THICKNESS AND GEODETIC MASS BALANCE CHANGES FOR THE TRIGLAV GLACIER (SOUTHEASTERN ALPS) FROM 1952 TO 2016
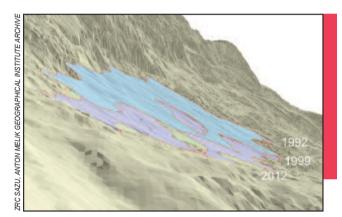
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Side view of the extent of the Triglav Glacier in 1992, 1999, and 2012, covering approximately 1 hectare.

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Thickness and geodetic mass balance changes for the Triglav Glacier (southeastern Alps) from 1952 to 2016

ABSTRACT: Various geodetic and lidar measurements performed on the Triglav Glacier (Julian Alps, Slovenia) make it possible to study not only the extent of the glacier but also changes in its thickness and volume. These measurements also make it possible to calculate the geodetic mass balance of the glacier. Thickness and volume changes were calculated using glacier area measurements from 1952, 1975, and 1992, and annually between 1999 and 2016. The mean thickness decreased from 39.2 m in 1952 to 2.45 m in 2012. The maximum thickness decreased from 48.3 m in 1952 to 5.2 m in 2007. The mean specific mass balance was calculated for the area of 1 hectare that the glacier covered in 2016. From 1952 to 2016, the annual specific mass balance was −0.45 m w.e.a^{-1}.

KEY WORDS: climate change, glacier thickness, glacier volume, geodetic mass balance, Triglav Glacier, Slovenia

Spremembe debeline in geodetske masne bilance Triglavskega ledenika (jugovzhodne Alpe) v obdobju 1952–2016

POVZETEK: Različne geodetske in lidarske izmere velikosti Triglavskega ledenika omogočajo, poleg preučevanja sprememb njegove površine, tudi preučevanje sprememb debeline in prostornine. Poznavanje teh sprememb omogoča tudi izračun geodetske masne bilance ledenika. Za ugotavljanje sprememb debeline in prostornine, smo uporabili meritve površine ledenika v letih 1952, 1975, 1992 ter meritve med letoma 1999 in 2016. Povprečna debelina ledenika se je zmanjšala iz 39,2 m leta 1952 na 2,45 m leta 2012. Največja debelina pa se je zmanjšala iz 48,3 m leta 1952 na 5,2 m leta 2007. Letno specifično masno bilanco smo ugotavljali za območje velikosti 1,0 ha, ki ga je ledenik pokrival leta 2016. Povprečna specifična masna bilanca v celotnem obdobju 1952–2016 je bila −0,45 m w.e.a^{-1} (metri vodnega ekvivalenta na leto).

KLJUČNE BESEDE: podnebne spremembe, debelina ledenika, prostornina ledenika, geodetska masna bilanca, Triglavski ledenik, Slovenija

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1 Introduction

Glacier area and volume changes are among the more visible consequences of climate change (Zängl and Hamberger 2004). Due to climate change, glaciers are disappearing worldwide (Zemp et al. 2015; Slater et al. 2020). In this regard, very small glaciers, or glacierets (Kumar 2011), such as the Triglav Glacier (Gabrovec et al. 2013, 2014), are especially threatened. Although small, these glaciers are still an important indicator of climate change (Lipar et al. 2021) because they respond to it more rapidly than larger glaciers (Brown, Harper, and Humphrey 2010; Colucci and Guglielmin 2015; Hughes 2018). In addition, small glaciers represent a numerically significant group, accounting for up to 80% of all glaciers located in mid- to low-latitude mountain ranges (Huss and Fischer 2016).

Changes in the area of the Triglav Glacier have been studied with direct measurements since 1946 (see Gabrovec et al. 2013, 2014 and references therein) and based on historical photographs and maps since 1829 (e.g., Triglav Čekada and Gabrovec 2013; Triglav Čekada, Zorn, and Colucci 2014; Triglav Čekada 2018). During the period studied, the glacier area decreased significantly (Figure 1), as did its thickness. Compared to area changes, which were studied in detail in the past (see Gabrovec et al. 2014), much less is known about thickness and volume changes. Based on geodetic measurements of the glacier in 1952 and 1999 and in 1952 and 2001, Gabrovec (2002a, 2002b) calculated the thickness and volume change. Verbič and Gabrovec (2002) calculated the volume of the Triglav Glacier based on ground-penetrating radar survey (GPRS) thickness measurements in 2000. Gabrovec (2008) later calculated the volumes of the Triglav Glacier for 1937, 1952, 1975, 1992, 1999, and 2005 based on photogrammetrically derived areas. Triglav Čekada and Gabrovec (2013) calculated the volumes of the glacier from 1976 to 2011 based on area measurements derived from non-metric photography, as well as using an empirical equation. The thickness of the glacier was also measured with GPRS in 2013. The GPRS thickness measurements were conducted at the same measuring points as in 2000 (Del Gobbo et al. 2016).

This article presents new calculations of thickness and volume changes as well as the first estimates of geodetic mass balance changes of the Triglav Glacier from 1952 to 2016. The calculations are based on digital terrain models (DTMs) developed based on geodetic tachymetric and photogrammetric area measurements of the glacier.

2 Data and methods

2.1 Geodetic, photogrammetric, and lidar measurements

Geodetic measurements on the Triglav Glacier have been performed regularly since 1999 (Triglav Čekada and Gabrovec 2008; Gabrovec et al. 2013, 2014), but the first tachymetric measurement was already made in 1952. Geodetic measurements made it possible to develop the DTMs that were used for thickness and volume calculations (Section 2.2.). The DTMs were derived from tachymetric or photogrammetrically acquired contour lines, and individual points on the surface of the glacier and glacier's perimeter.

Photogrammetric measurements were carried out with a calibrated medium-format Rolleimetric 6006 photogrammetric camera. Stereo photogrammetric measurements were conducted based on measured reference points by tachymetry and terrestrial or aerial photogrammetrically derived images. The results are presented on a map with a scale of 1:1,000 and a 5 m contour interval. The points on the surface of the glacier were measured at a density that depended on the annual area of the glacier, mostly at points where the terrain varied significantly, and so their number varies from year to year. The horizontal accuracy of these maps can be analytically estimated to be better than 20 cm (Triglav Čekada, Crosilla and Kosmatin Fras 2010), and vertical accuracy to be better than 0.5 m (taking into account, for example, the accuracy of control points used).

In addition to the detailed measurements of the glacier's area, the broader area around the glacier was measured three times between 1999 and 2016. In 2005, a special aerial stereo photogrammetric survey was performed with a large-format Leica RC 30 camera (Gabrovec et al. 2014) with an imaging scale of 1:4,000. A stereophotogrammetric acquisition of the area covering the approximate extent of the glacier in 1952 was performed. The results were mapped at a scale of 1:1,000.

In 2012 two aerial laser scanning surveys (lidar) were performed. The first lidar survey of the broader area around the Triglav Glacier was performed at the end of the accumulation period, on May 18th, 2012, and the second almost at the end of the ablation period, on September 18th, 2012 (Triglav Čekada et al. 2013). The latter was used in this study because it represents the local minimum of the glacier's area and depth. In both cases, a Riegl LM5600 laser scanner was used with a wavelength of 1550 nm, an average density of all points at 8 points/m², and an average flying height 700 m above the ground. Within the framework of the national aerial laser scanning of Slovenia, the broader area was again surveyed by lidar on August 8th, 2014 with a Riegl LMS-Q780 laser scanner with a wavelength of 1064 nm, an average density of 5 points/m², and a flying height 1000 m above the ground. The analytically determined vertical accuracy of all three lidar surveys is better than 30 cm, derived from equipment specifications and applied flying height above the ground (Triglav Čekada, Crosilla and Kosmatin Fras 2009). In 2014, a tachymetric survey of the glacier was also performed, and it was used to calculate the volume differences for 2014 (Figure 4) because lidar shows the glacier still very much under the snow. In all three lidar cases, a DTM with a cell size of 1 × 1 m was created from the laser point clouds.

The glacier measurements for 1975 and 1992 were based on stereo photogrammetric acquisition from the large-format Cyclical Aerial Surveying of Slovenia (CAS) aerial photographs. The results were mapped at a scale of 1:5,000, and the contour interval is 5 m. For 1992, a DTM with a cell size of 10 × 10 m was also created. CAS aerial photographs for 1975 were oriented in the D48/GK national coordinate system based on five identical reference points, which were clearly visible on the stereo images of special aerial photography from 2005. CAS aerial photographs for 1992 were oriented based on nine reference points from the 2005 stereo images. Due to the shadow cast by the peak of Mount Triglav on the central part of a snow-covered area of the glacier, the orientation and stereo acquisition of data from the 1975 imagery was more challenging. Thus, the resulting lower contrast inside the shadow area may have resulted in higher vertical errors.
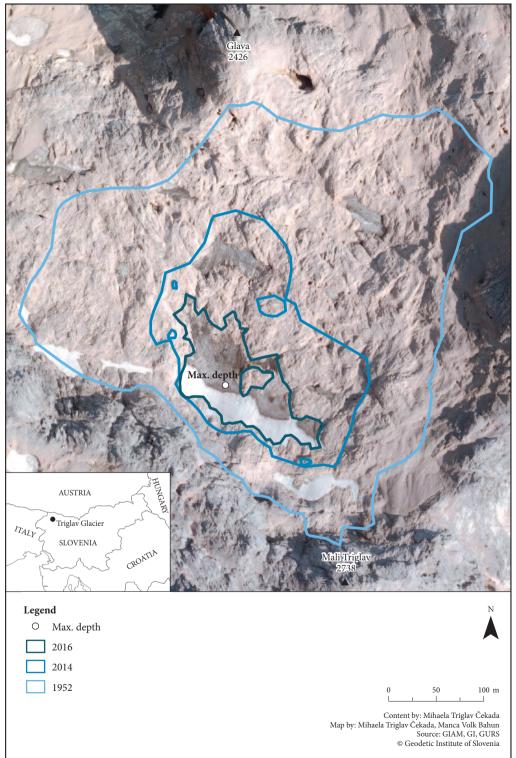
The area of the glacier was geodetically measured on September 8th, 2013, two weeks before the GPRS survey (September 22nd–24th, 2013; Del Gobbo et al. 2016). The 2013 DTM was created using both measurements: the glacier perimeter and points on the glacier's surface from the first measurement, and additional geodetic points from the glacier surface from the second one.

The measuring techniques used in the study years for area measurements are shown in Table 1. For 1975 and 2001, no areas are given because in these years the glacier was completely snow-covered. In these years the CAS photos were made in mid- and late October and the glacier was already covered with snow

Table 1: Measuring techniques applied for the Triglav Glacier area measurements (*snow-covered glacier).

Year	Survey/source date	Measuring techniques	Scale	Glacier area (hectares)
1952	October 4	Tachymetry	1:2,500	14.0
1975	October 29	Cyclical Aerial Surveying of Slovenia	1:5,000	*–
1992	September 8	Cyclical Aerial Surveying of Slovenia	1:5,000	4.3
1999	September 13–15	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	1.1*
2001	October 16–17	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	*–
2003	August 26–27	Medium-format aerial photogrammetric survey and tachymetry	1:1,000	0.6
2005	August 24–25	Special large-format aerial photogrammetric survey	1:1,000	1.2*
2007	September 13	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	0.6
2008	August 27–28	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.1*
2009	September 22–23	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	0.6
2010	September 14–15	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.5*
2011	September 13–14	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.4*
2012	September 18	Special aerial laser scanning (lidar)		0.6
2013	September 8	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	2.5*
2014	August 25	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	3.6
2015	September 9–10	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.7*
2016	September 24	Tachymetry and medium-format terrestrial photogrammetric survey	1:1,000	1.0*

Figure 1: The Triglav Glacier area in 1952, 2014, and 2016 presented on an orthophoto from August 26th, 2017. The location of the measured maximum thickness by GPRS from 2013 is marked »Max. depth.« ▶

Glava
2426

Max. depth ○

AUSTRIA

HUNGARY

ITALY ● Triglav Glacier

SLOVENIA

CROATIA

Mali Triglav
2738

Legend

○ Max. depth

☐ 2016

☐ 2014

☐ 1952

N

0   50   100 m

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(less than a meter thick) of a new accumulation season (Gabrovec et al. 2014), which has to be taken into account when interpreting the results. For the 1992 CAS photos, only the area of exposed ice is given, not including surrounding snow fields. Between 1999 and 2016, the area studied was mostly snow-covered. The glacier's actual snow-free area was only measured in 2003, 2007, 2009, and 2012.

Using area measurements, DTMs for all the study years were created and used for further thickness and volume calculations.

2.2 Thickness and volume

The relative thickness of the glacier, which is the vertical height difference between two years studied (Figure 2; Table 2), was calculated as the height difference between the two cells at the same location in the two DTMs applied (Figures 3, 4, and 6). During the glacier area measurements, glacier ice was not always exposed because at the end of the ablation period it was still covered with firn or snow (Table 1). For these years the calculated thickness and volume refer to the entire (i.e., combined) thickness of ice, firn, and snow, and not only the thickness of the ice.

The mean relative thickness of the glacier was calculated as the change in relative thickness in an area for which the volume change was studied; that is, for 14 hectares that the glacier covered in 1952 and for 1 hectare that the glacier covered in 2016. Because 2012 represents the glacier minimum in the period studied, sometimes (e.g., Table 3) the changes in relative thickness refer to the thickness change between the year studied and 2012.

The mean absolute thickness of the glacier (i.e., the mean difference between the surface of the glacier and the bedrock) was obtained taking into the account the mean relative thickness along with the GPRS measurements from 2013 (Del Gobbo et al. 2016). The 2013 GPRS measurements showed an ice layer averaging 1.95 m thick and a firn layer averaging 3 m thick (a total of 4.95 m).

To obtain the mean absolute thickness for 2012 as the glacier minimum in the period studied, 2.5 m (a mean relative thickness between 2013 and 2012) was subtracted from the 2013 GPRS-measured mean absolute thickness of 4.95 m (Del Gobbo et al. 2016) to obtain 2.45 m as the mean absolute thickness for 2012 (Figure 5).
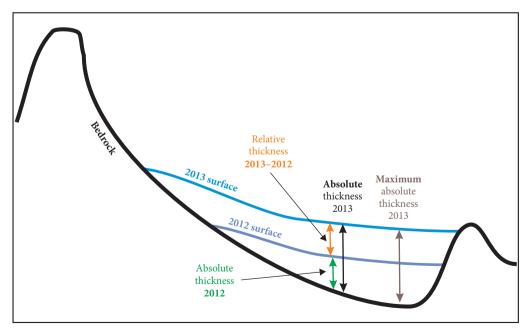

Figure 2: Sketch of relative and absolute thicknesses. The calculations refer to vertical thickness.

The maximum absolute thickness of the glacier was obtained for the location (cell) where the GPRS measurements in 2013 gave the maximum thickness of the glacier (Figure 1). For this cell, first the relative thickness between the year studied and 2013 was calculated. If the glacier was thicker in the year studied, then a layer of ice 5 m thick and layer of firn 3 m thick (8 m in total) from 2013 GPRS measurements (Del Gobbo et al. 2016) were added to the relative thickness, resulting in the maximum absolute thickness. If, in the year studied, the glacier was thinner than in 2013, the mean relative thickness was subtracted from the GPRS measurements from 2013 to obtain the maximum absolute thickness (Figure 5).

The volumetric changes of the glacier for 1952, 1975, 1992, 2001, 2005, 2012, and 2014 were calculated for an area of 14 hectares covered by the glacier in 1952 (Figure 3). Because the area of the glacier from 1999 to 2016 varied between 2.5 and 1 hectares, the volumetric changes in this period were also calculated for the area of 1 hectare that the glacier covered in 2016 (Figures 1 and 6). To allow better comparison through the entire period studied, the 1-hectare area from 2016 was also used for the volumetric change calculations for 1952, 1975, and 1992 (Tables 3 and 4).

The volumes were calculated using ArcGIS software, which allows calculation of volumes by producing a closed TIN (triangulated irregular network) by combining contour lines and individual points on the surface of the glacier and perimeter of the glacier. The TIN was then interpolated to a DTM raster with a grid size of 5×5 m.

2.3 Geodetic mass balance

Mass balance was introduced to compare changes in the mass of different glaciers. It describes the decrease or increase in the glacier's mass in the period studied. The mass balance is a product of volume change and the density of material in that volume. The mass balance can be measured directly (e.g., the glaciological mass balance) or indirectly (e.g., the geodetic mass balance, measured by geodetic methods; Tihbert et al. 2008; Zemp et al. 2010; Fischer 2011). Thus the geodetic mass balance can be calculated for all glaciers on which volumetric changes can be calculated and for which information is available on the density of snow, firn, and ice that has melted or newly accumulated (Fischer 2011; Huss 2013).

The mass balance measured for a specific location on the glacier is known as a specific mass balance and is described by the meters of water equivalent [m w.e.], or for the annual (net) specific mass balance in meters of water equivalent per year [m w.e. a^{-1}] (Benn and Evans 2010; Fischer 2011).

In the case of the Triglav Glacier, one glacial year was used as the base unit because geodetic measurements were mainly conducted at the end of the ablation period. For calculating the mass balance, an area of 1 hectare was used, which the glacier covered in 2016.

The use of adequate snow and ice densities is essential when calculating the mass balance. For example, newly fallen snow has a density between 50 and 200 kg/m³, firn (snow that has survived at least one ablation period) between 400 and 830 kg/m³, and glacial ice 830 to 917 kg/m³ (Benn and Evans 2010). However, in geodetic mass balance calculation, a uniform density for the entire volume change is often applied. For larger alpine-type glaciers, an average value of 850 kg/m³ is often used (Zemp et al. 2010; Fischer 2011). Thibert et al. (2008) give a density of 600 kg/m³ for firn measured in the summer and autumn months. According to another source, this density is characteristic for firn at a depth of about 15 m, whereas it is 500 kg/m³ at a depth of about 5 m (Schwerzmann et al. 2006). Huss (2013) gives two values, 600 kg/m³ and 700 kg/m³, for firn in the Alps for average depths up to 10 m.

On the Triglav Glacier, different layer densities were measured during the 2013 GPRS survey. A cross-section 1.75 m deep was dug into the firn. The first 20 cm represented a layer of new snow, which was deposited in early September, shortly before the measurements were conducted, and it had a density of 375 kg/m³, whereas a density of 600 kg/m³ was measured from 30 cm to the bottom of the cross-section (Del Gobbo et al. 2016).

In our calculations we used a uniform density of 600 kg/m³ for the whole period studied (Section 3.2). In the period 1952 to 1999 most of the lost thickness was due to the loss of glacier ice and in the period after 1999 most of the lost thickness was due to the loss firn and snow. In Figure 8 a comparison of mass balance is given for the period 1952 to 1999 taking into account a density of 860 kg/m³ (e.g., Zemp et al. 2010, 2015; Shahgedanova et al. 2012; Fischer, Huss, and Hoelzle 2015; Huss, Dhulst and Bauder 2015) and a density of 600 kg/m³.

3 Results and discussion

3.1 Thickness and volume

For the years for which the broader area of the Triglav Glacier was surveyed (1952, 1975, 1992, 2001, 2005, 2012, and 2014; i.e., 14 hectares that the glacier covered in 1952), the raster of relative thicknesses was calculated between the DTM for a selected year and the September 2012 DTM because the latter represents one of the glaciers' minimums in the period studied.

Figure 3 shows some reddish parts, which is the result of orientation errors contained in the DTMs from 1952, 1975, and 2001. These three years were transformed or oriented into the national coordinate system using a smaller number of reference points, all of which were inside the 14-hectare area; they were specifically located only around the narrow area representing the current glacier and Mount Glava. This results in the reddish parts mainly appearing in the east in the 1952 raster, in the east and west in 1975, and mainly in the west in 2001. In comparison, the model from 1992 is much better oriented because its orientation is based on nine points and not only five, as in the case of 1975. For these years, the vertical accuracy is mostly ± 2 m or better, but poorer vertical accuracy may be expected for 1975 due to the problems with stereo photogrammetric acquisition mentioned in Section 2.1 (more details are provided in Gabrovec 2008 and Gabrovec et al. 2009). Gabrovec (2008) argues that due to this the volume for 1975 is most probably underestimated.

In Figure 3, relative thickness up to 2 m is shown in white and light gray. Especially for the DTMs for 1952, 1975, and 1992, it must be taken into account that this may be in the domain of vertical errors. The relative thicknesses up to 10 m are shown in yellowish-green shades, and higher relative thicknesses are in shades of blue.
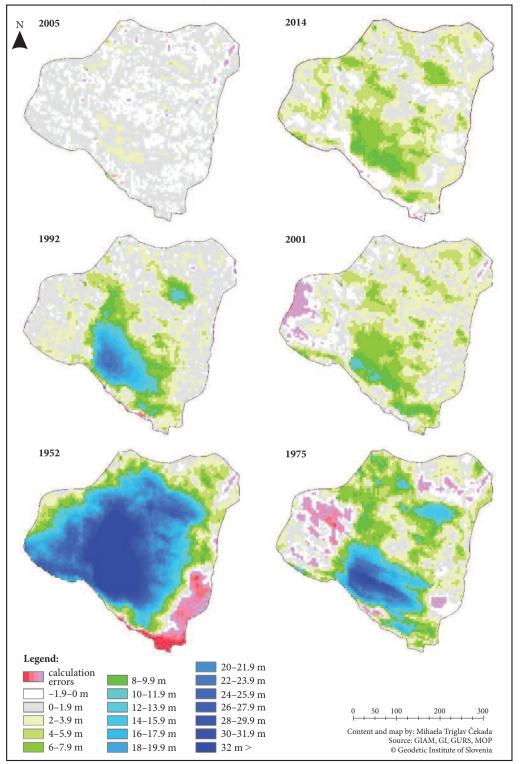
The 2001 and 2014 calculations show almost the same amount of snow and firn because in these glacial years the weather conditions were favorable (e.g., Vrhovec and Velkavrh 2001) for glacier preservation and the glacier ice remained hidden under the firn through the entire ablation period. The highest relative thicknesses can be found along Mount Triglav's rock wall (the southern side on the images in Figure 3); that is, in the area where the glacier has persisted for the last two decades. Similar relative thicknesses as in 2001 and 2014 can also be seen in Figure 4, where the relative thicknesses between the end of the accumulation period and the end of the ablation period in 2012 are presented (May–September). The snow accumulates in certain karst depression regardless of the year observed as a result of favorable microrelief conditions. There was on average 4.2 m more snow and firn in May compared to September 2012 (Figure 4).

Table 2: Changes in mean relative thickness and relative volume of the Triglav Glacier for the 14-hectare area covered by the glacier in 1952 and between two measurements in 2012 (*vertical accuracy for calculating mean relative thickness is ± 2 m or better, except for 1975, for which it may be poorer; **vertical accuracy is ± 0.6 m or better).

Period studied	Changes in mean relative thickness* (m)	Changes in annual mean relative thickness (m/year)	Changes in relative volume ('000 m³)
1975–1952	−10.0	−0.44	−1,407
1992–1975	−1.5	−0.09	−207
2001–1992	−1.3	−0.14	−181
2005–2001	−2.6	−0.64	−360
2012–2005	−0.4	−0.05	−51
2014–2012	2.9	1.46	411
September–May 2012	−4.2**		−591

Table 2 presents changes in relative thickness and relative volume between the years studied and the two measurements in 2012. The thickness and volume decrease is especially noticeable in the first two and

Figure 3: Relative thicknesses of the Triglav Glacier in 1952, 1975, 1992, 2001, 2005, and 2014 relative to the 2012 DTM. The maps present the area of 14 hectares covered by the glacier in 1952. The grid cell size is 5 × 5 m. The vertical accuracy for calculating mean relative thickness is ± 2 m or better (except for 1975, for which it may be poorer). In reddish areas, the thickness calculation is not correct due to the errors within DTMs. ➤

Legend:

calculation errors	8–9.9 m	20–21.9 m
−1.9–0 m	10–11.9 m	22–23.9 m
0–1.9 m	12–13.9 m	24–25.9 m
2–3.9 m	14–15.9 m	26–27.9 m
4–5.9 m	16–17.9 m	28–29.9 m
6–7.9 m	18–19.9 m	30–31.9 m
		32 m >

0   50   100   200   300

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a half decades and at the beginning of the twenty-first century. The change in the first two and a half decades was also noticed by Gabrovec (2008) and Triglav Čekada and Gabrovec (2013; Table 3). Due to favorable years for snow accumulation on the glacier from 2012 to 2014, glacier thickness increased, but as shown in Table 4 the decreasing trend continued in the following years (Figure 6).

Table 3 presents the mean relative thickness and relative volumes relative to 2012 compared to volume calculations previously published in the literature. To be able to directly compare our relative volumes with absolute volumes in the literature, one has to add to the relative volumes a volume of 14,700 m^3 (ice and firn) that the glacier amounted to in 2012. The 2012 volume was calculated from the area in 2012 (0.6 hectares; Table 1) and the mean glacier thickness in 2012 (2.45 m; see Section 2.2).These study's volume calculations are to some extent comparable with the volumes given by Gabrovec (2008) based on photogrammetrically derived areas and using the same data sources, although higher. Similar is true compared with values in Triglav Čekada and Gabrovec (2013) except for 1975, where our calculation is much lower, which may be connected to vertical errors for the 1975 calculation (see Section 2.1). The difference may also be attributed to the calculation errors of the source cited because the calculations are based on terrestrial non-metric photography and on an empirical equation. On the other hand, our calculations are much higher compared to the values in Gabrovec (2002b), which were acquired from DTMs based on the topographical maps of the glacier.

Some differences between our calculations and those from the literature may also partly be attributed to large thickness variability on very small glaciers, which cannot be satisfactorily summarized in empirical models. For the same reason, our glacier's mean relative thickness in 1975 is smaller than in 1992 because the former was calculated for a much larger area than the latter. This is not the case if the calculations are
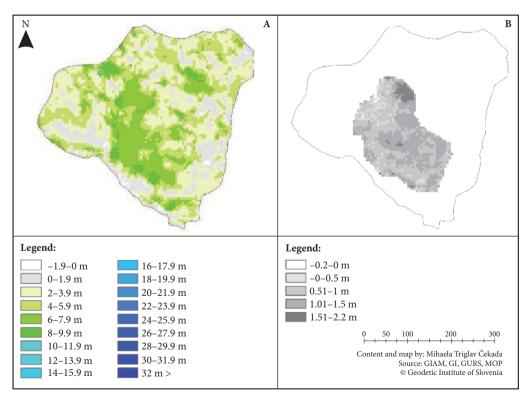

Figure 4: Relative thicknesses of the Triglav Glacier: a) between May and September 2012 and b) between August 8th and 25th, 2014 (the former is based on lidar data and the latter on the tachymetric survey). The grid cell size is 5 × 5 m. The vertical accuracy for calculating mean relative thickness is ± 0.6 m or better.

made only for the area of 1 hectare that the glacier covered in 2016 (Table 3). Calculations for the area of 1 hectare that the glacier covered in 2016 were primarily made from 1999 to 2016 (Figure 6) because during this period the area of the glacier mainly did not exceed 1 to 2.5 hectares (Table 1).

Table 3: Mean relative thickness (*vertical accuracy for calculating mean relative thickness is ± 2 m or better; except for 1975, for which it may be poorer), relative volume of the Triglav Glacier relative to 2012, and absolute volume. Columns 4, 7, 8, and 9 are summarized from the literature (for area, see Table 1): Gabrovec (2002b), Gabrovec (2008), and Triglav Čekada and Gabrovec (2013; two calculations) (**glacier area in 2016).

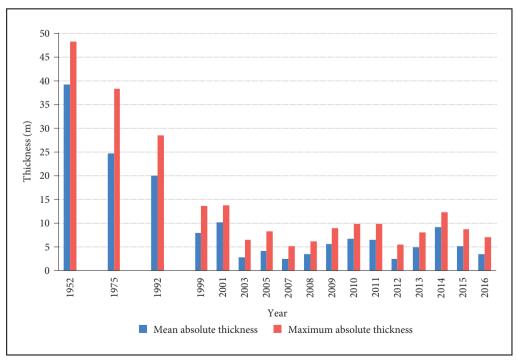| Survey/ source date	Study area (hectares)	Mean relative thickness* relative to glacier height in 2012 (m)	Mean thickness by Triglav Čekada and Gabrovec (2013) (m)	Relative volume relative to glacier height 2012 ('000 m^3)	Absolute volume ('000 m^3)	Volume by Gabrovec (2002b) ('000 m^3)	Volume by Gabrovec (2008) ('000 m^3)	Volume by Triglav Čekada and Gabrovec (2013) ('000 m^3)
October 4, 1952	14.0/1.0**	15.7/36.8**	–	2,206	2,221	1,500	2,000	–
October 29, 1975	14.0/1.0**	5.7/22.3**	14.5 (1976)	799	814	–	700	1,408/ 2,171.7 (1976)
September 8, 1992	14.0/1.0**	9.4/17.6**	9.3	406	421	>135	400	356/398.5
September 15, 1999	1.0**	5.4**	5.7	56	71	35 (2001)	60	60/70.5
August 25, 2005	1.0**	1.7**	5.7	17	32	–	20	5.8/27.5
September 15, 2010	1.0**	4.3**	4.6	43	58	–	–	27.5
September 24, 2016	1.0**	1.0**	–	10	25	–	–	–

Figure 5: Mean absolute thickness and maximum absolute thickness (including ice, firn, and snow) of the Triglav Glacier from 1952 to 2016. Mean absolute thickness is calculated from relative thickness between the selected year and 2012 for an area of 1 hectare and taking into the account GPRS 2013 mean absolute thickness. Maximum absolute thickness was calculated for the location of maximum GPRS thickness in 2013.

Our volumes are also much higher compared to the volumes calculated from GPRS measurements. According to the GPRS measurements, in 2000 the glacier volume was about 35,000 m³ (Verbič and Gabrovec 2002) and in 2013 about 7,400 m³ (Del Gobbo et al. 2016). The differences may partly be attributed to the errors connected with our modeling, but also with the fact that our glacier volumes contain a combined volume of ice, firn, and snow, and not only ice volumes, as is the case with the GPRS measurements.

Figure 5 shows that during the period studied the glacier's maximum absolute thickness decreased from 48.3 m (in 1952) to 5.2 m (in 2007), and its mean absolute thickness from 39.2 m (in 1952) to 2.45 m (in 2012). Similar thinning was reported by Gabrovec (2002a, 2000b), who calculated a thickness decrease up to 35 m for a shorter period (1952–1999/2001).

The lowest mean absolute thicknesses of the glacier were calculated for 2003, 2007, 2008, 2012, and 2016. In these years, the mean absolute thickness did not exceed 3.5 m. Even in these years, the glacial ice was still preserved under a layer of firn because the mean thickness of ice does not exceed 1.95 m, as mentioned above in the description of the 2013 GPRS measurement. In addition, the maximum absolute thicknesses in these years, measured for the same location where the maximum thickness was measured by GPRS in 2013, did not exceed 6.5 m.

Table 3 compares our mean relative thicknesses to the glacier mean thicknesses in Triglav Čekada and Gabrovec (2013). To be able to directly compare our relative thicknesses with those from the literature, it is necessary to add a mean glacier thickness from 2012 (2.45 m; see Section 2.2) to the relative thicknesses. For 1975 and 2005, our calculations of the mean glacier thickness are lower, and for 1992, 1999, and 2010 they are higher than in Triglav Čekada and Gabrovec (2013). Here the differences can also be attributed to the different methods and errors connected with the sources used.
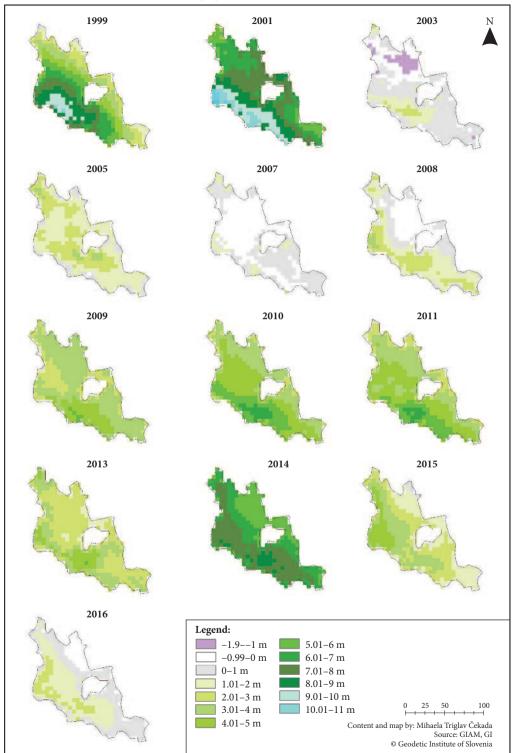
Figure 6 shows the differences in the relative glacier thickness (together for ice, firn, and snow) from 1999 to 2016 relative to 2012. In the favorable years for the glacier (1999, 2001, 2010, 2011, and 2014), surplus masses accumulated at the southern (i.e., the upper, highest, and steepest) part of the glacier alongside Mount Triglav's rock wall. In 2003, 2007, and 2008, the thickness of the glacier was almost the same as in 2012. The mass deficit is seen in the northern (i.e., the lower) part of the glacier. During six years between 2009 and 2014, excluding 2012, the glacier thickness increased. In 2015 and 2016 the glacier thinned again (Table 4).

Table 4: Changes in mean relative thickness (*vertical accuracy for calculating mean relative thickness is ± 2 m or better; except for 1975, for which it may be poorer) and annual mean relative thickness as well as changes in relative volume for the area of 1 hectare that the Triglav Glacier covered in 2016.

Time difference	Changes in mean relative thickness* (m)	Changes in annual mean relative thickness (m/year)	Changes in relative volume ('000 m³)
1975–1952	−14.5	−0.6	−149
1992–1975	−4.7	−0.3	−49
1999–1992	−12.1	−1.7	−124
2001–1999	2.3	1.2	23
2003–2001	−7.4	−3.7	−76
2005–2003	1.4	0.7	15
2007–2005	−1.7	−0.9	−17
2008–2007	1.0	1.0	10
2009–2008	2.1	2.1	21
2010–2009	1.2	1.2	12
2011–2010	−0.3	−0.3	−3
2012–2011	−4.0	−4.0	−41
2013–2012	2.6	2.6	27
2014–2013	4.1	4.1	42
2015–2014	−5.0	−5.0	−51
2016–2015	−1.8	−1.8	−17

Figure 6: Relative thicknesses of the Triglav Glacier relative to 2012 in the area of 1 hectare covered by the glacier in 2016. The grid cell size is 5 × 5 m. Vertical accuracy for calculating mean relative thickness is ± 2 m or better. ➤

Legend:

−1.9−−1 m	5.01–6 m
−0.99–0 m	6.01–7 m
0–1 m	7.01–8 m
1.01–2 m	8.01–9 m
2.01–3 m	9.01–10 m
3.01–4 m	10.01–11 m
4.01–5 m	

Content and map by: Mihaela Triglav Čekada
Source: GIAM, GI
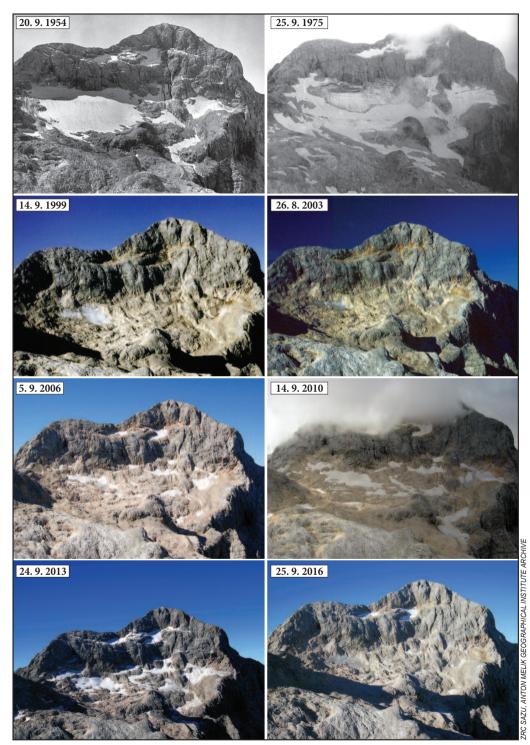© Geodetic Institute of Slovenia

0   25   50   100

Figure 7: The Triglav Glacier in selected years from 1954 to 2016.

Table 4 presents the inter-annual mean relative thicknesses and relative volumes of the Triglav Glacier, which were calculated for the area of 1 hectare covered by the glacier in 2016. In this area, the glacier thinned on average by 0.6 m per year between 1952 and 2016. The most significant reduction of relative thickness occurred from 1992 to 1999, when the glacier thinned on average by 1.7 m per year. Similar is reported by Gabrovec (2002a), who stated that the glacier thinned by 1 to 2 m annually in the late 1980s, and by 2 m at the beginning of the 1990s.

From 1999 to 2016, it thinned on average by 0.3 m per year, between 1999 and 2009 by 0.2 m per year, and between 2009 and 2016 by 0.5 m per year. The last can be attributed to accelerated thinning of the glacier in 2015 and 2016, when it thinned by 5 m in the glacier year 2014–2015 and 1.8 m in the glacier year 2015–2016. Figure 5 shows that all the surplus that accumulated on the glacier in 2013 and 2014 melted in 2015 and 2016.

For the Slovenian Alps, considerable changes in glacier thickness in the last half century are also reported for the Skuta Glacier (Triglav Čekada et al. 2020).

3.2 Mass balance

The mean specific mass balance between 1952 and 2007 was negative, between 2007 and 2010 it was positive, and it has fluctuated significantly in the last decade (Figure 8). The fluctuations can be explained by high accumulation of snow that fell on the glacier in favorable (i.e., snow-rich) years, and the total melting of this snow in the next (for the glacier, unfavorable) year. The annual mean specific mass balances for 1952 to 2016 are shown in Figure 9, where cumulative mass balances are also given.

The average annual specific mass balance for the entire period studied (1952–2016) was −0.45 m w.e.a^{-1}. This value is similar to the long-term average specific mass balance of −0.39 m w.e.a^{-1} for all Swiss glaciers
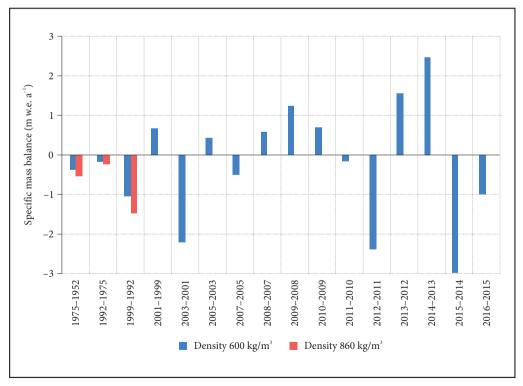

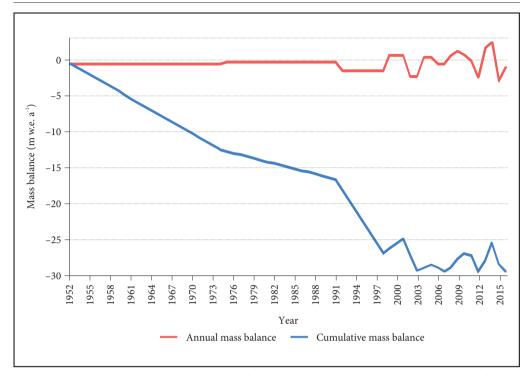Figure 8: Mean specific mass balance for the area of 1 hectare that the Triglav Glacier covered in 2016.

Figure 9: Annual specific mass balance and cumulative mass balance for the area of 1 hectare that the Triglav Glacier covered in 2016 (for uniform density 600 kg/m³).

from 1969 to 2006 (Fischer, Huss, and Hoelzle 2015) and −0.62 m w.e.a⁻¹ for the French Sarennes Glacier from 1952 to 2003 (Thibert et al. 2008).

After the turn of the century, the average annual mean specific mass balance on the Triglav Glacier was −0.07 m w.e.a⁻¹ from 1999 to 2009, −0.26 m w.e.a⁻¹ from 2010 to 2016, and −0.14 m w.e.a⁻¹ from 1999 to 2016. Comparing these data with the data for other Alpine glaciers from 1999 to 2009, it can be seen that the trend of annual specific mass balances for other European Alpine glaciers was predominantly negative and higher than that of the Triglav Glacier. Huss (2012) states for entire European Alps an annual specific mass balance of −0.99 m w.e.a⁻¹ and Hagg et al. (2012) give specific mass balance values between −0.9 m w.e.a⁻¹ and −0.5 m w.e.a⁻¹ for the group of five small glaciers in the Bavarian Alps. Zemp et al. (2015) give an average geodetically derived mass balance of −0.70 m w.e.a⁻¹ for more than 100 glaciers in the central Alps and a glaciological mass balance of −1.03 m w.e.a⁻¹ for a smaller number of glaciers. They also report a global geodetic mass balance average of −0.8 m w.e.a⁻¹ for the same period. In summary, in the Alps, the specific mass balance was approximately −1.0 m w.e.a⁻¹ in the first decade of the twenty-first century.

From 2010 to 2015, Huss, Dhulst, and Bauder (2015) give an annual specific mass balance of about −1.0 m w.e.a⁻¹ for the Austrian and Italian Alps, and −0.8 m w.e.a⁻¹ for the Swiss Alps. Carturan et al. (2016) give an annual specific mass balance between −1.79 and −0.76 m w.e.a⁻¹ for selected Italian glaciers from 2004 to 2013. In 2013, the specific mass balance values began to increase, similar to the Triglav Glacier in 2013 and 2014.

The values of the Triglav Glacier differ to some extent from the cited cases, which can be partly attributed to the fact that those studies mentioned mainly included larger glaciers. Abermann et al. (2009) already determined that the thickness of very small glaciers decreases more slowly in comparison to larger glaciers. The lower values of the annual specific mass balances obtained for the Triglav Glacier may also be related to favorable micro-relief conditions (Kuhn 1995) that help preserve it. Other studies of changes in mass balance for very small glaciers also show a significant impact of local micro-relief on the mass balance

in addition to the meteorological parameters (Kuhn 1995; Schöner and Böhm 2007; DeBeer and Sharp 2009; Shahgedanova et al. 2012; Colucci and Guglielmin 2015; Carturan et al. 2016; Huss and Fischer 2016).

4 Conclusion

The thickness and volumetric changes for the Triglav Glacier, as well as its mass balance, were determined for over six decades. During this period its maximum thickness decreased from 48.3 m (in 1952) to 5.2 m (in 2007) and its mean thickness from 39.2 m (in 1952) to 2.45 m (in 2012).

The mean annual specific mass balance was -0.45 m w.e.a^{-1} in the entire period studied (1952–2016), -0.07 m w.e.a^{-1} from 1999 to 2009, and -0.26 m w.e.a^{-1} from 2010 to 2016. The values obtained are lower if compared to the mass balances of other Alpine glaciers.

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