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20 YEARS OF GLACIER CHANGE: THE HOMOGENIZED GLACIER INVENTORIES FOR SOUTH TYROL 1997-2005-2017

Abstract: Galos S.P., Klug C. & Dinale R., *20 years of glacier change: the homogenized glacier inventories for South Tyrol 1997-2005-2017.* (IT ISSN 0391-9838, 2022).

This paper presents a set of three homogenized glacier inventories for the Italian region of South Tyrol for the years 1997, 2005 and 2017. Within this framework, in addition to the compilation of the 2017 inventory from newly recorded data, a complete re-evaluation of the 2005 regionwide laser scan data was performed, resulting in the creation of a new 2005 glacier inventory. Furthermore, a complete revision of the 1997 inventory was performed using modern methodology and taking into account the knowledge gained by compiling the newer inventories from high-resolution laser scan and photogrammetry data. The result is a homogeneous data set on the extent of South Tyrolean glaciers over the three recording dates which allows comparisons between the individual inventories and thus illustrates the glacier changes in the study area over two decades. The evaluation of the new 1997-inventory results in a glacier area of 121.9 km^2, which is about 12.2 km^2 (or 11%) larger than in the original inventory for 1997. This is mainly due to the inclusion of previously unrecorded glaciers, but is also owed to the improved recording of debris-covered subareas. Analyses over the 1997-2005 study period (1997-2017) show an area loss of about 18.1 km^2 (37.9 km^2) for the entire study area. This represents a relative loss of 14.8% (31.1%). While the relative area losses in the subperiod 1997-2005 (with the exception of the Texel Group: 24.7%) are still quite similar among the individual mountain groups with 13% (Hohe Tauern, Stubai Alps) to 19% (Zillertal Alps), a clear difference between the mountain groups west and east of the Eisack-River develops in the second subperiod 2005-2017. While the 1997-2017 losses in the west of the study area range between 25% (Stubai Alps) and 29% (Ötztal Alps), the values for the regions in the east range between 39% (Hohe Tauern) and 43% (Zillertal Alps). Again, the Texel Group is an exception with a loss of 45% which results from the fact that smaller, thinner or fragmented glaciers tend to show higher relative area losses than larger glaciers with thicker ice bodies. Analyses of digital terrain models of the years 1999, 2005 and 2016/17 yield a mean ice thickness loss across all studied glaciers of 8.8 m for the 1999 to 2005 subperiod, increasing to 17.6 m by 2016/2017. This corresponds to a volume loss of 1.1 (2.1) km^3 or a mass loss of about 0.9 (1.8) gigatons. Here, larger glaciers that are clearly out of balance and have large areas at low elevations tend to experience greater losses in mean ice thickness than small glaciers that respond more rapidly to warming or fragmented glaciers that often persist only under favored topographic conditions. In the current study period, which was characterized by very unfavorable climatic conditions for the glaciers, topographic factors seem to be more decisive than differences in regional climatic conditions, both in terms of area and surface height changes.

Key Words: Climate change, Glacier inventory, Airborne laser scanning, Aerial imagery.

Riassunto: Galos S.P., Klug C. & Dinale R., *20 anni di variazioni glaciali: gli inventari armonizzati per i ghiacciai dell'Alto Adige (1997-2005-2017).* (IT ISSN 0391-9838, 2022).

Questo articolo presenta il risultato dell'omogeneizzazione dei catasti dei ghiacciai dell'Alto Adige 1997, 2005 e 2017. In particolare, il lavoro comprende la compilazione del nuovo catasto dei ghiacciai 2017, elaborato grazie ai nuovi dati di base acquisiti a tale scopo, nonché la completa rianalisi dei dati laser scanner risalenti all'anno 2005, disponibili per tutta l'area di studio, con produzione del nuovo catasto dei ghiacciai 2005, e la revisione del catasto 1997 avvalendosi delle più moderne tecnologie oggi disponibili e delle conoscenze maturate nella compilazione dei catasti più recenti che si fondano su dati laser scanner e fotogrammetrici ad alta risoluzione. Il risultante dataset omogeneo dell'estensione dei ghiacciai altoatesini copre due decadi e il confronto tra i singoli catasti documenta quindi l'evoluzione e le modificazioni del glacialismo in questo territorio durante tale lasso di tempo. L'area glacializzata del nuovo catasto 1997 è pari a 121.9 km^2, ossia di circa 12.2 km^2 (11%) superiore rispetto a quella del catasto 1997 originale. Questo è dovuto soprattutto alla considerazione di alcuni apparati glaciali precedentemente non rappresentati ma è anche la conseguenza di una migliore valutazione delle aree glaciali coperte da detrito. L'analisi del periodo 1997-2005 (1997-2017) restituisce una riduzione della superficie glaciale pari a 18.1 km^2 (37.9 km^2) riferita

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a tutta l'area di studio. Questa corrisponde ad una perdita relativa del 14.8% (31.1%). Mentre le variazioni areali del sotto-periodo 1997-2005 (fatta eccezione per il Gruppo di Tessa: -24.7%) sono piuttosto simili per i vari gruppi montuosi e comprese tra -13% (Alti Tauri, Alpi Breonie) e -19% (Alpi Aurine), nel secondo sotto -periodo 2005-2017 risulta una evidente differenza tra i gruppi montuosi a ovest ed est del Fiume Isarco. Per il ventennio 1997-2017 le riduzioni della superficie glaciale nella parte occidentale dell'area di studio risultano così comprese tra il 25% delle Alpi Breonie ed il 29% delle Alpi Venoste, mentre nella parte orientale esse si attestano tra il 39% degli Alti Tauri e il 43% delle Alpi Aurine. Il Gruppo di Tessa rappresenta di nuovo un'eccezione con una perdita di superficie glaciale pari al 45% che è conseguenza diretta del fatto che i ghiacciai piccoli, sottili e frammentati sono soggetti a maggiori riduzioni areali relative rispetto ai ghiacciai più grandi e spessi. Dall'analisi dei modelli digitali del terreno degli anni 1999, 2005 e 2016/17 risulta una perdita media di spessore di ghiaccio pari a 8.8 m per il sotto-periodo tra il 1999 ed il 2005, che diventa di 17.6 m se si estende l'intervallo temporale fino al 2016/2017. Questo implica una riduzione di volume di 1.1 (2.1) km^3 corrispondente ad una perdita di massa dell'ordine di 0.9 (1.8) giga-tonnellate. I ghiacciai più grandi, evidentemente fuori equilibrio e con ampie porzioni di superfici a quote relativamente basse tendono a esibire riduzioni di spessore in media maggiori rispetto ai ghiacciai più piccoli che rispondono più rapidamente al riscaldamento del clima o rispetto ai ghiacciai più frammentati che spesso si mantengono solo in ragione di condizioni topografiche favorevoli. Nel periodo di studio, caratterizzato da condizioni climatiche molto sfavorevoli per i ghiacciai, i fattori topografici sembrano essere più rilevanti rispetto alle differenze climatiche regionali, in termini sia di area totale sia di distribuzione delle superfici con la quota.

Termini Chiave: Cambiamento climatico, Catasto dei ghiacciai, Laser scanner aviotrasportato, Foto aeree.

INTRODUCTION

In recent years, shrinking mountain glaciers have become one of the most obvious signs of climate change and are therefore particularly in the public eye and in the focus of climate research and related impact studies (e.g., Fox-Kemper & *alii*, 2021 and references therein). A periodic and systematic recording of glacier extents is crucial for a range of applications in climate science and hydrological research. May it be for calculations of glacier volume (e.g., Gardner & *alii*, 2011), for projections of run-off and the contribution to sea level rise (e.g., Marzeion & *alii*, 2017), or as a basis for glacier mass balance programs and related re-analyses (Zemp & *alii*, 2013; Galos & *alii*, 2017).

For a directly affected region, such as South Tyrol, the importance of glaciers goes beyond that of climate indicators or contributors to sea level rise. In some areas, for example the Vinschgau, they play an important role in the water cycle and are thus relevant for the seasonal availability of water for agriculture or energy production (e.g., Secchieri & Valentini, 1992; Galos & *alii*, 2015; Dinale & *alii*, 2017). Furthermore, the glaciers of the region play a certain role for tourism. Be it as a resource for glacier skiing, as a component of nature discovery trails or simply as an aesthetic landscape element, which characterizes some places and valleys in South Tyrol in particular.

It is in this sense that the motivation behind a systematic and periodic survey of the region's glacier areas and the analysis of corresponding changes is understood. The findings from such studies serve, on the one hand, for the long-term planning of adaptation strategies in the aforementioned economic sectors and, on the other hand, also as a valuable information basis in the projection and management of resources and natural hazards.

In this context the Agency for Civil Protection of the Autonomous Province of Bolzano has been systematically collecting and updating glaciological data on a regional scale during the past decades which resulted in several glacier inventories and other valuable data sets for addressing the aforementioned issues.

Background and motivation for this study

A sound interpretation of glacier changes based on comparisons of individual glacier inventories over longer periods of time is usually difficult, especially since both the methodology of data collection and that of analysis have changed over time (e.g., Paul & *alii*, 2009). Early glacier inventories from the first half of the 20^{th} century are mostly based on laborious topographic field measurements carried out by hand. Accordingly, the number of individual measurement points is usually small in these cases. For inaccessible areas or areas considered to be of little interest, the data situation is often particularly poor, so that certain glaciers were not recorded at all. Often, such data gaps then extend through the subsequent inventories, which were and still are often compiled on the basis of existing inventories. In addition, the documentation of the exact methodology is in many cases insufficient or difficult to follow.

With the advent of photogrammetric datasets in the second half of the 20^{th} century, this changed to some extent, as these datasets (when properly archived) in principle allow for later re-evaluations. Since the late 20^{th} century, satellite and other remote sensing products became increasingly important. Corresponding data offer new possibilities, especially on large spatial scales (e.g., Paul & *alii*, 2009). However, for smaller-scale applications such as over the area investigated by this study, only the developments of the last two decades brought significant progress, especially in the field of airborne laser altimetry (e.g., Abermann & *alii*, 2010 and references therein), new high-resolution satellite products such as Pléiades (Berthier & *alii*, 2014; Rieg & *alii*, 2018) or Sentinel (e.g., Paul & *alii*, 2020; Barella & *alii*, 2022), but also through new developments in the field of digital photogrammetry (Rossini & *alii*, 2018). In particular, high-resolution and periodic terrain models, but also image correlation techniques, offer greatly improved possibilities for detecting the increasingly important debris-covered glacier surfaces (Klug & *alii*, 2018; Barella & *alii*, 2022). These improved methods and the associated detection of areas that were not included in earlier inventories naturally give rise to problems in comparison with historical inventories. Actual temporal changes in glacierized areas are thus difficult to separate from those differences resulting from altered methodologies. For this reason, it is necessary to develop strategies that make it possible to record temporal developments of glaciers as reliably as possible.

Consequently, the aim of the present study is the compilation of a homogenous set of three glacier inventories

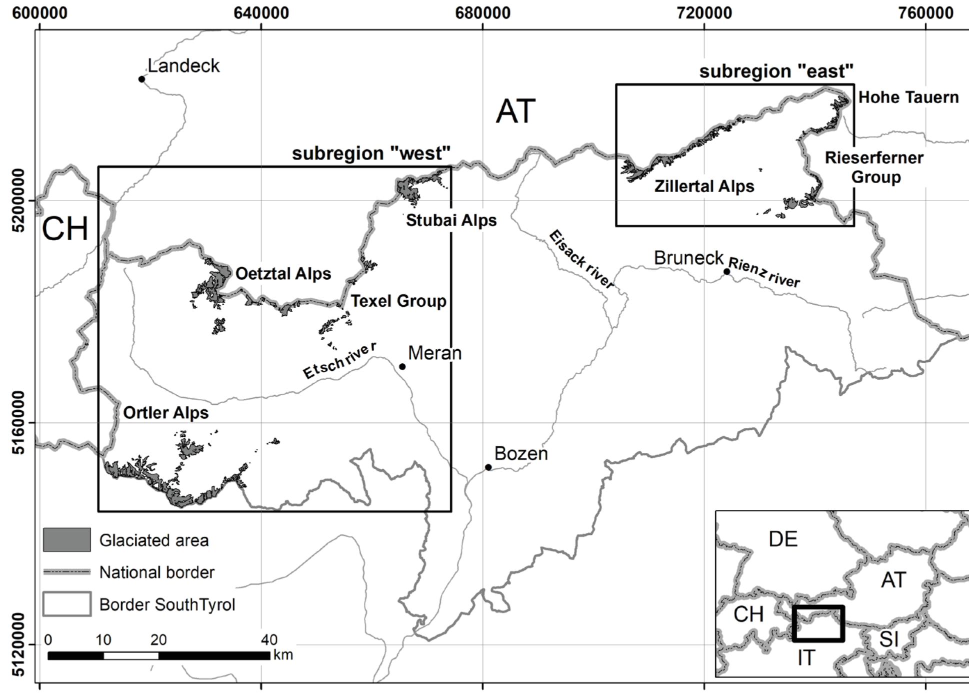

FIG. 1 - Map of the study region with the main mountain Groups and the locations of the investigated glaciers.

referring to 1997, 2005 and 2017 to enable meaningful comparisons of the respective glacier extents by mountain groups, altitudinal levels and for the entire study area. This was achieved by aligning the analysis methods for all three inventories (as far as possible) and, most importantly, by applying consistent criteria in delineating glacier areas for the respective recording dates.

STUDY REGION AND PREVIOS WORKS

In principle, the study area covers the entire province of South Tyrol (ca. 7400 km^2), but especially, of course, the high mountain areas with altitudes well above 2000 m a.s.l. and, in the case of glaciers extending beyond the national or regional borders, small subareas of neighboring countries (Austria) and regions (Trentino, Lombardy, Veneto). The recorded glaciers are situated in eight main mountain groups (see fig. 1): Sesvenna Group, Ortler Alps, Ötztal Alps, Texel Group, Stubai Alps, Zillertal Alps, Hohe Tauern and Rieserferner Group.

In addition to the national Italian glacier inventories of 1925 (Porro, 1925), 1959 (CGI-CNR, 1961; 1962), 1989 (Ajassa & *alii*, 1994; 1997), 2006 (Salvatore & *alii*, 2015) and 2015 (Smiraglia & *alii*, 2015; Smiraglia & Dolaiuti, 2015), several glacier inventories with exclusive focus on the region of South Tyrol exist dating from the years 1983, 1997 and 2006. While the inventory of the year 1983 (Valentini, 1985) is only available in tabular form, the inventories of the years 1997 (Kerschner, 2006) and 2006 (Knoll & Kerschner, 2009; 2010) already provide areal information in the form of shapefiles based on the evaluations of photogrammetric aerial photographs and, in the case of 2006, also of high-resolution airborne laser scans.

Besides the complete regional inventories described above there are records for certain subdomains of the region (e.g., Galos & *alii*, 2015) and a number of studies dedicated to describing the state of glaciers in certain mountain groups or valleys of the study region (e.g., Simony, 1865; Finsterwalder, 1890; Desio, 1967; Secchieri, 2000; Rossi, 2004; Carturan & *alii*, 2013; D'Agata & *alii*, 2014; Savi & *alii*, 2021).

DATA AND METHODS

The data set on the homogenized South Tyrolean glacier inventories 1997, 2005 and 2017 consists of three shapefiles (SGI-hom-1997, SGI-hom-2005 and SGI-hom-2017) and is supplemented by an MS-Excel file with the evaluations of glacier changes and a technical report (Galos, 2023). The shapefiles are available in the geographic coordinate system ETRS89 / UTM Zone 32N (EPSG:25832) and all evaluations refer to these specifications. The data set (Galos & *alii*, 2023) is available at the Zenodo repository and glacier outlines are also accessible via the geo-browser web portal of the regional administration of the Autonomous province of Bolzano under the following URL: https://maps.civis.bz.it.

In addition to an identification by the glacier names in German and Italian, as well as several identification codes (WGMS- and CGI-code) and a geographic assignment according to mountain groups and geographic coordinates, the inventories presented here focus on the most meaningful parameters that can be determined as objectively as possible, such as the area and elevation indicators, as well as other essential topographic parameters. The inclusion of parameters that cannot be meaningfully determined from the available data sets, such as the height of the equilibrium line (ELA), the classification according to glacier form, activity or similar, was deliberately omitted out of scientific conviction. The applied nomenclature and units follow the guidelines of Cogley & *alii* (2011).

In the following, the data basis and the methods used are briefly described for each of the three inventories.

The homogenized South Tyrolean Glacier Inventory 2017 (SGI-hom-2017)

The strong glacier retreats during the past decades due to accelerated atmospheric warming necessitate a periodic repetition of glacier inventories at intervals of about a decade. Since the last region-wide recording of glacier data was performed based on the airborne laser-scans from 2005, campaigns were conducted in 2016 and 2017 on behalf of the Agency for Civil Protection of the Autonomous Province of Bozen - South Tyrol, to collect stereo orthophotos of glacierized areas throughout the region of South Tyrol. These data collections were handled by the companies Terra Messflug and AVT which, in addition to organizing the flights, also performed the data processing. The calculation of a DTM with a resolution of 0.5 m was then carried out in the frame of the project GLISTT (Interreg V-A Italy-Austria 2014-2020) at the Institute of Geography at the University of Innsbruck. Analyses and the compilation of the glacier inventory were performed in cooperation with the Institute of Atmospheric and Cryospheric Sciences (ACINN).

The data acquisitions were unfortunately spread over two years and took place for the western part of the study area (Ortler Group, Ötztal Alps, Texel Group and Stubai Alps) on 29.09.2016 and for the eastern part (Zillertal Alps, Hohe Tauern and Rieserferner Group) on 29.08.2017. Furthermore, an additional campaign was carried out on 5.10.2016 to fill supposed gaps in the data set of 29.09.2016.

The analyses presented in this paper refer to the 2016 recording year for the "West" area (Ortler Group, Ötztal Alps, Texel Group and Stubai Alps) and to the 2017 recording year for the "East" area (Zillertal Alps, Hohe Tauern and Rieserferner Group). Despite the fact that the data bases originate from two different years, the resulting inventory is referred to as SGI-hom-2017 for simplicity.

The horizontal resolution of the aerial images is 0.1 m and the quality can be described as good to very good throughout. The images are almost free of disturbances such as clouds. However, in some regions a thin layer of fresh snow and rather rarely the weak exposure in shaded areas complicate the optical evaluations.

The digital terrain model (DTM) used to derive topological key numbers has a horizontal resolution of 0.5×0.5 m and was calculated from the photogrammetrically derived and filtered point clouds. For a part in the west of the study area, another high-resolution DTM is available from a laser scan survey in September 2013 (Galos & *alii*, 2015). This concerns the glaciers in the Ortler and Texel groups and the very largest part of the Ötztal Alps and thus about two-thirds of the glacierized area of the study area. In the aforementioned areas, these data were also used to create differential DTM (dDTM) in order to gain additional reference points when delineating the 2016 glacier areas.

The homogenized South Tyrolean Glacier Inventory 2005 (SGI-hom-2005)

During the compilation process for the SGI-hom-2017 it turned out that the existing inventory for 2006 (Knoll & Kerschner, 2010) was not comparable to the new inventory due to a number of reasons. First, a number of glaciers in the study region was not listed in the 2006 inventory. Second, the delineation methodology seemed to be substantially different and the consideration of debris covered ice areas was insufficient. For these reasons a re-evaluation of the 2005 data was performed.

The main basis for the compilation of the 2005 inventory was hence the data from the 2005 laser-scan survey by the Province of Bolzano (Zanvettor & *alii*, 2006). For the present analyses, the point clouds provided by the Province of Bolzano were filtered and subsequently a DTM with 1×1 m resolution was calculated, which allowed a uniform determination of the glacier boundaries for the year 2005 and the entire investigation area. The acquisition of laser-scan data in late summer/fall 2005 took place under mostly very favorable conditions with little fresh snow or other disturbing factors. Nevertheless, a few gaps exist in the data set, a larger one unfortunately just at Texelferner, the largest glacier in the Texel Group. However, the impact on the present analyses could be minimized by filtering and thorough interpolation of the DTM.

The dDTM 2017-2005 was calculated as the difference between the 2016/17 photogrammetric DTM and the 2005 laser scan DTM at a 1x1 m horizontal resolution. This allowed a precise delineation especially in areas where significant vertical changes occurred during the corresponding period (fig. 2). The dDTM offers a particular advantage with respect to debris-covered glacier areas, which can also be delineated quite accurately (e.g., Galos & *alii*, 2015; Klug & *alii*, 2018) given that significant surface elevation change due to melt occurred during the investigation period.

Furthermore, the orthophotos acquired by the Autonomous Province of Bolzano from 2006 with a horizontal resolution of 0.5×0.5 m provided an important help in the preparation of SGI-hom-2005. This dataset is also available for the entire study area in good to very good quality and provides additional information in areas with minor vertical surface changes and in the case of terrain changes that have not (directly) resulted from the melting of glacial ice.

Due to the availability of high-quality data, but especially due to the high-resolution dDTM 2017-2005 which allows an accurate delineation of glacierized terrain even in heavily debris covered areas (fig. 2), the resultant inventory SGI-hom-2005 in a way represents the reference dataset for the other two homogenized inventories SGI-hom-2017 and SGI-hom-1997.

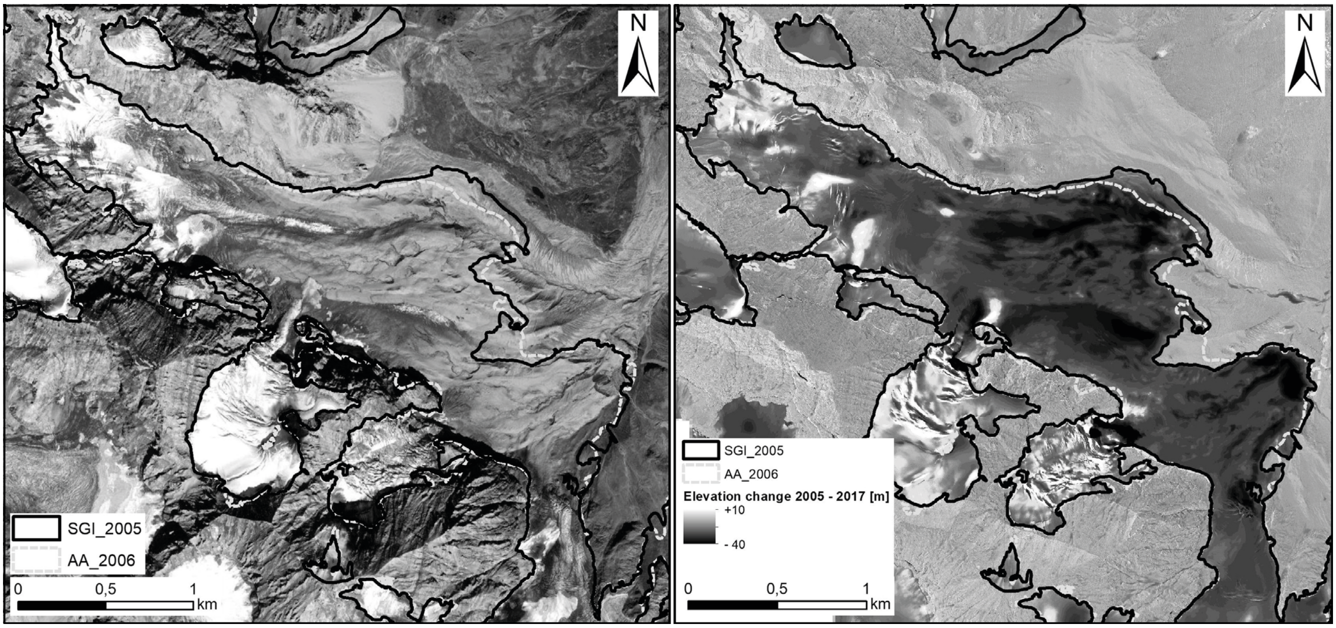

FIG. 2 - Glacier outlines based on dDTMs. While the optical classification of glacierized terrain based on orthofotos (left image) can be challenging, dDTM data (right image) often enables for a straight forward delineation, even in the case of marked debris cover as in the example of Suldenferner. The grey dashed line shows the glacier margin as derived for the inventory AA2006 (Knoll & Kerschner, 2010), while the black solid line indicates the margin by the homogenized Inventory SGI-hom-2005.

The homogenized South Tyrolean Glacier Inventory 1997 (SGI-hom-1997)

Comparability issues also required a full re-evaluation of the existing 1997 inventory. This was necessary due to methodological differences in the existing 1997 inventory (explicitly not due to a lack of quality in the existing evaluations). The re-evaluation was primarily based on the 1992-1997 orthophotos of the Province of Bolzano. These data are meanwhile freely available through the geodata catalog of the Provincial Cartography at: http://geokatalog.buergernetz.bz.it/geokatalog. Unfortunately, this dataset has a relatively poor quality. Especially the rectification of the aerial photographs is insufficient, resulting in horizontal displacements of 50 m and significantly more in some cases. This problem made an exact delimitation of the glaciers often laborious and partly difficult since manual georeferencing of small areas had to be applied in many cases. An important help was provided by the 1999 color orthophoto, which is also available via the geo-catalog and has a much better rectification and resolution.

Since no DTM is available for the 1992/97 orthophotos, the DTM from the 1999 orthophotos was used to calculate the topographic parameters of the glaciers. The delineation of the glacier areas was done purely on the basis of the optical data, without the aid of a dDTM, since the calculated dDTM 2005-1999 was not suitable for glacier delineation due to the low resolution of 20 m and various weaknesses in the basic evaluation, even after a thorough co-registration carried out.

Precise dating of the 1992/97 orthophoto tiles was also not possible in the context of this study due to lack of appropriate metadata. Despite the relatively broad period of coverage, the resulting inventory is referred to as the homogenized 1997 inventory (SGI-hom-1997) for simplicity.

Criteria for the inclusion of glacierized areas in the new inventories

The general criterion for the inventory of glacierized areas was the proven presence of ice with an extent of 5000 m^2 or more at the respective time of recording. The corresponding proof was either directly based on optical data or indirectly, for example by the presence of crevasses or marginal crevasses in debris-covered areas or by significant surface changes from the dDTM that cannot be explained by erosional processes. While the delineation of such areas for 2005 based on the dDTM was mostly reliable and relatively objective, the determination of the corresponding areas for the 1997 and 2017 inventories required more intuition and experience.

The lower end of the recorded size spectrum of 5000 m^2 was undercut in a few exceptional cases. It should be mentioned that a typical lower limit for the size of glacier areas to be considered in large-scale inventories is 0.1 km^2 (e.g., Schiefer & *alii*, 2008). However, the proportion of glaciers with an area smaller than 0.1 km^2 recorded in this work for 1997 is just under 5% (6 km^2).

Basically, all areas within the national borders of South Tyrol that could be classified as glacierized on the basis of the available data were included in the inventories. However, glacier areas that do not drain into South Tyrol were only included if they reached an area of 0.5 km^2 in the 1997 inventory. Two examples are the Niederjochferner in the Ötztal Alps and the Zebruferner in the Ortler Group. For both glaciers, only the parts located in South Tyrol were included in the inventories. The largest unconsidered glacier areas are located on the eastern main ridge of the Ötztal where the national border runs over the upper parts of Gurglerferner and Schalfferner which both drain to

Austria. Most of the glaciers that straddle the state border were cut along the boundary line. However, in those cases where the majority of the glacier is located in South Tyrol and/or the national boundary is not accompanied by a clear watershed and consequently also the meltwater of the glacier portion outside the territory drains into South Tyrol, the entire glacier was included in the inventory. A special case is the Gepatschferner, where the delineation of the South Tyrolean portion, also for hydrological reasons, does not follow the political border, but the watershed. However, the total area of the portion covered in this way hardly differs from that of the South Tyrolean portion with respect to the administrative boundaries.

Calculation of surface elevation and mass change

The calculation of surface changes from the dDTMs followed the well-established methodology (e.g., Cogley & *alii*, 2011; Zemp & *alii*, 2013). For the calculations of vertical changes between inventories, the corresponding DTMs were each co-registered using the method of Nuth & Kääb (2011) and brought to a uniform horizontal resolution. In the case of the 2016/17-2005 dDTM, the resolution used for the analyses was 2 m. The co-registration performed eliminated systematic discrepancies in the underlying DTMs and reduced the mean squared vertical deviation of the DTMs from each other to approximately 0.2 m.

For the orthophotos 1992/97 no DTM is available and so the DTM from the orthophotos 1999 had to be used. The latter is available in a resolution of 20×20 m and partly shows larger vertical errors in the range of several meters. In addition, the deviations from the 2005 laser scan DTM over stable areas in several cases show a tiled structure in the extent of the 1997 orthophoto sections, which once more shows inadequacies in the georeferencing or orthorectification of the images.

Consequently, the horizontal resolution for both the 2005-1999 and 2017-1999 dDTMs is 20 m, and the mean square vertical deviation (over stable areas) of the underlying DTMs from each other is still about 1.5 m after co-registration. This relatively large error, due to the limited quality of the 1999 DTM, should be taken into account in the evaluations in that, especially for smaller glaciers, elevation and volume changes should not be assessed for individual glaciers. On larger spatial scales such as the entire study area, individual mountain groups, but also for larger glaciers (> 1 km^2), the results seem reasonably meaningful.

RESULTS AND DISCUSSION

Changes in glacier area by mountain groups

The total glacierized area in SGI-hom-1997 is 121.9 km^2. This value decreased to 103.8 km^2 by 2005 and subsequently to 84.0 km^2 in SGI-hom-2017 which corresponds to a loss of 18.1 km^2 (14.8%) between SGI-hom-1997 and SGI-hom-2005 and 37.9 km^2 (31.1%) compared to SGI-hom-2017. The loss from SGI-hom-2005 to SGI-hom-2017 is 19.9 km^2 (19.1%). Thus, the total area of the studied glaciers in SGI-hom-2017 amounts to 84.0 km^2 (tab. 1). Relative area losses by mountain group are shown in fig. 3.

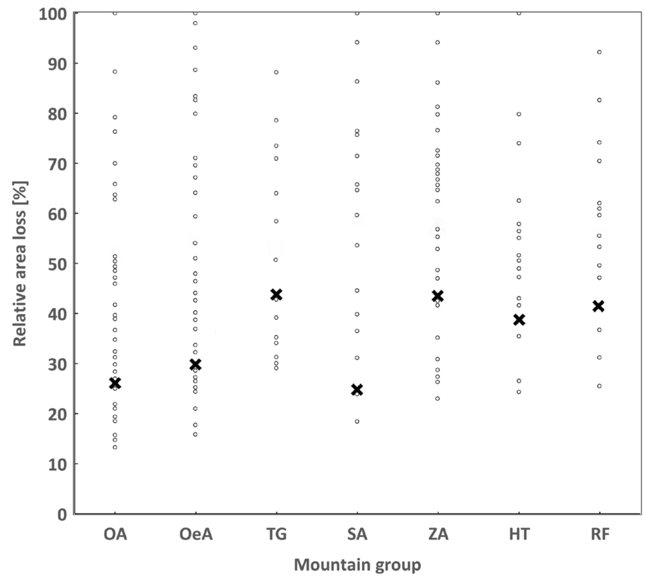

FIG. 3 - Relative area loss for the period 1997 to 2017 by mountain groups: Ortler Alps (OA), Ötztal Alps (OeA), Texel Group (TG), Stubai Alps (SA), Zillertal Alps (ZA), Hohe Tauern (HT) and Rieser Ferner Group (RF). Dots indicate values for individual glaciers / ice bodies while the bold X marks the value for the entire mountain range respectively.

With about 39% or just under 47.4 km^2, the Ortler group represented the largest share of the glacierized areas in South Tyrol in SGI-hom-1997 (tab. 1). It was followed by the Ötztal Alps with about 24% (29.1 km^2), the Zillertal Alps with about 12% (15 km^2) and the Stubai Alps with about 10% (12.4 km^2). Smaller areas are found in the Rieserfernergruppe with 7.4% (9.0 km^2), the Hohe Tauern with about 5% (5.6 km^2), the Texelgruppe with just under 3% (3.4 km^2) and a glacier in the Sesvennagruppe which, however, only accounts for about 0.1% of the total area and no longer appears in the SGI-hom-2005.

In the comparison between the SGI-hom-1997 and the SGI-hom-2005 (see tab. 2), the Texel group (apart from the total loss of the last glacier in the Sesvenna Group) shows the largest relative area loss of almost 25% (0.8 km^2), followed by the Zillertal Alps with 19% (2.8 km^2) and the Rieserferner Group with -17% (-1.5 km^2). In the other regions, the losses for this subperiod are quite homogeneous around 13 or 14% (Ortler group: 6.7 km^2, Ötztal Alps: 3.8 km^2, Stubai Alps: 1.6 km^2, Hohe Tauern: 0.7 km^2).

In the second subperiod between the SGI-hom-2005 and the SGI-hom-2017, the largest relative area changes of almost -30% are consistently recorded in the eastern part of the study area (Zillertal Alps, Hohe Tauern, Rieserfernergruppe), while the decreases in the western regions are much smaller with -13% in the Stubai Alps to -18% in the Ötztal Alps. Again, the Texel group is the exception with -27%. The reasons for the regional differences

TABLE 1 - Glacierized areas by mountain groups during the study period. The number of glacier parts N, the total glacierized area S_{ref} (km^2), the relative share S_{rel} (%) in the total glacierized area as well as the average size S_{mean} (km^2) of recorded glacier parts at the recording dates.

	SGIhom_1997				SGIhom_2005				SGIhom_2017			
REGION	N	S_{ref}	S_{rel}	S_{mean}	N	S_{ref}	S_{rel}	S_{mean}	N	S_{ref}	S_{rel}	S_{mean}
Sesvenna Group	1	0.1	0.1	0.08	0	0.0	0.0		0	0.0	0.0	
Ortler Alps	89	47.4	38.9	0.53	107	40.7	39.2	0.38	116	34.8	41.5	0.30
Ötztal Alps	70	29.1	23.8	0.42	78	25.3	24.3	0.32	92	20.6	24.6	0.22
Texel Group	27	3.4	2.8	0.13	36	2.6	2.5	0.07	37	1.9	2.2	0.05
Stubai Alps	25	12.4	10.2	0.50	35	10.8	10.4	0.31	50	9.4	11.2	0.19
Zillertal Alps	56	15.0	12.3	0.27	64	12.2	11.7	0.19	151	8.5	10.2	0.06
Hohe Tauern	30	5.6	4.6	0.19	35	4.8	4.7	0.14	52	3.4	4.1	0.07
Rieserferner Group	27	9.0	7.4	0.33	33	7.4	7.2	0.23	51	5.3	6.3	0.10
South Tyrol	325	121.9	100.0	0.38	388	103.8	100.0	0.27	549	84.0	100.0	0.15

TABLE 2 - Absolute and relative change of glacierized areas by mountain groups during the study period.

	1997-2005		2005-2017		1997-2017	
REGION	ΔS_{ref} [km^2]	ΔS_{ref} [%]	ΔS_{ref} [km^2]	ΔS_{ref} [%]	ΔS_{ref} [km^2]	ΔS_{ref} [%]
Sesvenna Group	-0.1	-100.0			-0.1	-100.0
Ortler Alps	-6.7	-14.1	-5.9	-14.5	-12.6	-26.5
Ötztal Alps	-3.8	-13.0	-4.6	-18.4	-8.4	-29.0
Texel Group	-0.8	-24.7	-0.7	-26.8	-1.5	-44.8
Stubai Alps	-1.6	-12.9	-1.4	-13.4	-3.0	-24.5
Zillertal Alps	-2.8	-18.8	-3.6	-29.8	-6.5	-43.0
Hohe Tauern	-0.7	-12.8	-1.4	-29.5	-2.1	-38.6
Rieserferner Group	-1.5	-17.2	-2.1	-28.5	-3.7	-40.9
South Tyrol	-18.1	-14.8	-19.9	-19.1	-37.9	-31.1

in this second subperiod are partly due to the fact that the evaluations east of the Eisack river already record the very strong changes caused by the particularly unfavorable summer of 2017, while in the west of the study area the data recording already took place in 2016. The area reduction in summer 2017 is likely to have been about -5% in the east of the study area and thus cannot fully explain the differences. Thus, another reason for the large losses in this region can also be found in the topography of the glaciers. Cirque glaciers with comparatively low ice thickness are more frequent in the east of the study area than in the western mountain groups. With the same loss of ice thickness, this means a comparatively larger area loss. Thus, these glaciers have also often already disintegrated into several individual parts, which is reflected in a small average size of the partial areas (see tab. 1).

In addition to these topological factors, different effects of the rather glacier-friendly years 2013 and 2014 may also play a role within the study area. Such were still visible in the 2016 data, especially in the higher regions of the Ortler group, where in some places smaller increases in area due to new firn bodies were recorded. It is unclear whether the corresponding effects in the eastern mountain groups were similarly "sustainable" as in the western part of the study area.

However, the topography of the glaciers seems to play the most important role in this respect. This is also shown by the glaciers of the Texelgruppe which, with a relative loss of -27%, represent the "outlier" in the western half of the study area. The high losses there are attributed to the small average size of glaciers, which in turn leads to larger relative area changes.

For the overall period 1997-2017 the regional pattern is similar. There the Texel Group shows the largest relative decrease with -45%. Also for this period, the eastern mountain groups show the significantly larger losses with -39% in the Hohe Tauern to -43% in the Zillertal Alps than the western groups (exception Texelgruppe) with -25% in the Stubai Alps and -29% in the Ötztal Alps (tab. 2).

Differences between the homogenized and the existing inventories for 1997 and 2006 arise mainly for the following reasons: first, some glaciers that were not part of the old inventories were included in the new, homogenized, inventories; second, the delineation technique used here allows for improved identification of debris-covered glacier areas, making such areas better represented in the new inventories; and third, in many cases, the glacier extents shown refer to a different date than in the existing inventories. For example, all extents in SGI-hom-1997 refer to the 1992/97 orthophotos, whereas in some cases the extents in the old inventory seemed to be derived from the 1999 orthophotos. The extents in SGI-hom-2005 refer to the laser scan data 2005, while in the old inventory AA2006 in many cases the glacier outlines rather seem to be derived from the orthophoto 2006.

As a result, the homogenized inventory for 1997 now shows a total area of 121.9 km^2, compared to a glacier area of 109.7 km^2 in the old 1997 inventory (+11%). The total area in SGI-hom-2005 is 103.8 km^2, while in AA2006 an area of 93.4 km^2 (+11%) was recorded.

Changes in glacier area by altitude levels

Looking at the distribution of glacierized areas by altitude, they extend from the summit areas of the highest elevations in the study area to altitudes partly well below 2500 m a.s.l. The highest glacierized point in SGI-hom-2017 is located at 3896 m a.s.l. on the Oberer Ortlerferner, while the debris-covered tongue of the nearby Marltferner forms the lowest glacierized point at 2175 m a.s.l. It is noteworthy that the two points mentioned are separated by a horizontal distance of less than 2.7 km. The two mentioned glaciers are at the same time those with the greatest altitudinal extension. Marltferner, with its highest point at 3839 m a.s.l., has an elevation range of 1664 m, while the Oberer Ortlerferner, with its lowest point at about 2248 m a.s.l., covers an elevation range of 1648 m, which is only slightly less. However, on both glaciers the lowest points are separated from the accumulation areas in terms of ice dynamics, and mass transport to the lower sections in both cases takes place mainly via (ice) avalanches from the main part of the Oberer Ortlerferner. The glacier units connected by ice dynamics with the greatest altitudinal extent of over 1200 m each are Suldenferner, Niederer Ortlerferner and Nasenhornferner. All of them also located in the direct vicinity of the highest peak of the region.

The altitude ranges of the glacierized areas in the other mountain groups vary considerably, with the Texel Group showing the lowest value with a range of 633 m (2629-3262 m a.s.l.).

The median elevation of glacierized areas in the study area was 3049 m a.s.l. in SGI-hom-2017 while it was 3026 m a.s.l. in SGI-hom-2005 and about 2963 m a.s.l. in SGI-hom-1997.

The values for the glacier areas by altitude levels and their changes are shown in fig. 4. The largest glacierized areas in the SGI-hom-1997 with a total of 19.5 km^2 refer to the altitude level 3000-3100 m a.s.l. For the inventories SGI-hom-2005 and 2017, the area maximum shifts to the level of 3100-3200 m a.s.l. with 17.1 and 15.1 km^2, respectively. The largest decreases in absolute terms occur in the 1997-2005 period in the 2900-3000 m a.s.l. level (-3.1km^2), while the largest decrease for the 2005-2017 subperiod (-3.4 km^2) occurs in the 2800-2900 m a.s.l. level. The largest area decrease over the entire period of -6.4 km^2, is also apparent in the 2800-2900 m a.s.l. elevation level. As expected, the largest relative losses over all periods occur in the lowest altitudes, where they increase from about -35% for the period 1997-2005 to over 50% for the entire study period.

Even the highest regions of the study area are affected by significant decreases in glacier area. Thus, at the altitudes of 3500-3600 and 3600-3700 m a.s.l., the area loss from 1997 to 2005 is still around -16%, and by 2017 the respective losses increase to -26 and -20%. While slight increases can still be observed in the highest altitude level in the summit area of the Ortler from 1997 to 2005, the sign also turns here for the 2017 inventory and decreases, albeit not significant ones, are recorded over the entire period.

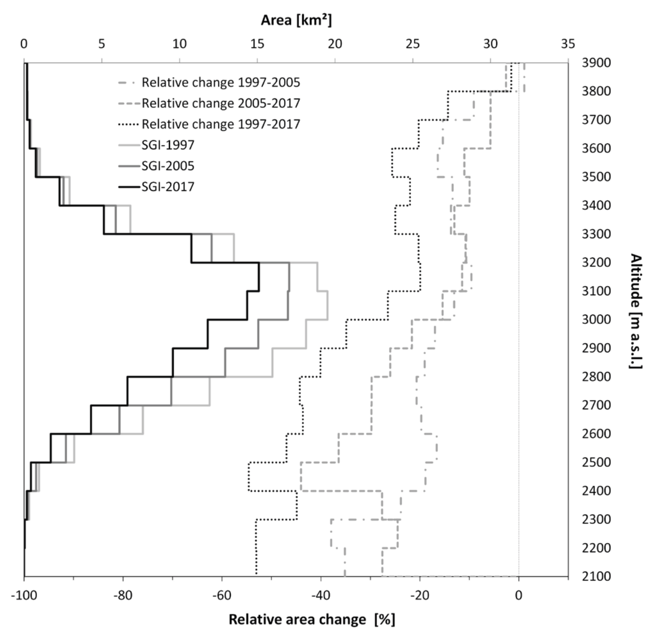

FIG. 4 -The distribution of glacierized areas S_{ref} for the three homogenized inventories by elevation and the relative change between the recording dates.

Changes in glacier area by size class

By far the most glacier areas in the study area fall into the class smaller than 0.1 km^2 for all three inventories. While this class still counts 172 partial areas in SGI-hom-1997, their number increases to 248 in SGI-hom-2005 and even to 432 in SGI-hom-2017 (tab. 3). At the same time, the total area of this size class changes only slightly in the three inventories from 6.0 km^2 in SGI-hom-1997 to 5.6 km^2 in SGI-hom-2005 and finally to 6.1 km^2 in the 2017 inventory. This impressively shows the strong trend towards increasing fragmentation of the glaciers in the study area into (very) small parts due to massive melting processes during the study period. On the other hand, it becomes clear that (very) small glaciers (parts), despite their large number, provide only a very small relative share of the total glacier area of the study area and are thus of minor importance overall, especially with respect to their hydrological potential.

At the other end of the spectrum are the two largest glaciers in the study area, the Übeltalferner and the Suldenferner, which is heavily covered with debris in large parts. These two glaciers alone already account for about 11.3% of the glacierized area in the study area in SGI-hom-1997,

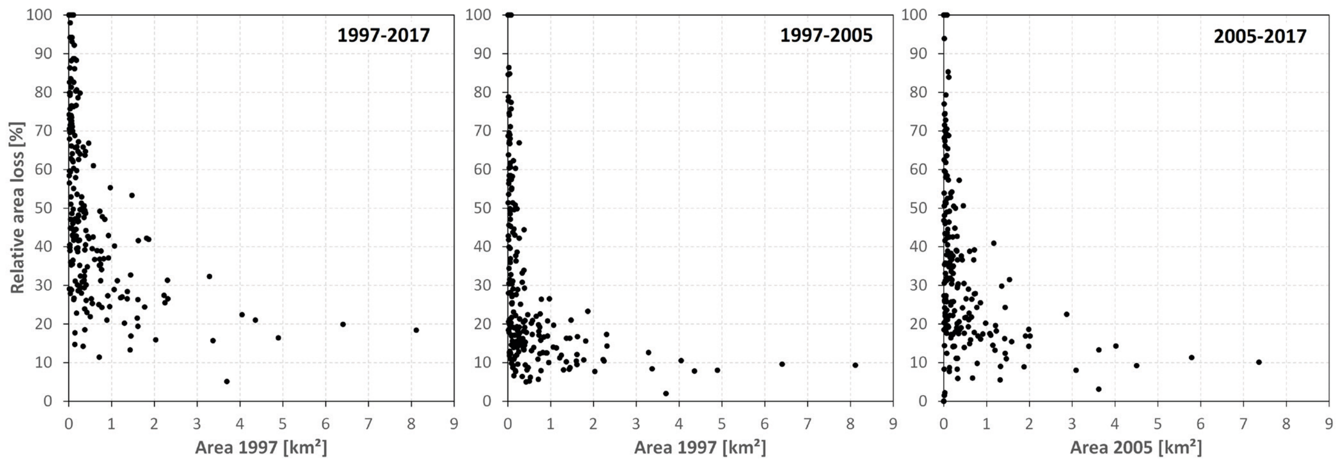

FIG. 5 - Relative area loss (%) versus areal extension (km^2) for the period 1997-2017 (left) and the two subperiods 1997-2005 (middle) and 2005-2017 (right).

and the proportion increases to 13.5% in SGI-hom-2017. At the same time, these glaciers also show the lowest relative area loss, -8.6% by 2005, and -17.8% by 2017, respectively (fig. 5).

Most of the glacier area is accounted for by the rest of the spectrum, i.e., the size range 0.1-5 km^2. It is also worth mentioning that in SGI-hom-2017, only 20 ice bodies still fall within the 1-5 km^2 size range. In the SGI-hom-1997 there were still 27, in the SGI-hom-2005 25. Also in the classes 0.1-0.5 km^2 and 0.5-1 km^2 the trend towards a clear reduction of area and fractionation into smaller parts is reflected. For both classes there is a steady decrease in glacier area (tab. 3).

Changes in surface height, volume and mass

While a high-resolution DTM is available for each of the SGI-hom-2005 and SGI-hom-2017 inventories, this is unfortunately not the case for SGI-hom-1997. Consequently, the 1999 DTM also had to be used to analyze the vertical changes in the surface and thus the volume changes between the inventories.

Thus, on the basis of the available data, the mean vertical surface change was calculated for all glacier surfaces in the study area. Since the significance (apart from the period 2005-2017) for individual glaciers is low, the results are only differentiated according to mountain groups and altitude levels.

In the course of the evaluations, the geodetic balances of the glaciers were also calculated over the study period. This was done according to the established methodology (e.g., Cogley & *alii*, 2011). An average density of 850 kg/m^3 was used to convert the change in glacier volume to mass change following Huss (2013).

The elevation change averaged over the glacierized part of the study area between 1999 and SGI-hom-2017 is -17.58 m which corresponds to a volume change of -2.1 km^3 or a mass change of about 1.8 gigatons. The altitudinal distribution of changes in surface elevation and volume is shown in fig. 6.

At the tongues of larger glaciers, the surface elevation losses sometimes amount to about 100 m. Examples are above all Langtaufererferner and Langenferner. Gains of up to a few meters, on the other hand, are only recorded at spatial small-scale, in particularly protected locations with special accumulation conditions with avalanche or wind influence. Such areas are found preferentially around the Ortler.

There are also clear differences in the mean elevation change between the mountain groups. While the glaciers of the Texel group show the lowest loss with -15.1 m, the value for the Stubai Alps and the Rieserferner Group amounts to about -21.8 m. It is also interesting to note that the glaciers in the eastern part of the study area do not show significantly higher values, unlike the area changes. Part of the explanation for the spatial differences can be provided by the fact that there is a correlation between glacier area and mean elevation change, i.e. very large glaciers show large decreases in mean elevation. The high value in the Stubai Alps is therefore related, for example, to the dominance of the Übeltalferner and its neighbor the Hangenderferner. These two glaciers, with mean elevation changes of -23.5 m and -27.2 m, in SGI-hom-1997 together represent about 75% of the glacier area of the Stubai Alps on South Tyrolean territory.

In the case of the Suldenferner, the second largest glacier in the study area, the strong debris cover in the ablation area leads to a below-average mean elevation change of -8.3 m.

Overall, topological factors again seem to play a much greater role than local climatic effects. It is also worth mentioning that the well-studied mass balance glaciers in the region consistently show losses, above the large scale average (tab. 4). While the relatively small Weißbrunnferner and the Westlicher Rieserferner appear to be relatively representative of the study area in terms of mean elevation change over the second subperiod 2005-2017, no mass balance glacier appears representative of the study area over the overall period 1999-2017.

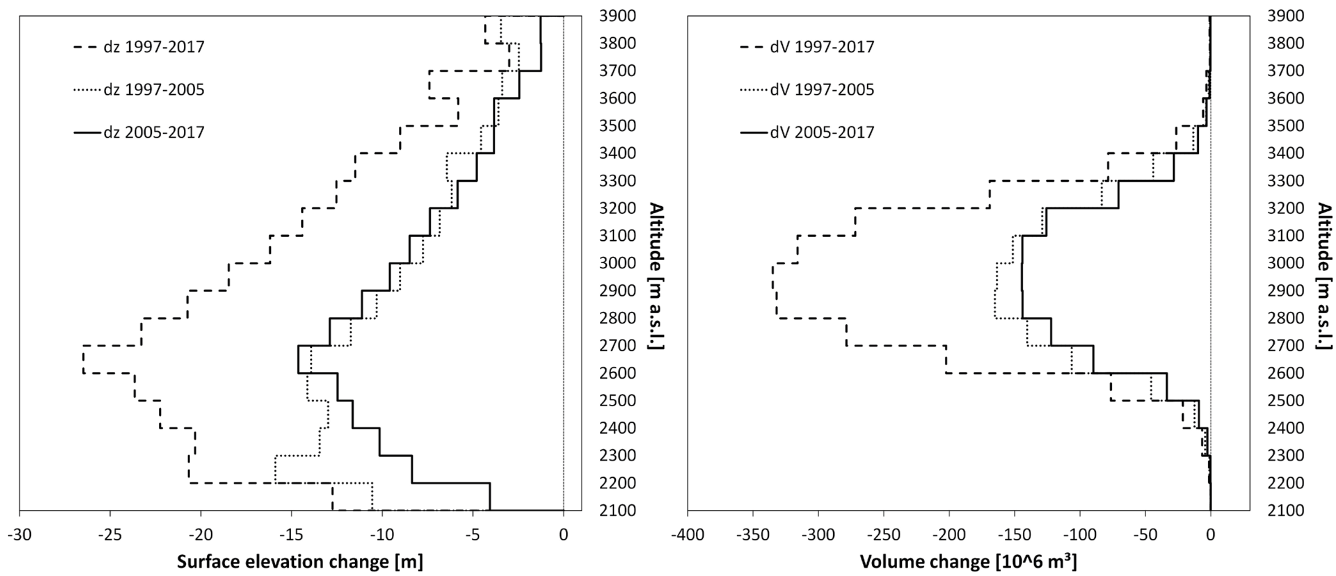

FIG. 6 - Change of surface elevation and glacier volume versus altitude.

TABLE 3 - Number N of glacier units and the glacierized area S_{ref}, their average size S_{mean} as well as their share S_{rel} in the total glacier area according to size classes for the three homogenized inventories.

	SGIhom-1997				SGIhom-2005				SGIhom-2017			
Size Class [km²]	N	S_{ref} [km²]	S_{mean} [km²]	S_{rel} [%]	N	S_{ref} [km²]	S_{mean} [km²]	S_{rel} [%]	N	S_{ref} [km²]	S_{mean} [km²]	S_{rel} [%]
< 0.1	172	6.0	0.035	4.9	248	5.6	0.023	5.4	432	6.1	0.014	7.3
0.1-0.5	94	23.5	0.250	19.3	90	21.1	0.235	20.3	77	17.8	0.232	21.2
0.5-1.0	30	21.7	0.723	17.8	23	15.7	0.683	15.1	19	13.1	0.687	15.5
1.0-5.0	27	57.0	2.109	46.7	25	48.8	1.951	47.0	20	41.3	2.067	49.2
> 5.0	2	13.8	6.899	11.3	2	12.6	6.302	12.1	1	5.6	5.648	6.7
All Classes	325	121.9	0.375	100.0	388	103.8	0.268	100.0	549	84.0	0.153	100.0

TABLE 4 - Key figures of glacier change for the mass balance glaciers of the region. The glacier areas S_{ref} in the three homogenized inventories, their relative change ΔS_{ref}, the mean elevation change ΔZ_{mean}, and the cumulative specific geodetic balance $B_{tot.geod}$ over the different subperiods.

				1997(99)-2005			2005-2017			1997(99)-2017		
Glacier	S_{ref} 97	S_{ref} 05	S_{ref} 17	Δs_{ref}	ΔZ_{mean}	$B_{tot\ geod}$	Δs_{ref}	ΔZ_{mean}	$B_{tot\ geod}$	Δs_{ref}	ΔZ_{mean}	$B_{tot\ geod}$
	[km²]	[km²]	[km²]	[%]	[m]	[kg/m²]	[%]	[m]	[kg/m²]	[%]	[m]	[kg/m²]
Langenferner	2.31	1.91	1.58	-17.3	-8.89	-8267	-16.9	-12.15	-11,284	-31.3	-21.76	-20,246
Weissbrunnferner	0.66	0.52	0.40	-22.0	-14.90	-14,226	-21.7	-9.55	-9106	-39.0	-23.09	-22,052
Übeltalferner	8.11	7.36	6.62	-9.3	-11.02	-9825	-10.1	-13.58	-12,153	-18.4	-23.51	-22,009
Hangenderferner	1.13	0.98	0.78	-13.8	-12.34	-11,269	-20.2	-16.39	-15,496	-31.2	-27.16	-24,794
West. Rieserferner	2.25	2.01	1.67	-10.4	-13.36	-11,975	-16.9	-9.57	-8886	-25.5	-22.48	-20,153
South Tyrol	121.90	103.84	83.97	-14.8	-8.828	-8104	-19.13	-9.054	-8368	-31.11	-17.58	-15,966

Fractionation and debris cover

The present study reveals significant fractionation of glacier areas, especially in the smaller size classes. Tab. 3 shows that the number of recorded glacier parts increased massively over the study period from 325 in SGI-hom-1997 to 388 in SGI-hom-2005 and finally to 549 in SGI-hom-2107. This increase is particularly strong in the smallest size class up to 0.1 km^2, which shows an increase from 172 to 248 and finally 432 glacier areas. A relatively high proportion of such small glaciers and parts of glaciers are located in the mountain groups in the east of the study area, which means that they are particularly affected by this trend and its effects in the second subperiod of the study period. During the 1997-2005 period, 43 of the glacier areas recorded in SGI-hom-1997 disappeared throughout the study area, increasing to 69 by 2017. Of the 388 areas recorded in SGI-hom-2005, 58 failed to survive into SGI-hom-2017.

Observed trends suggest that this number will increase massively by the next inventory and that the trend toward splitting into multiple subplots will continue, or probably increase. The ever-thinning of glaciers also leads to a further weakening of the ice dynamics. The widespread disappearance of distinct ice falls and crevasse zones, especially in the second subperiod between SGI-hom-2005 and SGI-hom-2017 is clearly observed.

Although the proportion of debris-covered areas was not explicitly quantified in this study, observations also show an increase in this regard. Due to accelerated deglaciation rates, reduced glacier dynamics, and increased input of debris from nearby slopes that are becoming ice-free and unstable, a further increase in these areas can be expected. The increasing relevance of debris-covered areas should therefore be taken into account both in further data collection and in subsequent evaluations.

Uncertainties and shortcomings

Uncertainties of the results are difficult to estimate in the case of the numbers for glacier areas. While the accuracy of the results for the change in glacierized area for the entire study area is most likely in the range of a few percent, the uncertainties related to the absolute values also depend to a not insignificant extent on the exact definition of a glacierized area. In the end, the latter remained unresolved in this study. Nevertheless, the present study covered the largest part (most likely > 95%) of the hydrologically and climatologically relevant glacier areas in the study area.

The uncertainties of the calculated elevation changes are consistently in the range of the mean square deviation of the DTMs from each other, i.e., in the range of about 1.5 m or below for the periods in which the 1999 DTM is applied and about 0.2 m or below for the period 2005 to 2017. Thus, with respect to volume and mass changes, errors in the 1999 DTM are dominant in the 1999-2005 and 1999-2017 subperiods, whereas for the 2005-2017 subperiod, uncertainties are considered to be much smaller and the relative influence of uncertainties in glacier area is larger.

However, it should be noted that in the case of the analyses based on the 1999 DTM, interpretations for Individual Glaciers are problematic due to larger errors in the DTM, and even the results for individual elevation levels and size classes should be read with the larger error bars in mind. In the case of the dDTM 2017-2005 in contrast, statements for individual glaciers are possible in most cases. For in-depth information in this regard the reader is referred to the technical report (Galos, 2023).

As already mentioned, the aim of the present work was to create a homogeneous and comparable data set for the inventory of the glaciers of South Tyrol at three "points" in time. This goal implies that (minor) compromises have to be made in perfecting the individual inventories. If, for example, no data were available for a certain glacier at one of the three measurement times, this glacier was not recorded in the inventory in question, and for reasons of comparability it was also omitted from the other two inventories in the homogenized data set. Although such effects are negligible when considering the mountain groups or the entire study area, this aspect should be taken into account when evaluating the inventories in detail.

CONCLUSION AND OUTLOOK

This study presents a consistent and thus comparable data set on glacier extents in South Tyrol at three points in time: 1997, 2005 and 2016/17. For this purpose, besides the compilation of an inventory for 2017 from newly acquired date, a full re-evaluation of the data sets used for the existing inventories of 1997 and 2006 was performed resulting in the new inventories SGI-hom-1997 and SGI-hom-2005.

The result of the reanalysis of the 1997 data is a glacier area of 121.9 km^2, about 12.2 km^2 (or 11%) larger than in the original inventory. The SGI-hom-2005 reveals a glacier area of 103.9 km^2 compared to 93.4 km^2 in the existing inventory AA2006.

These differences are mainly due to the improved coverage of debris-covered glaciers or subareas and the inclusion of several glaciers that, for unknown reasons, did not appear in the existing inventories.

The three newly created and homogenized inventories now allow an analysis of glacier changes in the study area over a period of approximately two decades. The comparison between the three homogenized inventories shows a reduction in area of about 38 km^2 (31%) for the entire study area. The only glacier of the Sesvenna Group in the SGI-hom-1997 is already not recognizable in the data for the SGI-hom-2005 and is therefore considered to have melted. With the exception of the Texel group, which recorded the largest relative area loss of -45%, the declines in the regions west of the Eisack are otherwise noticeably smaller, at -25% to -29%, than in the eastern regions, where losses of between 39% and 43% are recorded. However, this difference only becomes apparent in the second subperiod (2005-2017) of the study period and is mainly due to the disintegration of the glaciers there, which are often relatively thin and/or have a small structure, in this particularly glacier-unfriendly period. Thus, it becomes clear that the determining factor for the declines is the topography of the glaciers, and differences in local climatic conditions are of minor importance. Thus, smaller, fragmented and shallower cirque glaciers tend to show higher relative area losses than larger and thicker valley glaciers.

The opposite is true for surface elevation changes, where the largest values tend to occur at the larger glaciers that are far out of balance and thus often have large area fractions in comparatively low-lying regions, which in turn leads to large amounts of melt at the surface. Thus, the size class above 5 km^2 with the two largest glaciers of the study area, Übeltalferner and Suldenferner, also shows the largest vertical change of more than -20 m on average. This is despite the fact that large parts of the Suldenferner are covered by debris which significantly reduces melting. Even in the smallest class of glaciers with an area of less than 0.1 km^2, the surface changes still amount to -9.5 m on average, and thus the mean for the total period over all glaciers studied is -17.58 m with -8.8 m over the subperiod 1999-2005, and -9.1 m over the period 2005-2017 (reference area 2005), respectively. At least in the current study period, but especially in the second subperiod of 2005-2017, which was characterized by generally very unfavorable climatic conditions for glaciers, it seems that also in terms of vertical changes, topography is the dominant factor for spatial variations of changes in the study area. Differences in regional climatic conditions mostly play a minor role.

Extension of the homogenization to further inventories

In principle, the extension of the homogenization efforts in the study area of the present work to historical inventories seems reasonable, provided that the data basis allows a transfer of the methodology used and area-wide surveys. Specifically, an inclusion of the 1983 inventory, which is only available in tabular form up to now, suggests itself. After an initial examination of the corresponding orthophotos, this project seems possible in principle, but both the data quality (resolution and contrast) and the snow conditions in some areas make it difficult to delineate the glacier areas with the accuracy used in this study. A final statement on the usefulness of a corresponding project requires further data checks and a more in-depth discussion.

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