.e., in only 14 years. The average rate of melting for this period can be calculated in ca. 5 million of m^3 of ice per year (4.25 million m w.e. a^{-1}, with an average mass balance rate of -0.7 m w.e. a^{-1}).

In order to correctly assess the magnitude of ice losses from the Sulden Glacier, values have to be put in the context of regional water availability and water usage (Galos & *alii*, 2015). In fact, in the Vinschgau/Venosta valley, the water volume provided by the Sulden Glacier alone corresponds to about 11% of the total volume of water used every year for agricultural purposes (Zucaro & Cesaro, 2009). Unfortunately, the cumulative ice losses from all the glaciers of such a very dry valley – where currently irrigation from glacier-fed streams is crucial for cultivation (e.g., Penna & *alii*, 2021) – will tremendously impact its socio-economical future under any current future climate scenario.

CONCLUSION

In this study we have integrated bibliographic resources, aerial images, and digital elevation models to reconstruct the history of the Sulden Glacier over the last 200 years, providing one of the longest time series of a glacier front variations in the Italian Alps. Our results highlight the importance of studying the whole glacier body and not only its frontal dynamics, as glacier variations depended not only upon general climatic forcing but also on the dynamics of the different ice bodies composing the glacier. In fact, the dynamics of the whole ice mass was highly impacted by individual glacier characteristics (e.g., debris-covered versus clean) as well as by local geomorphic features (e.g., presence of valley steps promoting ice fragmentation and formation of dead ice bodies).

The fluctuations observed in the Sulden Glacier during the last 200 years are in agreement with the dynamics of others Alpine glaciers, with important phases of glacier advances and retreats distributed along the 19th century and a major retreating phase characterizing most of the 20th century, which became exacerbated in the first two decades on the 21st century. The impressive, rapid advances occurred in the 19th century were likely caused by intense volcanic eruptions – superimposed on the terminal phase of the Little Ice Age – which determined extremely cold summers and wet winters in the immediate subsequent years. Similarly to most glacier worldwide, instead, the glacier melting phase characterizing the Sulden Glaciers over last 120 years may be directly associated to the global, long-lasting phase of warmer – and drier – conditions since the end of Little Ice Age. The recent – mostly since the 1990s – accelerated warming due to anthropogenic greenhouse gasses emissions has greatly impacted the Sulden Glacier, whose ice losses over the last ~30 years are estimated to be around -0.7 m w.e. a^{-1}.

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(Ms. received 4 October 2021, accepted 15 November 2021)