

Multi-Method Investigation of Dynamic Processes in Rapidly Changing Alpine Glaciers

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Ice fall zone Gepatschferner

"[...] a man who keeps company with glaciers comes to feel tolerably insignificant by and by. The Alps and the glaciers together are able to take every bit of conceit out of a man and reduce his self-importance to zero if he will only remain within the influence of their sublime presence long enough to give it a fair and reasonable chance to do its work."

Mark Twain ¹

¹Mark Twain (1880): A Tramp Abroad

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Abstract

Glacier retreat due to climate change is significant and well investigated on a regional scale. Much less is known about local effects, especially in the proglacial area. This thesis focuses on glacial changes and new methods to tackle the processes therein. The glacial changes within the catchment of the river Fagge, in the upper Kaunertal valley, are investigated by combining different direct glaciological, geodetic and geophysical methods. Alongside long-term monitoring of glacier flow velocities at adjacent glaciers, the investigation focuses on the glacier tongue of Gepatschferner. In addition to the direct measurements of the ice motion and the determination of the surface mass balance, the ice thickness and the thickness of subglacial sediments is measured with vibroseismic soundings. Changes in total area, elevation and volume are calculated from multiple high-resolution digital elevation models from airborne laser scans. These detailed glaciological investigations are part of the joint project PROSA, which focuses on the geomorphodynamics of the entire proglacial system and aims at balancing the sediment budget therein.

The presented cumulative doctoral thesis consists of three publications and additional results from the glaciological part of PROSA. This includes long-term monitoring of glacier flow velocities (Paper 1), detailed investigations of the process development of a surface depression at the tongue of Gepatschferner (Paper 2), and an approach at closing the balances of ice, water and sediments on the glacier tongue (Paper 3).

It turned out that the formation of circular and funnel-shaped surface depressions occurs as a consequence of increased glacier retreat rates. Additionally, the process of the depression development in turn increases the retreat rates. This exemplary development was caused by the evacuation of subglacial sediments after a heavy precipitation event and by decreasing glacier dynamics as a result of negative glacier mass balances. Beside the mass balances, the horizontal motion and especially the vertical motion of the glacier provide valuable information on the glacier state, such as measured in the long-term program on Kesselwandferner. The magnitudes of the mass exchanges showed the influence of extreme events, which exceed mean daily and even annual turnovers, as well as the role of the melt water production at the glacier tongue of Gepatschferner and its severe effect on the glacial runoff regime of the river Fagge.

Kurzfassung

Die Gletscherschmelze in Folge des Klimawandels ist signifikant und auf regionaler Ebene gut untersucht. Weniger untersucht sind dabei lokale Effekte im Speziellen im proglazialen Bereich. Diese Arbeit beschäftigt sich mit den glazialen Änderungen und neuen Methoden zur Untersuchung der Prozesse. Mit einer Zusammenschau verschiedener direkt glaziologischer, geodätischer und geophysikalischer Methoden werden die glazialen Änderungen im Einzugsgebiet der Fagge im oberen Kaunertal untersucht. Neben dem Langzeitmonitoring von Gletscherfließgeschwindigkeiten benachbarter Gletscher, liegt der Fokus der Untersuchungen im Speziellen auf der Zunge des Gepatschferners. Zusätzlich zur direkten Messung der Eisbewegung sowie der Erfassung der Oberflächenbilanz der Zunge werden mit Hilfe der Vibroseismik sowohl die Eisdicken als auch die Dicke subglazialer Sedimente untersucht. Die Berechnung von Flächen-, Höhen- und Volumsänderungen der Gletscher erfolgt auf Basis multipler hochaufgelöster digitaler Höhenmodelle aus Airborne Laser Scans. Diese detaillierten glaziologischen Untersuchungen sind Teil des Projektbündels PROSA welches sich mit der Geomorphodynamic des gesamten proglazialen Systems befasst und auf die Bilanzierung des Sedimenthaushalts abzielt.

Die hier vorliegende kumulative Doktorarbeit setzt sich aus drei Veröffentlichungen sowie zusätzlichen Ergebnissen aus dem glaziologischen Teil aus PROSA zusammen. Der Rahmen reicht dabei vom Langzeitmonitoring der Gletscherfließgeschwindigkeiten (Artikel 1) über die Detailuntersuchung des Prozessablaufs der Trichterbildung auf der Zunge des Gepatschferners (Artikel 2) bis zum Ansatz des Schließens der Bilanzen von Eis, Wasser und Sedimenten am Beispiel der Gletscherzunge (Artikel 3).

Es zeigte sich, dass die Bildung von kreis- und trichterförmiger Senken als Folge verstärkter Schmelzraten zu sehen sind. Zusätzlich wird die Rückverlagerung der Gletscherzunge durch den Prozessablauf der Trichterbildung verstärkt. Ursache für diese beispielhafte Entwicklung war neben einem Starkniederschlagsereignis, welches zum Ausspülen subglazialer Sedimente führte, die abnehmende Eisdynamik aufgrund negativer Gletschermassenbilanzen. Neben dem Massenhaushalt, liefern die Horizontalbewegung und vor allem die Vertikalbewegung des Gletschers, wie sie etwa im Langzeitmessprogramm am Kesselwandferner erfasst werden, wertvolle Information über den Gletscherzustand. Bei den Größenordnungen der Massenumsätze zeigte sich einerseits der Einfluss von Extremereignissen welche mittlere tägliche und sogar jährliche Umsätze übersteigen, auf der anderen Seite aber auch den maßgeblichen Anteil der Schmelzwasserproduktion der Gletscherzunge des Gepatschferners und somit den großen Einfluss auf das glaziale Abflussregime der Fagge.

1. Introduction

The present work is set up in the form of a cumulative doctoral thesis of three publications in the field of glaciology. The majority of this work originates from the glaciological subproject in the interdisciplinary joint project PROSA in the region of the upper Kaunertal (Heckmann et al., 2012; Heckmann and Morche, 2019). Within this subproject, detailed investigations were carried out on the recent changes at the tongue of Gepatschferner and on an approach of balancing ice, water and sediments. Together with long-term monitoring of glacier surface velocities, these investigations set the frame of this thesis.

1.1. Focus On Glaciers: A Brief History

During the past centuries the focus of interest on glaciers changed according to the problems that occurred at the interface of human and environment. Early reports mostly cover catastrophic events which attracted the attention of the general public and of scientists on to glaciers and their behaviour. One of the best-known sequences of catastrophic events in the Tyrolean Alps are the ice lakes of Vernagtferner and their outburst floods in the Rofental valley (Ötztal Alps, Austria). The first report dates back to the year 1600 (Richter, 1892; Nicolussi, 1990), when Vernagtferner dammed a lake after a period of rapid glacier advances, so-called surges (Hoinkes, 1969). Further events of this kind were reported for the years 1680, 1772 and 1845, which also mark the beginning of observations and early glaciological investigations of glacier advances (e.g. Walcher, 1773; Stotter, 1846; Schlagintweit and Schlagintweit, 1850; Finsterwalder, 1897; Finsterwalder and Hess, 1926). Nicolussi (2012) gives a detailed overview on the history of the advances and the maximum glacier extents of Vernagtferner.

Since the end of the Little Ice Age around 1850, the glaciers in the Austrian Alps have been retreating, apart from shorter periods with glacier advances, the latest one during the 1970s and 1980s, when about 75% of Austrian glaciers showed positive length changes (Patzelt, 1985). The retreat of the glaciers also changed the focus of interest to key issues within the changed relations between humans and the environment. Questions about the consequences of retreating glaciers became even more important during the most recent decades, when increased retreat rates were observed. In the tourism sector, glaciers have always been prestige objects, yet they also affect mountain infrastructure like roads and tracks. These are endangered

by increasing rock fall activities and mudflows from recently deglaciated areas and thawing permafrost. In glacier ski resorts, the increasing ice melt results in great challenges to the maintenance of the infrastructure and snow management becomes even more important (Fischer et al., 2011, 2016a). In the field of hydropower and water management, glacial changes lead to a change in water supply. The peak discharge from ice melt during the summer season, which characterizes a glacial runoff regime, flattens and a discharge peak from snow melt during spring and early summer becomes more important. While the warming in recent decades has increased the amount of meltwater from glaciers, it continues to decrease their size, two opposing effects that will lead to a maximum in glacial runoff in the near future (Braun et al., 2000; Huss et al., 2008). Depending on the mountain region, this maximum was already reached, for example, at the beginning of the millennium on Jamtalferner glacier (Silvretta), when the largest negative specific glacier mass balance, of a 30-year survey, occurred in 2018, but the maximum volume change had already been measured in 2003 (Fischer et al., 2016b; Fischer and Janicke, 2019). The water supply from glacier ice melt as drinking water resource is not relevant for the Austrian Alps because precipitation and ground water storage are the main sources for drinking water. However, this is an important issue on a global perspective, especially in regions where glacial water supply is needed for irrigation and as drinking water during dry seasons, such as in the Peruvian Andes or Pakistan and the North of India (e.g. Viviroli et al., 2007; Kehrwald et al., 2008; Immerzeel et al., 2010). Another important glaciological topic on a global scale is the effect of glacier melt on global sea level rise (e.g. Marzeion et al., 2012; Church et al., 2013; Gregory et al., 2013; Zemp et al., 2019), its pattern and effects at the human-environment interface (Marzeion et al., 2014). This is one of the most important current topics, in particular as a considerable part of the world's population lives in near-costal regions (Small and Nicholls, 2003).

The basis of the above-mentioned fields of research are long-term data and the growing need for spatial and temporal high-resolution basic data. In addition, multi-method approaches, which are particularly relevant for modern applied glaciology, are needed, for example, to investigate dynamic processes and changes therein. This becomes even more important for investigations on inter-systematic processes, like within the interdisciplinary joint-project PROSA between the glacial and proglacial systems.

1.2. The Joint Project PROSA

The project "High resolution measurements of the morphodynamics in rapidly changing **PRO**glacial **S**ystems of the **Alps**" focused on the catchment of the upper

Fagge river upstream from the Gepatsch hydropower reservoir in the Kaunertal and was started in 2012 (Heckmann et al., 2012).

The main goal of the joint project PROSA was the detailed quantification of geomorphological processes of single subsystems, changes therein and the inter-systematic connections within the principle of sediment cascades. The integrated approach of sediment cascades (Becht et al., 2005; Burt and Allison, 2010; Morche et al., 2017) is based on the sediment delivery, transport and storage within single subsystems. This means that detailed investigations in different subsystems and their linkages enable analyses of geomorphological system processes, changes and feedbacks. In the joint project PROSA, interdisciplinary investigations in geomorphology, hydrology, geology, geodesy, geophysics and glaciology were performed (Heckmann and Morche, 2019). The glaciological investigations in PROSA account for essential parts in this thesis.

Within the sediment cascade system and regarding the overarching research question on the sediment budget of the catchment, glaciers provide deposition area, they transport deposited material and they are a source of sediments due to bedrock erosion and exaration. In this context, questions arise on the actual and expectable changes in glacier mass balance, glacier dynamics as well as in the magnitude of subglacial changes. Within the glaciological part of PROSA, the spatial and temporal variability of these processes is investigated by a multi-method approach with a focus on the glacier tongue of Gepatschferner. Given the topographic conditions of this glacier, with a wide accumulation area on a plateau and a narrow outlet valley, the ice flow dynamics at the glacier tongue are expected to be high along with an expected high mass loss and strong retreat rates due to the low altitude of the glacier terminus. The motion of the glacier tongue and, on top of that, the long-term monitoring of glacier surface velocities provide valuable important data basis and is given in Paper I (Stocker-Waldhuber et al., 2019) in this thesis.

Investigations on the subglacial sediment thicknesses and changes therein using vibroseismic soundings on Alpine glaciers is new (Eisen et al., 2010; Polom et al., 2014). Here, the question arises if subglacial sediment layers can be detected, their thicknesses resolved and changes therein determined by multiple surveys. And besides the magnitude, what are the causes and effects of changes in thickness of subglacial sediment layers and do they contribute to increasing glacier retreat rates, as shown on the example of the development of funnel-shaped surface depressions in Paper II (Stocker-Waldhuber et al., 2017).

These investigations aim to determine the magnitudes of the mass exchange and attempt to close the balances of ice, water and sediments through the tongue of Gepatschferner, given in Paper III (Stocker-Waldhuber and Kuhn, 2019). Additional results, especially from the glaciological investigations in PROSA, are given in

Chapter 4 as complementary information to the three publications.

The investigations in this framework provide fundamental insights on the magnitudes of mass exchanges of glacial processes, especially on the example of the upper Kaunertal and the Gepatschferner. These results will form the basis for further investigations on open questions like the sediment transport from the glacier plateau to the glacier tongue. And, given the great importance of long-term monitoring as basic data, the investigations on ice flow velocities and glacier mass balances will be continued.

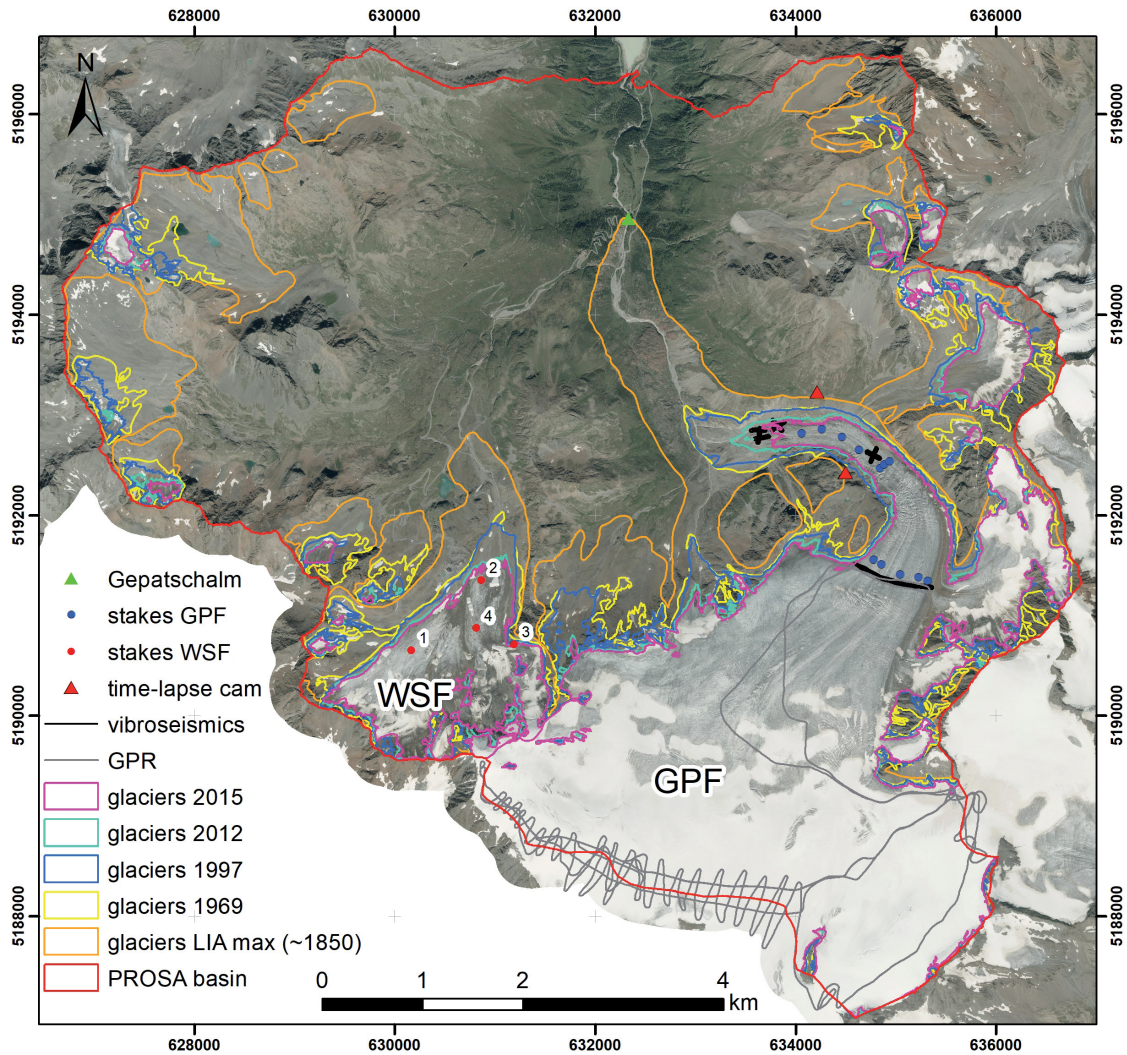


Figure 1.1.: Overview of the glacier area since LIA maximum within the PROSA catchment, the stake positions at WSF (Weißseeferner) and GPF (Gepatschferner, cf. Fig. 4.1), GPR (ground penetrating radar) and vibroseismic profiles and the position of automatic time-lapse cameras. Background: Orthophoto 2015, data source: Land Tirol – data.tirol.gv.at

2. Methods and Basic Data

For the purposes of this thesis, different direct and indirect glaciological and geodetic methods came into operation. In the following chapter these methods and basic data are summarized. Detailed information about the methods, uncertainties and accuracies are given in the publications (cf. Chap. 3 and Appx. A – C).

2.1. Glacier Mass Balance

Different methods come into operation for measurements of glacier mass balances. Basically, a differentiation is made between the surface mass balance as a relative elevation change due to accumulation or ablation, and the total mass balance of the glacier, which results in an absolute elevation change of the surface. For a comparison of the results between the surface mass balance and the total mass balance of a glacier, additional processes, which contribute to the absolute elevation change of the glacier surface, have to be taken into account. For instance, the ice dynamics as submergence and emergence flow, as well as convergence and divergence, result in elevation changes of the glacier surface. Basal processes also lead to an elevation change of the surface, such as basal melt, changes in the thickness of subglacial sediments and bedrock erosion. Additionally, on the surface, the densification of snow and its metamorphosis to firn and ice as a process of subsidence result in an elevation change.

The time frame is set by the availability of the basic data, such as DEMs (digital elevation models) from ALS (airborne laser scan). In terms of long-term monitoring, especially when the direct glaciological method is used, the time frame is set by the glaciological year with fixed dates. The definition of the glaciological or hydrological year varies by nations, for example, from 1 November of one year to 31 October of the subsequent year in Germany, to 1 October to 30 September in Switzerland and, so far, also in Austria. Within the current version of ÖNORM B 2400: 20160301, the hydrological year was set to 1 November to 31 October. However, within the framework of this thesis and the associated publications, the time frame of the glaciological year and also the hydrological year, if written, is defined as the period between 1 October of one year and 30 September of the subsequent year, in particular to avoid changes within long-term monitoring. Additionally, a distinction is made between the seven months of winter mass balance as the accumulation until 30th of April and the remaining five months of ablation as the summer mass balance of the

glacier surface.

The direct glaciological method (Hoinkes, 1970; Cuffey and Paterson, 2010) is used for determining glacier surface mass balances and has a long glaciological tradition. For example, on Hintereisferner, where the direct glaciological investigations started in 1953, or at the neighbouring Kesselwandferner in 1965. Ablation and accumulation are measured at ablation stakes, by snow depth soundings and at snow pits. The determination of the water equivalent (*w.e.*), which is needed for balancing, is done by a density-dependent conversion of snow depths to (*w.e.*) and ice melt to (*w.e.*). An integration over the glacier area results in the specific surface mass balance (b [*mm*, *cm* or *m w.e.*]) as a mean glacier-wide value, as well as the net mass balance (B [$m^3 w.e.$]) as water equivalent of the volume change at the glacier surface. Other important characteristic values of the surface mass balance determined by the direct glaciological method are the ELA (equilibrium line altitude) and the AAR (accumulation area ratio).

The total mass balance of the glacier is determined on the basis of geodetic methods by measurements of the surface altitude and elevation changes, which are then converted to mass changes via the ice, firn and snow densities. These methods range from in situ observation of altitudes with theodolite and tachymeter via measurements with differential global position system (DGPS) and remote-sensing techniques like photogrammetry, terrestrial and airborne laser scans (TLS and ALS), to satellite-based remote sensing.

2.2. Ice Flow Velocities

Flow velocities at the glacier surface are calculated from geodetic data by referencing the data and a time-dependent displacement from repeated measurements. Apart from modern satellite-based methods like DInSAR (Differential Interferometric System Aperture Radar), measurements with DGPS and earlier data from theodolite and tachymeter were applied within the framework of this thesis. The positions of ablation and accumulation stakes, like on Kesselwandferner, or stones on Hintereisferner, are measured and their motion is calculated from the displacement. The stones on Hintereisferner are arranged within cross profiles along the glacier width. In the course of the measurements, the stakes and stones are reinstalled at their starting points. Due to the elevation change of the surface between the readings, the starting point is the projected position to the xy-plane. This means that the velocity is given as the horizontal displacement. The effective flow path would be raised by the vertical contribution due to the surface slope for measurements at stakes and at stones and additionally the vertical effect of surface ablation (cf. Fig. 2 by Schneider (1970) in Appx. A, Stocker-Waldhuber et al. (2019)).

2.3. Glacier Thickness and Subglacial Sediments

The thickness of snow, firn and ice, as well as the thickness of subglacial sediments is measured with various geophysical methods. Within the work of this thesis, vibroseismic soundings and GPR (ground penetrating radar) came into operation. The GPR System GSSI Sir 4000 with the 3200 MLF (16 – 80 MHz ,) antenna was used (GSSI, 2015a,b). Former investigations were done with the digital scopemeter Fluke 105B (Span et al., 2005; Fischer et al., 2007).

Investigations of snow, firn and ice with GPR are based on the propagation speed of an electromagnetic wave, which depends on the material specific electromagnetic properties and also on its wavelength or frequency. The GPR signal is recorded in relation to the travel time. For measurements of snow and ice a dielectric constant, which represents the ratio of permittivity of the material to the permittivity in vacuum, of 3 is recommended (GSSI, 2015a). The higher this material-specific constant, the slower the propagation velocity of the GPR signal within the material. This constant is needed for the time-to-depth conversion of the records and results in typical values of the velocity of around 0.168 m/ns for ice (e.g. Glen and Paren, 1975; Robin, 1975; Kovacs et al., 1995; Span et al., 2005). The frequency of the signal varies by antenna length. The decision on the antenna length is based - with some limitations - on the investigated material, the expected thickness and the required resolution. The penetration depth and the vertical resolution both depend on the frequency, but with different signs. The higher the frequencies, the higher the resolution, but with decreasing penetration depths. So the decision on the antenna length is always a compromise of these two. Additionally, other parameters like temperature and liquid water content also strongly affect signal velocity and penetration depth. In contrast to ice, the permittivity of liquid water is high and leads to severe signal weakening, especially at high frequencies (Span et al., 2005). At low temperatures, the liquid water content of the glacier ice, firn, and especially the snow pack, is low and thus raises the feasibility of radar measurements. So the best conditions for these measurements are during the high and late winter season until a mostly rapid increase of liquid water within the snowpack. For thickness measurements of the snow cover, firn layers and the transition line from snow or firn to ice, often high central frequencies from 400 – 900 MHz come into operation (Helfricht et al., 2014). But with these frequencies, the penetration depth is in the order of magnitude of a few metres to decametres, depending on temperature and liquid water content. Central frequencies below 80 MHz (GSSI 3200 MLF) were used for measurements of the glacier ice when the thicknesses was expected to be greater than 20 m . Former investigations on the glaciers treated in this thesis applied central frequencies of 4 and 7.5 MHz (Span et al., 2005; Fischer et al., 2007).

Vibroseismic soundings are used for glaciological investigations mainly at the great ice shelves and on Antarctic glaciers (Eisen et al., 2010; Hofstede et al., 2013; Kristoffersen et al., 2014). With the invention of the signal source ELVIS (Electrodynamic Vibration System, <http://www.geosym.de/>), which is small enough for manual movement, a new method became feasible for measurements on Alpine glaciers. First investigations on an Alpine glacier were performed on Colle Gnifetti (Diez et al., 2013; Polom et al., 2014). Within the joint project PROSA, repeated vibroseismic soundings were taken for investigations of the thickness of ice and the thickness of subglacial sediments at the tongue of Gepatschferner. A snow streamer with 72 geophones at regular intervals on a total length of 144 *m* was especially developed and the ELVIS source was adapted for these investigations. The vibrator source emits a 10 seconds sweep from 30 – 240 *Hz*. Analyses of refraction and reflection seismology give information on the thickness of ice and sediments as well as on the shear wave velocity and material properties, structure and layering. As this method is new for Alpine glaciers, the investigations on Gepatschferner aimed primarily on detecting subglacial sediment layers, analysing their thickness and changes therein from repeated measurement. The investigations on Gepatschferner consequently contributed to the further development of the signal and recording systems.

2.4. DEMs and DoDs

Raster-based data and their analyses play an important role in modern glaciology. They allow positioning various parameters for spatial viewing and regionalization, which facilitates and even improves process monitoring. An important basis for these applications are DEMs (digital elevation models). Their resolution and accuracies have substantially improved in recent decades. This is due to the development of methods from early photogrammetric methods to LIDAR (light detection and ranging) data acquisition like ALS and TLS (airborne/terrestrial laser scanning). The generation of DEMs on glacier surfaces has specific problems because of the physical properties of snow, ice and water and consequently depends on the recording time within the annual, seasonal and daily cycle. Large snow-covered regions with less structured surfaces complicate the determination of the surface elevation. Another problem, especially for terrestrial scans, is a low angle of incidence, in particular for high elevations relative to the collection site. Both effects mostly occur in upper glacier regions and accumulation areas. Liquid water severely weakens the laser pulse due to absorption. This mainly concerns the ablation areas and depends on the season and daytime. As a result, data gaps are more frequent on glacier surfaces due to the lower point densities, especially within the ablation areas. Filling the gaps leads to higher uncertainties at glacier areas compared to the surrounding

topography and depends on the size of the gap and the interpolation methods. However, DEMs provide an important data basis for the location of the glacier boundaries, the glacier extent and area-altitude distribution. Based on multiple DEMs, glacier changes in area, elevation and volume are calculated with DoDs (DEMs of difference). Consistent coordinate systems and grid sizes of the initial DEMs are crucial requirements for calculating DoDs (Abermann et al., 2010; Wheaton et al., 2010; Bollmann et al., 2011). By calculating DoDs, the level of detection (LoD) gains special significance. It is calculated from the error propagation and can be seen as a threshold for the distinction between errors and actual measurable changes between the initial DEMs. The attainable precision has changed from the decametre to the centimetre scale in the course of development from early photogrammetric methods to modern laser-based techniques. Examples of recent LiDAR-based calculations of morphodynamic processes, within the PROSA project, are those at the proglacial moraine of Gepatschferner between 2013 and 2014 with a LoD of 0.2 *m* (Dusik et al., 2019) and 0.12 *m* for DoDs of the root zone of the Gepatsch reservoir between 2012 and 2015 (Hilger, 2017).

For the Austrian glaciers, four glacier inventories from the LIA (Little Ice Age) maximum to the present provide information about the glacier extent and the area-altitude distribution from DEMs. The first Austrian glacier inventory (GI 1) dates to the year 1969, from aerial photography with a DEM grid size of 5x5 *m* (Patzelt, 1980; Groß, 1987). This inventory is the only one where nearly all Austrian glacier regions were recorded within one specific year. The second glacier inventory (GI 2) mainly covers the period from 1997 to 1998, some smaller glacier regions to 2002, with a resolution of 5x5 *m* (Lambrecht and Kuhn, 2007; Kuhn et al., 2012). A glacier inventory for the LIA maximum (GI LIA), based on historic cartography, was published together with the third glacier inventory (GI 3) from 2005-2012, on the basis of ALS Data and a resolution of 1x1 *m* (Fischer et al., 2015). DEMs from historic cartography from 1922 and 1971 on Gepatschferner, as well as changes in length, area and volume, were investigated by Hartl (2010). Within the PROSA project, multiple ALS surveys were conducted as data basis for the generation of DEMs. Details on the flight dates and available DEMs are given by Hilger (2017). For the glaciological investigations, mainly DEMs from July and September 2012 and July and September 2015 were used.

2.5. Hydrological Model OEZ

The conceptual hydrological model OEZ was developed during the 1980s at the Department of Atmospheric and Cryospheric Sciences (formerly: Institute of Meteorology and Geophysics) at the University of Innsbruck, and further extended

and improved (Kuhn et al., 1982; Kuhn and Batlogg, 1998, 1999; Kuhn, 2000, 2003). The most recent publication provides modelling results for 86 glacierized basins in North and South Tyrol (Kuhn et al., 2016). The model is based on the hydrological balance of precipitation (P), runoff (R), evaporation (E) and storage (S):

$$P - R - E - S = 0 \quad (2.1)$$

OEZ reproduces the annual cycle of the balance within the glaciological year (October to September of the following year) on a monthly basis and a resolution of 100 *m* elevation bands of a specific catchment. Measured runoff, temperature and precipitation are the basic input data to the model. Additional important input data are the area-altitude distributions of the basin, forest and glacier area and the geodetic glacier mass balances from DoDs. Model verification is based on the measured catchment runoff at a gauging station. One criterion for modelling the hydrological balance is a maximum allowable tolerance of ± 20 *mm* between the modelled and measured specific monthly runoff. The liquid water storage is used for the compensation of the monthly and annual balances. The differentiation between rain and snow and the calculation of the snow and ice melt is done with the degree-day method, a method which is often used in glacier mass balance modelling (e.g. Braithwaite, 1984; Jóhannesson et al., 1995). Additionally, the adjustment of the modelled glacier mass balance is controlled by the redistribution of snow from the surrounding topography to the glacier area. The evaporation is parametrized in relation to forest, glacier and glacier free areas.

The calculated runoff differentiates between runoff from snow melt, from glacierized and unglacierized areas, from ice melt, runoff due to rain and runoff from the liquid water storage. The Pardé coefficient describes the runoff characteristic of the catchment as the ratio between the mean monthly runoff to the mean annual runoff. The greater the Pardé coefficient, the greater the annual cycle of the catchment runoff, which is typical for highly glacier-covered basins and characteristic for a glacial regime. Climate change, in terms of changes in temperature and precipitation, can be applied in a further step to OEZ, for example, on the basis of the IPCC climate scenarios (Stocker et al., 2013). This allows modelling the impact of these changes on the catchment runoff and the specific changes of the glacier meltwater supply, which is the negative part of the glacier mass balance. Additionally, modelling future scenarios allows for changes in the glacier coverage as a consequence of changes in temperature and precipitation or even for modelling without glaciers as an extreme scenario. These model results provide important information for estimating future runoff development, which is, for instance, useful for water and hydropower management (Kuhn et al., 2007).

3. Publications

The three glaciological publications in the Appendix A to C are the basis of this thesis, from long-term monitoring of glacier surface velocities to a case study of the development of a funnel-shaped surface depression, to an approach to close the balances of ice, water and sediment fluxes through the glacier tongue.

Measured glacier surface velocities provide an important data basis needed for various modellings within the glacier and climate system, for example, from the illustration and modelling of ice dynamics and mass balances to the contribution of glaciers to sea level rise, and from modelling early glacier extent and state to future scenarios. Results of these modellings in turn offer conclusions on the impact on the human-environment system interactions and developments therein. Data sets on glacier surface velocities on Alpine glaciers are rare, especially for long time series, as in Paper 1:

3.1. Paper I: Long-term Records of Glacier Surface Velocities in the Ötztal Alps (Austria)

On Hintereisferner in the Ötztal Alps (Austria), horizontal flow velocities have been measured since 1895 at stone lines, in the form of cross-profiles along the glacier width, and later also at ablation stakes. With more than 100 years, this long-term data set is among the longest series worldwide. On neighbouring Kesselwandferner, annual flow velocities have been measured since 1965 at ablation and accumulation stakes along the centre flow line of the glacier. On Kesselwandferner, vertical motion is measured in addition to the horizontal motion. The determination of 3D velocities gives valuable information on the glacier state and the glacier-specific response time to a climate signal. Furthermore, on the two neighbouring glaciers, Taschachferner and Gepatschferner, surface velocities have been measured since 2009 at ablation stakes. Multiple measurements within the ablation season on these two glaciers provide information on subseasonal variation of the surface velocity. The seasonal fluctuation is directly caused by the weather conditions within one year and offers conclusions on the annual, winter and summer mass balance of the glacier. Strong negative summer mass balances, for example, also lead to a strong increase of the seasonal flow velocity. The glacier state in general is reflected by the interannual development of the glacier motion and depends on the glacier-specific response time

to a disturbance or to changes within the climate signal. The response time mainly depends on the specific topographic conditions of a glacier and in particular the size, ice thickness and slope angle.

This paper was published in ESSD (Earth System Science Data) as a data paper. The paper focuses on the long-term data sets of the flow velocities on well investigated Alpine glaciers and gives a short comparison with glacier mass balance measurements. Velocity data provide additional information to characteristic values of the mass balance measured in situ, like the specific balance, the AAR (accumulation area ratio) or the ELA (equilibrium line altitude). For example, when ELA rises above the summits, which happened more often in recent decades, additional information, such as variations of the transient snow line or information from flow velocities, is needed for interpretations on the glacier state.

3.2. Paper II: Funnel-shaped Surface Depression – Indicator or Accelerant of Rapid Glacier Disintegration? A Case Study in the Tyrolean Alps

The effect of the glacier state becomes evident at the glacier tongue and front. Measurements of the glacier front variation have a long tradition (e.g. Fritzscher, 1898) and thus include retreating and advancing periods. The basic prerequisite for a glacier advance is the propagation of a relevant climate signal to the terminus with respect to the glacier-specific response time and the strength of the signal. The longer the response time of a glacier, the stronger the climate signal required for an advance of the terminus. This can lead to totally different fluctuations, like advance and retreat at two adjacent glaciers during the same time (Kuhn et al., 1985). Advancing periods since LIA maximum, as happened during the 1920s and 1980s, contrast with strong retreating rates of recent decades, which are also accompanied by a disintegration of glacier tongues. Gepatschferner, for instance, has retreated by -675 m since 2009, when detailed investigations were started at the glacier tongue (Sec. 4.2, Fig. 4.3). At that time a shallow depression became visible at the lowermost part of the glacier tongue which drew the attention of the investigations to this feature until the whole area became ice free. The development raised the question on the causes of this process and whether it was a consequence and/or an accelerant of the increasing retreat rates of the terminus.

Different methods came into operation for the investigation of the development of the funnel-shaped surface depression. The direct glaciological method was used

to determine the surface ablation at stakes. The motion of the stakes and their elevation changes were calculated from DGPS measurements. DoDs from multiple high-resolution ALS data returned the volumetric changes of the depression. In addition, GPR and the new method of vibroseismic soundings came into operation for determining the ice thickness and the thickness of subglacial sediments.

It turned out that the development of the depression was directly connected to the main subglacial meltwater channel and the glacier retreat as a consequence of negative mass balances of the glacier. On the one hand, changes within the subglacial sediments or increasing basal melt due to thermal energy within a meltwater channel can cause the subsidence of the ice above. On the other hand, this process becomes only visible as a depression at the surface if the ice mass gain from the glacier dynamics does not compensate the mass loss. In the case of Gepatschferner, the flow velocities at the tongue are decreasing, even to almost nil at the terminus, as a consequence of the negative mass balances and thus a lack of mass gain to the area of the depression. Another reason was an extreme precipitation event in July 2012, which caused a rapid evacuation of the subglacial sediment layers, which in turn caused an acceleration of the subsidence process. In the further course, the breakthrough of the glacier surface and the ongoing exposure of the bare ground at the centre of the depression led to a rapid retreat of the terminus. So, such a depression is both indicator and accelerant of rapid glacier disintegration. Similar structures and processes were observed and compared in this study on Mittelbergferner, Sulztalferner and Hintereisferner. Current examples on other Alpine glaciers in Austria, like on the glaciers Pasterze (Kellerer-Pirklbauer and Kulmer, 2018), Schlatenkees and Grünaufener, are part of a growing number of circular and funnel-shaped depressions on glacier tongues as a strong sign of increasing glacier disintegration (Figs. 3.1 and 3.2).



Figure 3.1.: Formation of funnel-shaped surface depressions at the glacier tongue of Schlatenkees (Hohe Tauern). Please note the different photo locations and orientations. The viewing direction changes from south-east in the upper photo, taken in August 2010, to north-east in the lower photo taken in August 2017.

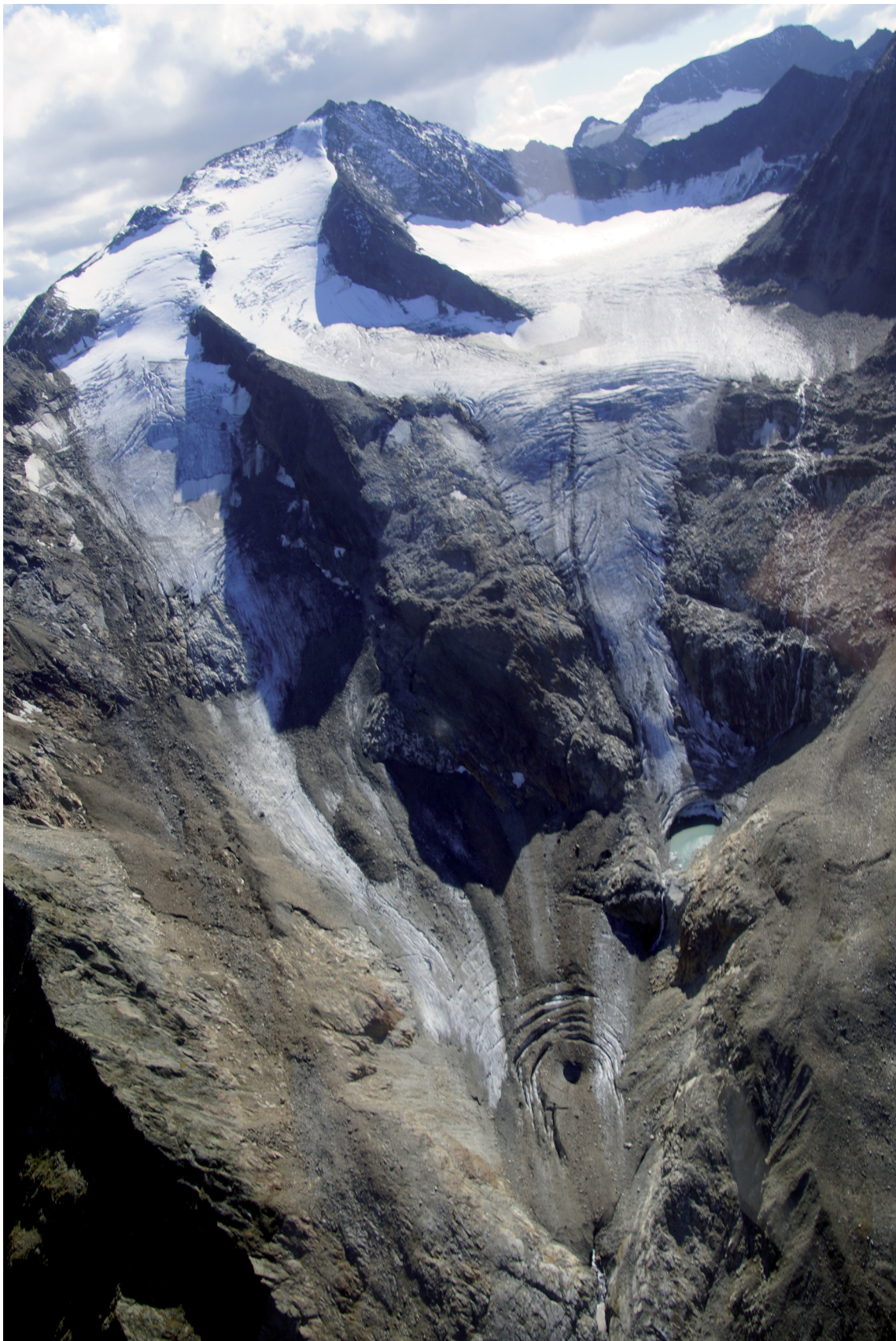


Figure 3.2.: Grünaufener (Stubai Alps) in September 2018 (Photo: A. Fischer).

3.3. Paper III: Closing the Balances of Ice, Water and Sediment Fluxes Through the Terminus of Gepatschferner

The third article is published as a chapter in the book of Heckmann and Morche (2019) and is set up as a conceptual approach to closing the balances of ice, water and sediments. Beside the theoretical approach, the magnitudes of the mass exchange through the tongue of Gepatschferner are determined and estimated with a synopsis of different methods.

At the root zone of the glacier tongue, at an altitude of 2875 *m a.s.l.*, the mass flux of ice (Q_i) through the cross section and the transport of sediments from the glacier above (M_{top}) represent the mass gain to the terminus. These processes have a positive effect on the surface elevation of the glacier tongue. Negative elevation changes are caused by ablation as surface and basal melt ($a_s + a_b$) and bedrock erosion and exaration ($\partial h_r / \partial t$). Negative as well as positive effects on the surface elevation come from the advection of ice thickness ($u * \partial H_i / \partial x$), convergence and divergence of the ice flow ($H_i * \partial u / \partial x$) and from changes within the thickness of subglacial sediments ($\partial H_{sed} / \partial t$). Slope processes bring a lateral mass transport (M_{lat}) from surrounding slopes like Schwarze Wand (*SW*) or moraines to the glacier. The terminus is the interface to the glacier forefield with the deposition of moraine material and the bedload transport (M_{bed}) and the transport of suspended solids (M_{sus}) within the glacial stream. Within the concept of a sediment cascade, the glacier is both a sediment source and an intermediate stage for the transport of material.

On the one hand, storage of water in the form of glacier ice (Jansson et al., 2003) is expressed through the hydrological balance as a remainder of precipitation, evaporation and runoff (Eq. 2.1). On the other hand, the storage of the ice in the glacier tongue is the sum of ice flux to the tongue and the surface and basal melt at the tongue. The connection to the sediment balance is based on the elevation change of the glacier surface. This means that the absolute elevation of the surface, which is determined from ALS surveys, is the sum of the elevation of the bedrock topography, the thickness of subglacial sediments and the thickness of ice. The temporal change is calculated with DoDs.

On the example of Gepatschferner, the mean elevation change of the surface of the glacier tongue between 04.07.2012 and 22.08.2015 was -10.8 m . The directly observed ablation at the surface within the same period amounted to about 15.6 m , which was partially compensated by the mass flux to the tongue with 6.2 m as the mean gain allocated to the area of the tongue.

4. Additional Results

Within the glaciological subproject of the joint project PROSA, the glacial changes within the catchment of the upper Fagge river were investigated, down to the root zone of the Gepatsch reservoir. This chapter summarizes the most important changes and complements the three papers in this thesis. The results are separated into the surface mass loss of the glacier tongue of Gepatschferner $< 2900\text{ m}$ and ice melt on Weißseeferner since 2012, changes in length, area, elevation and volume since LIA maximum and results from the hydrological modelling using OEZ.

4.1. Surface Mass Balance Gepatschferner Below 2900 m

Table 4.1.: Characteristic annual values of the surface mass balance at the tongue of Gepatschferner $< 2900\text{ m}$ (cf. Fig. 4.1); A: Area; B: net mass balance; b: specific mass balance.

	2012	2013	2014	2015	2016	2017	2018
$A\text{ [km}^2\text{]}$	1.459	1.479	1.369	1.336	1.336	1.336	1.336
$B\text{ [10}^3\text{ m}^2\text{]}$	-6263.6	-5056.3	-3897.5	-5942.5	-4380.0	-5648.6	-6306.7
$b\text{ [mm]}$	-4292	-3418	-2847	-4448	-3278	-4228	-4720

The measured ice melt at the stake positions at the tongue of Gepatschferner represents the negative part of the surface mass balance. As the glacier tongue is part of the total ablation area, the negative part of the balance equals the surface mass balance, which means accumulation is zero. Snow accumulation that may occur within crevasses contributes negligibly, some orders of magnitudes less than the ice mass balance. In terms of the surface mass balance, the ice mass flux to the tongue need not be considered, in contrast to geodetic investigations of the total mass balance, which were done for the third paper in this thesis (Sec. 3.3, Appx. C, Stocker-Waldhuber and Kuhn (2019)).

The glacier tongue below 2900 m covers an area of about 1.4 km^2 . From 2012 to 2018, mass loss at the glacier surface was between 3.9 and $6.3 \cdot 10^6\text{ m}^3$ per year, which corresponds to a specific mass balance of -2847 and -4720 mm w.e. (Tab. 4.1). Figure 4.1 shows the annual spatial distribution of the surface mass balance

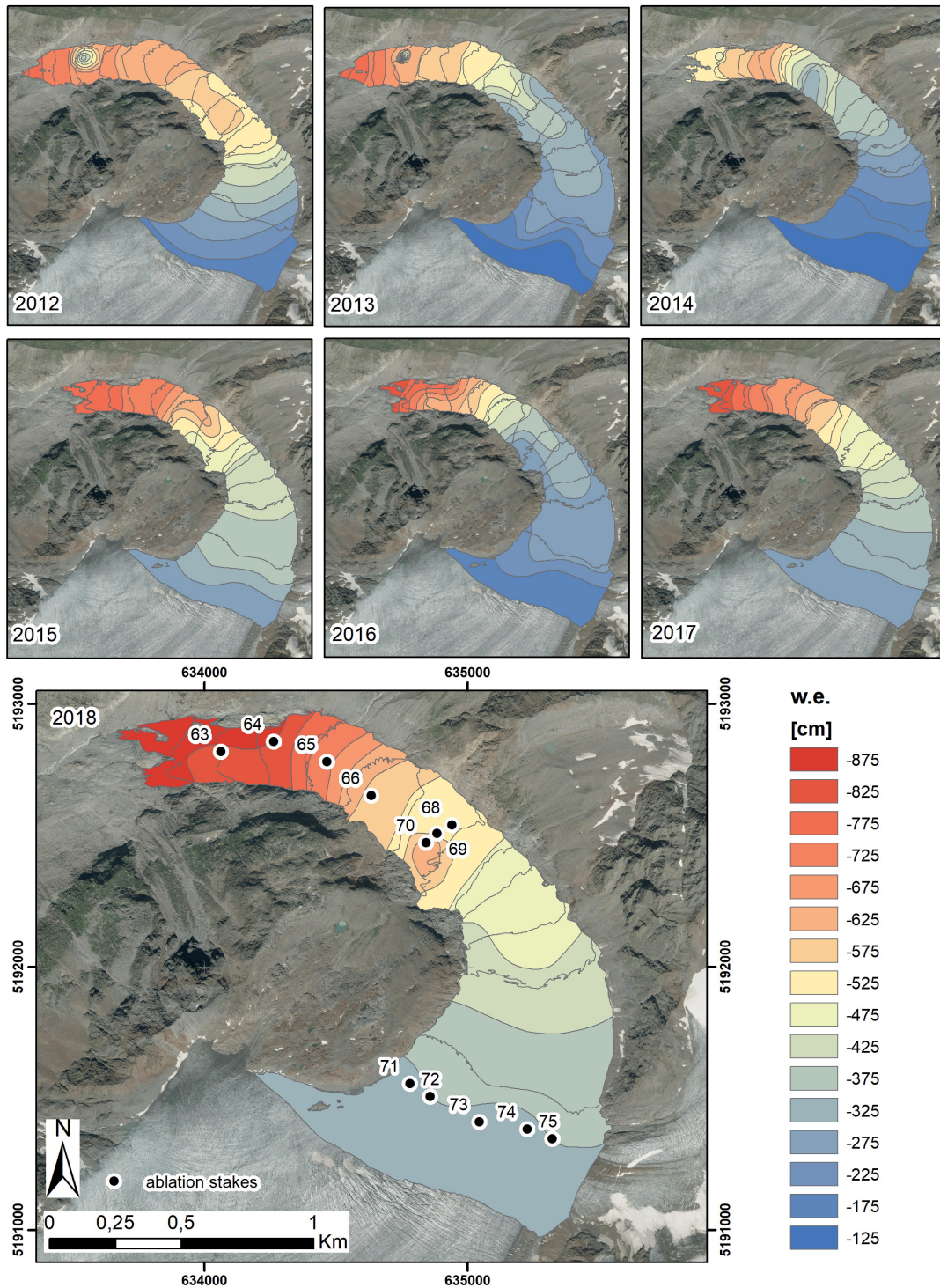


Figure 4.1.: Distribution of the annual surface mass balance [cm w.e.] of the GPF tongue < 2900 m (cf. Tab. 4.1), the positions of the stakes and their numbering. Background: Orthophoto 2015, data source: Land Tirol – data.tirol.gv.at

$< 2900\text{ m}$ from 2012 to 2018. The annual loss in these years ranges from -875 to -125 cm w.e. At the ablation stakes, the measured ice melt starts from a minimum of about one metre at the highest stakes within the upper cross profile (stake 70–75) and reaches maximum annual values of -9.5 m of ice at the lowermost stake 63 in 2018 (Tab. 4.2). Stake positions 60 and 61 became ice-free in 2015. The region around stake 62 became ice-free in 2017 after the emergence of a funnel-shaped surface depression (Sec. 3.2, Appx. B, Stocker-Waldhuber et al. (2017)). Within the cross profile (67–70), below the icefall zone, stake position 67 had to be abandoned in 2014 due to increasing rockfall activity from the Schwarze Wand (Vehling et al., 2017, 2019). Mean annual ablation values at the glacier tongue ranged from -5.1 to -7.3 m of ice. The determination of the mean values includes the mean values from the stake cross profiles 67–70 and 71–75. Thus the mean values relate to the zone along the centre flow line of the glacier tongue. In contrast to the melt on Gepatschferner, ablation at four stake positions on Weißseeferner was only -1.6 to -3.6 m of ice (Tab. 4.2) due to the different, mainly northern, exposition of Weißseeferner and the higher altitude of the stakes. The temporal development of the ablation is a direct consequence of the weather conditions during the ablation season (Tab. 4.3). In addition to the beginning of the ablation season, the end of the ablation season due to snowfall is of crucial importance, which becomes evident when comparing the years 2017 and 2018 (Fig. 4.2).

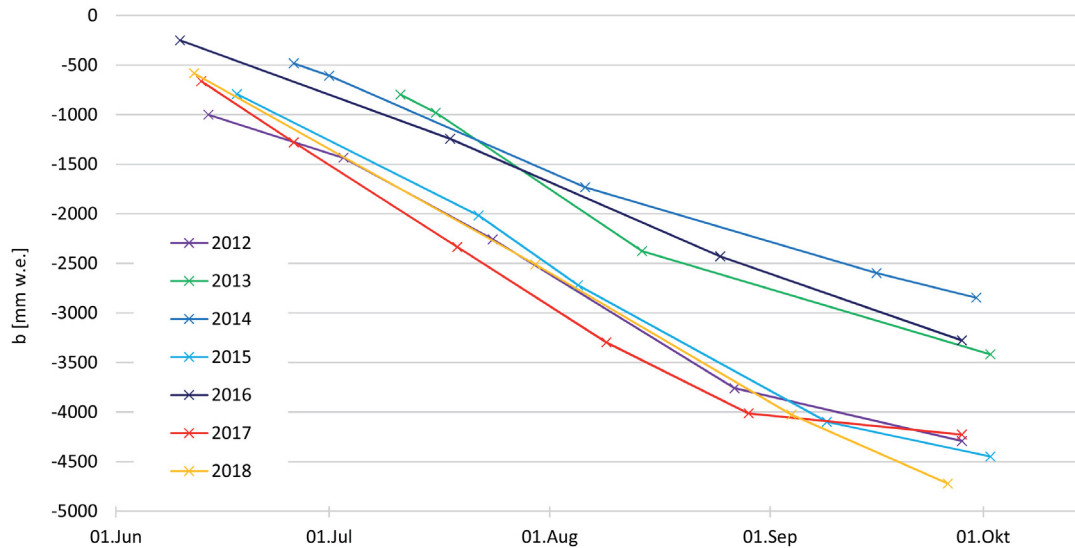


Figure 4.2.: Development of the specific surface mass balance (b) of the glacier tongue of Gepatschferner $< 2900\text{ m}$ during the summer months, from 2012 to 2018 calculated from the direct mass balance measurements (cf. Tab. 4.3).

Table 4.2.: Annual ablation [$m\ ice/a$] at the stakes on Weißsee- and Gepatschferner.
 Weißseeferner: stakes 1–4; Gepatschferner: stakes 60–75 (Position of the stakes: cf. Figs. 1.1 and 4.1).

stake nr.	2012	2013	2014	2015	2016	2017	2018
1	-2.33	-1.85	-1.85	-2.59	-1.05	-3.46	-3.94
2	-3.25	-3.13	-1.94	-3.13	-2.02	-3.93	-3.54
3	-2.47	-1.92	(-0,39)	-1.68	-1.25	-2.34	-1.81
4	-3.41	-2.27	-1.37	-3.99	-2.02	-4.02	-4.90
mean WSF	-2.87	-2.29	-1.72	-2.85	-1.59	-3.44	-3.55

stake nr.	2012	2013	2014	2015	2016	2017	2018
60	-8.26	-8.26	-5.90	ice free			
61	-7.95	-7.98	-5.91	ice free			
62	-4.17	-6.96	-6.06	-8.72	-9.10	ice free	
63	-7.33	-6.58	-6.59	-8.51	-7.12	-8.52	-9.20
64	-6.98	-6.45	-6.84	-8.20	-8.39	-7.71	-9.50
65	-7.14	-6.04	-4.84	-7.85	-6.31	-7.26	-8.06
66	-6.56	-5.28	-3.39	-6.16	-5.19	-6.35	-6.54
67	-5.91	-3.73	rockfall Schwarze Wand				
68	-6.24	-4.80	-4.31	-6.86	-4.21	-5.25	-5.85
69	-6.59	-4.85	-4.50	-6.40	-3.96	-5.46	-5.97
70	-5.92	-2.99	-4.73	-5.33	-3.40	-5.95	-8.14
mean 67-70	-6.26	-4.09	-4.51	-6.20	-3.86	-5.55	-6.65
71	-2.87	-2.20	-1.81	-3.68	-2.36	-3.33	-3.54
72	-3.12	-2.78	-1.77	-4.37	-2.83	-3.76	-3.89
73	-2.26	-1.31	-1.14	-3.42	-2.13	-3.17	-3.44
74	-2.35	-1.62	-1.40	-3.25	-1.77	-3.33	-3.51
75	-2.20	-2.72	-1.61	-4.20	-2.57	-3.65	-4.05
mean 71-75	-2.56	-2.13	-1.55	-3.78	-2.33	-3.45	-3.69
mean GPF	-6.36	-5.97	-5.07	-7.06	-6.04	-6.47	-7.27

Table 4.3.: Annual percentage distribution (100% at the end of each measurement season) of the specific mass balance (b) and intermediate values at each measurement date at the glacier tongue of Gepatschferner $< 2900\text{ m}$ (cf. Fig. 4.2); B : net mass balance.

glaciological year	date	b [%]	b [$mm\text{ w.e.}$]	B [$m^3\text{ w.e.}$]
2011/2012	14.06.2012	23	-1001	-1461
	03.07.2012	33	-1435	-2094
	24.07.2012	53	-2257	-3294
	27.08.2012	88	-3759	-5486
	28.09.2012	100	-4292	-6264
2012/2013	11.07.2013	23	-797	-1179
	16.07.2013	29	-981	-1451
	14.08.2013	69	-2375	-3514
	02.10.2013	100	-3418	-5056
2013/2014	26.06.2014	17	-483	-661
	01.07.2014	21	-608	-832
	06.08.2014	61	-1733	-2372
	16.09.2014	91	-2597	-3556
	30.09.2014	100	-2847	-3898
2014/2015	18.06.2015	18	-792	-1058
	22.07.2015	45	-2017	-2695
	05.08.2015	61	-2721	-3635
	09.09.2015	92	-4099	-5476
	02.10.2015	100	-4448	-5943
2015/2016	10.06.2016	8	-250	-333
	18.07.2016	38	-1243	-1661
	25.08.2016	74	-2430	-3246
	28.09.2016	100	-3278	-4380
2016/2017	13.06.2017	16	-662	-885
	26.06.2017	30	-1279	-1709
	19.07.2017	55	-2335	-3119
	09.08.2017	78	-3297	-4405
	29.08.2017	95	-4013	-5362
	28.09.2017	100	-4228	-5649
2017/2018	12.06.2018	12	-584	-780
	30.07.2018	53	-2510	-3354
	04.09.2018	85	-4026	-5379
	26.09.2018	100	-4720	-6307

4.2. Glacier Changes in Length, Area and Volume

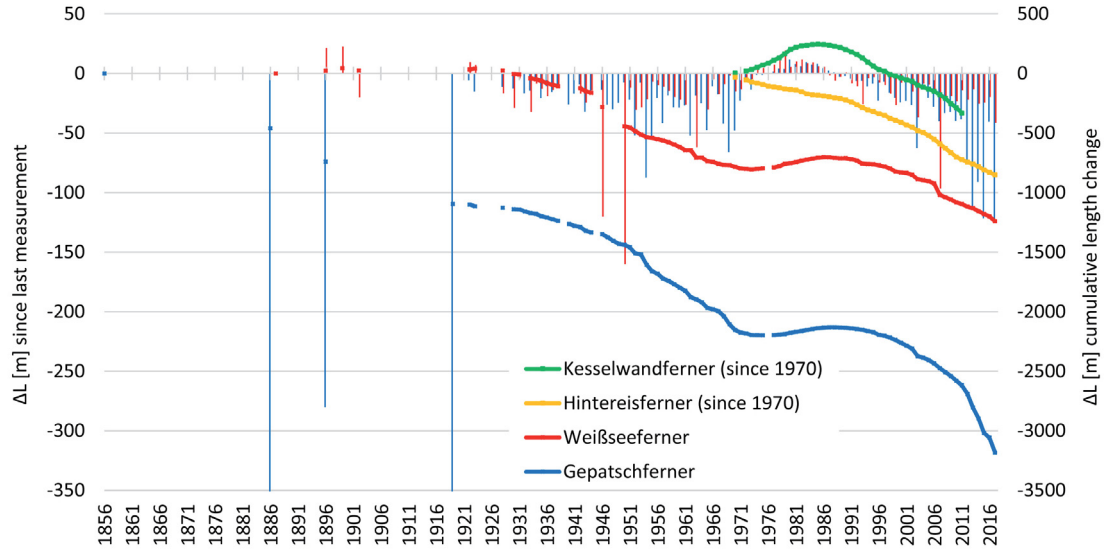


Figure 4.3.: Length change of the glacier termini of Weißseeferner and Gepatschferner, plus Hintereisferner and Kesselwandferner since 1970. The bars (Gepatschferner and Weißseeferner) refer to the left ordinate axis and result from the period since the last measurement. The lines refer to the right ordinate axis and show the cumulative length change since the beginning of the measurements on Gepatschferner and Weißseeferner and since 1970 on Hintereisferner and Kesselwandferner. Data source: Austrian Alpine Club (published annually: e.g. Lieb and Kellerer-Pirklbauer, 2018)

The first glacier marks for measuring glacier front variations at Weißseeferner were installed in 1887 and those on Gepatschferner as early as 1856 (Fritzs, 1898). This was only one year after Gepatschferner reached the LIA maximum extent in 1855. Subsequent sporadic measurements were taken during the early years, measurements since 1930 were performed almost annually with few exceptions. In total, the glacier front variation from the beginning of measurements until 2017 amounts to -1.2 km on Weißseeferner and -3.2 km at Gepatschferner (Fig. 4.3). Only a few advancing periods interrupted the almost continuous retreat. The best investigated advancing period since LIA maximum was measured during the 1970s and 1980s with $+70\text{ m}$ at Gepatschferner and $+100\text{ m}$ at Weißseeferner. Earlier advances during the 1890s and 1920s were only measured on Weißseeferner. As a consequence of the multiannual time span between the measurements during these early advancing periods, the maximum advances may not have been detected. The retreat rates increased in recent decades, especially on Gepatschferner. Maximum values of more than 100 m per year were among the largest glacier retreat rates in Austria (Lieb and Kellerer-Pirklbauer,

2018). From 2009, when ablation measurements on Gepatschferner started, until 2017, the cumulative length change amounted to -675 m , or -492 m since 2012, the beginning of the PROSA investigations. As a consequence of these retreat rates, the lowermost stakes 60–62 became ice-free (Tab. 4.2).

In addition to the glacier retreat of the terminus, ice melt at the peripheral glacier areas, bare ground within steep glacier slopes, like the north face of the summit Weißseespitze, or solid rocks protruding from the glacier surface, have an important effect on the areal changes (Tab. 4.4). The PROSA basin, which is the catchment of the upper Fagge river down to the root zone of the Gepatsch reservoir, covers an area of about 62 km^2 . At the end of the Little Ice Age, the glaciers covered an area of 34 km^2 or 55% of the catchment area. This ratio decreased to about 30% in 2015. The largest portion was observed on Gepatschferner with 25% of the total area. A ratio of 3.6% of Weißseeferner (2.2 km^2) in 2015 is comparably small. These values, in Table 4.4 referred to as F (fraction), refer to the total PROSA basin area, which is given as 100%. Changes in glacier area in the table refer to each previous glacier extent. In total, the glaciers within the PROSA catchment lost 46% of their area from LIA maximum to 2015.

Mean elevation changes from DoDs, referred to the glacier area, represent the glacier volume changes since 1969 (GI 1) and on Gepatschferner since LIA maximum in 1855 (Tab. 4.5). Within this period the glacier volume of Gepatschferner changed by -0.9 km^3 , with a mean elevation change of -41.5 m . 45% of that occurred at the glacier area below 2900 m . In comparison, all glaciers in the PROSA catchment lost a volume of 0.4 km^3 between 1969 and 2015. During the most recent period 2012–2015, the mean elevation change of all glaciers was -1.4 m , which corresponds to a volume of $-26 * 10^6\text{ m}^3$. 34% of this change comes from the glacier tongue of Gepatschferner below 2900 m , which is only 2.4% of the total PROSA glacier area in 2012. The spatial distribution of the elevation changes from DoDs for each period reveals the influence of the tongue of Gepatschferner for the total investigated area (Fig. 4.4).

Table 4.4.: Glacier areas (A) and changes within the PROSA catchment (cf. Sec. 1.2) from the Little Ice Age (LIA) to 2015; F : ice-covered fractions of the total catchment area (100%) of the respective glacier areas or partial glacier areas (e.g. Gepatschferner $< 2900\text{ m}$).

	<i>year</i>	$A\text{ [km}^2\text{]}$	$\Delta A\text{ [km}^2\text{]}$	$\Delta A\text{ [\%]}$	$F\text{ [\%]}$
PROSA catchment		61.71			100.0
glaciers PROSA	LIA	34.01			55.1
	1969	23.71	-10.30	-30.3	38.4
	1997	21.39	-2.32	-9.8	34.7
	2006	20.36	-1.03	-4.8	33.0
	2009	19.20	-1.17	-5.7	31.1
	2012	19.01	-0.19	-1.0	30.8
	2015	18.41	-0.60	-3.1	29.8
Gepatschferner	LIA	22.07			35.8
	1969	17.75	-4.32	-19.6	28.8
	1997	16.91	-0.84	-4.7	27.4
	2006	16.38	-0.53	-3.1	26.5
	2009	15.73	-0.65	-4.0	25.5
	2012	15.61	-0.12	-0.7	25.3
	2015	15.28	-0.33	-2.1	24.8
Weißseeferner	LIA	4.45			7.2
	1969	2.93	-1.53	-34.3	4.7
	1997	2.74	-0.19	-6.5	4.4
	2006	2.63	-0.10	-3.8	4.3
	2009	2.39	-0.24	-9.3	3.9
	2012	2.34	-0.05	-1.9	3.8
	2015	2.21	-0.13	-5.6	3.6
Gepatschferner $< 2900\text{ m}$	LIA	4.76			7.7
	1969	1.90	-2.86	-60.0	3.1
	1997	1.85	-0.05	-2.8	3.0
	2006	1.59	-0.26	-13.8	2.6
	2012	1.46	-0.13	-8.4	2.4
	2015	1.34	-0.12	-8.4	2.2

Table 4.5.: Elevation and volume changes (Δz , ΔV) of the glaciers in the catchment of PROSA, at Weißseeferner, Gepatschferner and at the Gepatschferner tongue below 2900 m . The percentage of volume change of each region is given in relation to the volume change of all the glaciers in the PROSA catchment (100%) for each period.

	glaciers PROSA			Weißseeferner		
	Δz [m]	ΔV [$10^6 m^3$]	ΔV [%]	Δz [m]	ΔV [$10^6 m^3$]	ΔV [%]
1969-2015	-16.5	-390.89	100	-23.9	-69.91	18
1997-2015	-10.1	-216.49	100	-13.7	-37.42	17
2006-2015	-8.2	-167.38	100	-10.4	-27.42	16
2012-2015	-1.4	-26.23	100	-2.6	-5.97	23

	Gepatschferner			Gepatschferner < 2900 m		
	Δz [m]	ΔV [$10^6 m^3$]	ΔV [%]	Δz [m]	ΔV [$10^6 m^3$]	ΔV [%]
1855-2015	-41.5	-915.82		-84.4	-401.58	
1969-2015	-16.2	-287.88	74	-43.9	-83.43	21
1997-2015	-9.7	-163.55	76	-36.4	-67.36	31
2006-2015	-7.9	-129.47	77	-23.6	-37.54	22
2012-2015	-1.2	-18.89	72	-6.0	-8.80	34

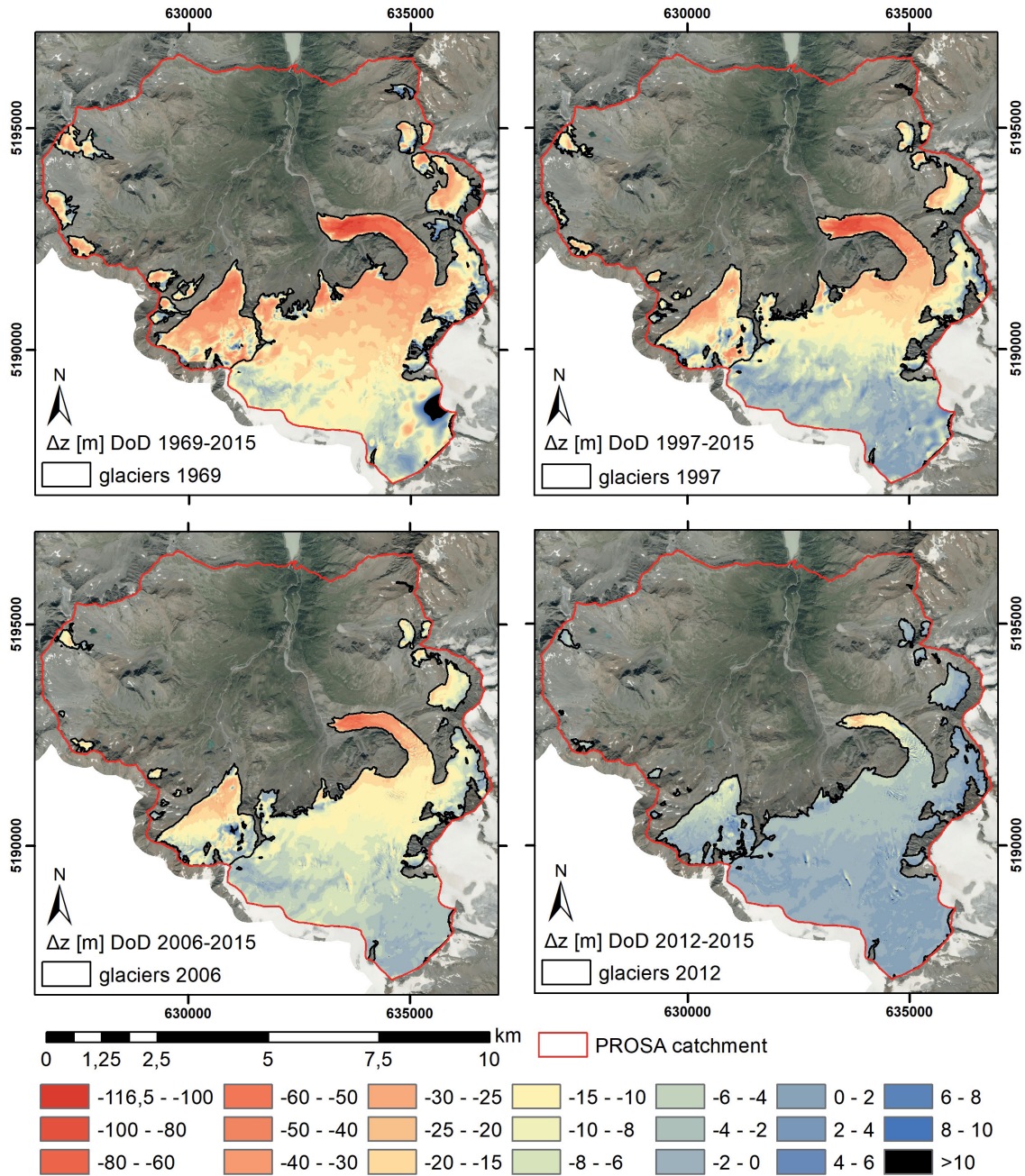


Figure 4.4.: Spatial distribution of the elevation changes at the glaciers within the PROSA catchment from DoDs (cf. Tab. 4.5). Background: Orthophoto 2015, data source: Land Tirol – data.tirol.gv.at.

4.3. Hydrological Modelling With OEZ

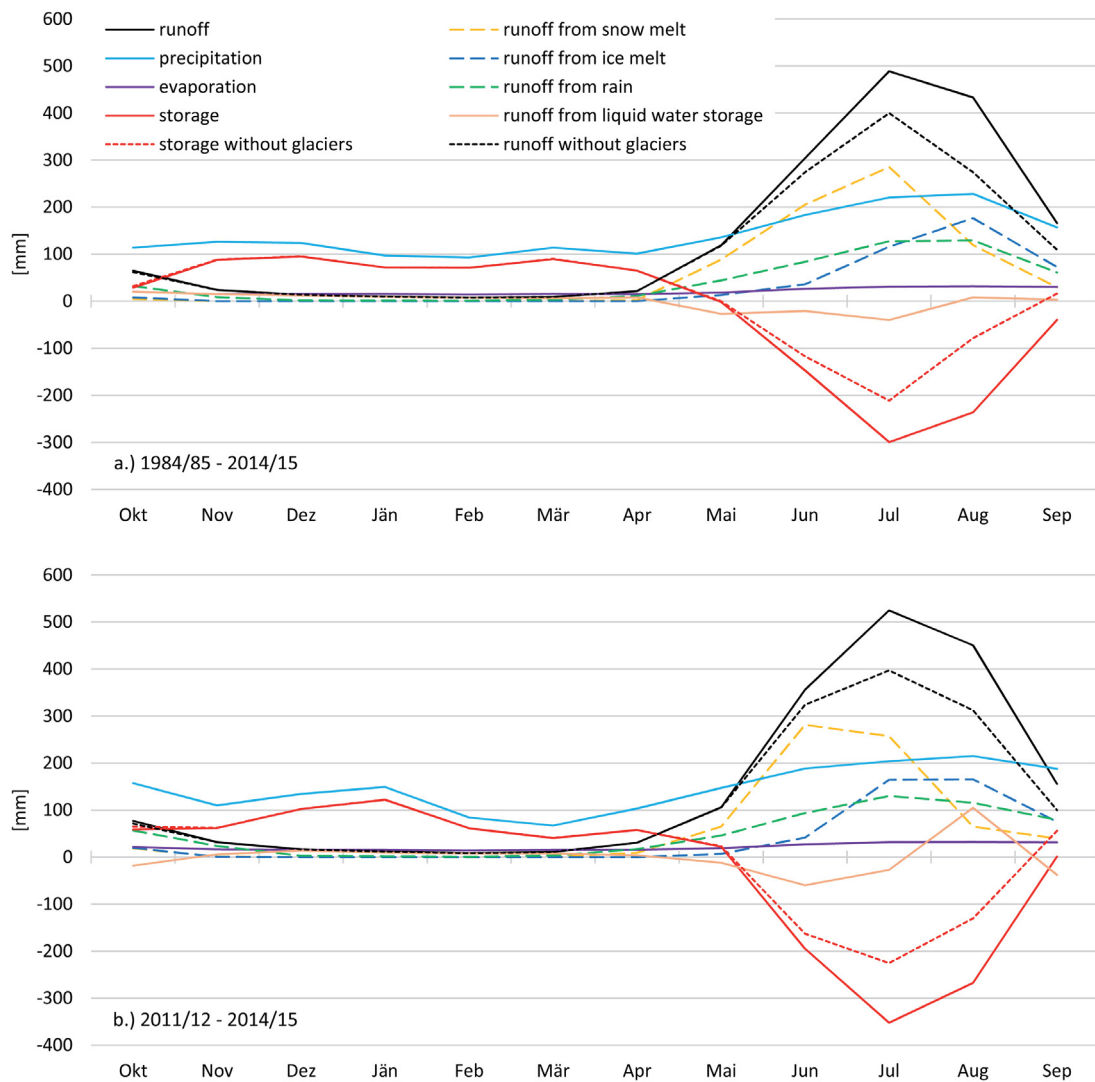


Figure 4.5.: Components of the hydrological balance from OEZ modelling for the mean period (a) 1984/85–2014/15 and (b) 2011/12–2014/15 (annual values cf. Tab. 4.6).

With the OEZ model, the flow regime within the PROSA basin down to Gepatschalm (position cf. Fig. 1.1, catchment area: $54,7 \text{ km}^2$) was modelled for the mean periods of the glaciological years 1884/85 to 2014/15 and for the period 2011/12 to 2014/15 (Fig. 4.5). In addition to the hydrological balance of precipitation, runoff, evaporation and storage (Eq. 2.1), the runoff is separated into its individual components. These are runoff from snow melt, from ice melt, from rain and runoff from the liquid water storage. In total, the runoff represents a glacio-nival regime with a peak in midsummer with a maximum Pardé coefficient of 3.5. To assess the effect of glacier ice melt, the glacier area was set to zero for both periods in an additional

model run. This reduces the runoff peak by the amount of the glacier melt water supply. As a result, annual values of the mean specific basin runoff indicate a change of the basin storage from -216 mm to $+123 \text{ mm}$ for the period 1985–2015 without glaciers and to $+71 \text{ mm}$ for the period 2012–2015 (Tab. 4.6). This means that, under current conditions of climate-means of temperature and precipitation for both periods but without glaciers, a positive storage from accumulated snow remains at the end of the hydrological year. The runoff from the liquid water storage is balanced in the course of the year and is thus equal to zero (Kuhn et al., 2016). Within the annual cycle, the liquid water storage drains during the accumulation period and fills up during the ablation season. The positive runoff from the liquid water storage in August in the modelling of the period 2012–2015 results from the short period when annual specific fluctuations become more evident.

Table 4.6.: Annual mean specific values [mm] of the components of the modelled hydrological balance for the periods 1984/85–2014/15 and 2011/12–2014/15 (annual cycle cf. Fig. 4.5); LWS: liquid water storage.

	annual mean (1985–2015)	annual mean (2012–2015)
precipitation	1693	1746
runoff	1661	1779
evaporation	249	255
storage	-216	-288
runoff from LWS	0	0
runoff from snow melt	734	737
runoff from ice melt	422	473
runoff from rain	504	570
runoff without glaciers	1322	1420
storage without glaciers	123	71

5. Discussion

Glaciers are sensible indicators to climate change. Depending on duration and magnitude of a change in the climate signal and consequently in the mass balance, this disturbance is transported to the glacier terminus with the glacier-specific response time. Thus, the glacier state can be investigated by long-term monitoring of glacier mass balances, ice flow dynamics and the terminus fluctuations. Long time series of flow velocities on Kesselwandferner and Hintereisferner provide valuable basic information, which is needed as an example for modelling future glacier development. 3D velocities like those determined at stakes on Kesselwandferner are particularly appropriate as an indicator of glacier state. This is especially relevant at the transition from submergence to emergence, which is not considered by surface mass balance monitoring. On Kesselwandferner, this becomes evident since the end of the advancing period (1970s and 1980s), with an increase in the elevation range of this transitional region from submergence to emergence flow (Fig. 5 in Paper I, Appx. A, Stocker-Waldhuber et al. (2019)). During investigations of the surface mass balance, as the direct result of the seasonal weather conditions during one year, ELA frequently shifted to altitudes above summits in recent decades. In such years, additional information, for example from ice flow velocities or from the transient snowline and its variability are of particular importance.

The response to a climate signal can vary considerably, as presented by the two adjacent glaciers Hintereisferner and Kesselwandferner. The reasons are topography and the area-altitude-distribution (Kuhn et al., 1985). Compared to Gepatschferner and Weißseeferner, which are also neighbouring glaciers to Kesselwandferner and Hintereisferner, the different response times become evident from the time series of the fluctuations of the glacier termini (Chap. 4, Sec. 4.2, Fig. 4.3). The advance in the period of the 1970s and 1980s first started on Kesselwandferner, followed by Weißseeferner and a few years later on Gepatschferner, while Hintereisferner did not show any advance during that time. Such fluctuations may either be amplified or attenuated, dependent on the topographic conditions of the terminus area. In the early 1970s, the tongue of Hintereisferner was long and thick and rested in the flat part of the valley, unlike the tongue of Kesselwandferner, which was short and thin and its terminus was situated at a steep part of the terrain. In contrast to the glacier advance, observed retreat rates on Gepatschferner are higher because of topographic conditions and especially the low altitude situation of the terminus compared to the other glaciers.

Recently accelerating retreat rates are the consequence of increasing negative glacier mass balances. Additional signs of disintegration, like the formation of circular and funnel-shaped surface depressions, are both a result of increasing retreat rates and an accelerant (Fig. 5 in Paper II, Appx. B, Stocker-Waldhuber et al. (2017)). The depression on Gepatschferner emerged as a consequence of a lack of a mass gain as ice mass flux to this region concurrent with the evacuation of subglacial sediment layers following the relocation of the subglacial meltwater channel during an extreme precipitation event. The sediment balance within the PROSA basin indicated a volume of around $20,000 \text{ m}^3$ as the remainder of the balance of this event to be assigned to the subglacial source (Hilger et al., 2019).

In addition to the surface depression as a sign of disintegration, the increasing ice melt at the glacier tongue and the decreasing ice dynamics affect the glacier retreat rates. The decreasing ice dynamics become evident from the decreasing surface velocities at the tongue of Gepatschferner. Measurements of the surface mass balance also showed increasing ablation rates. The most negative ablation of 9.5 m of ice was measured at the end of the glaciological year 2018. As a consequence of the ongoing ice melt after the end of the hydrological year, the ice melt of the whole ablation season in 2018 amounted to more than 10 m of ice at stake 64. In comparison, the mass balance on Mullwitzkees (Hohe Tauern), for example, showed a similar summer mass balance to the tongue of Gepatschferner, but at nearly double the glacier area (Stocker-Waldhuber et al., 2014, 2016; Stocker-Waldhuber and Fischer, 2019). This difference can be explained by the topography, the area-altitude-distribution and the exposition. Mullwitzkees covers an elevation range from about 2700 m to 3400 m and is mainly exposed to the south. So the terminus of Gepatschferner is situated at an altitude about 500 m lower than that of Mullwitzkees.

The magnitude of the ice melt at the tongue of Gepatschferner compared to the whole glacier and all the glaciers in the PROSA basin, or the above-mentioned Mullwitzkees, indicates the significance and impact of this low elevation glacier tongue for glacier melt water production. This becomes even more evident by the mean elevation and volume changes. The glacier tongue of Gepatschferner below 2900 m contributed 47% to the total volume change of Gepatschferner during the period 2012–2015. In relation to the total PROSA basin, the glacier tongue contributed 34% to the total volume change of all the glaciers while covering an area of just 2.4%. Consequently, the glacio-nival runoff regime of the Fagge river is mainly controlled by Gepatschferner and especially the glacier tongue. This also shows in the hydrological modelling. In case of decreasing glacier meltwater supply, the peak discharge shifts to the early summer months and is controlled by snow melt. This becomes evident when comparing the runoff from snowmelt and the runoff from ice melt in Figure 4.5 (Chap. 4, Sec. 4.3). The peak discharge from snow melt occurs in June and July,

depending on the modelling period, while the peak discharge from ice melt happens during August.

The mass flux to the glacier tongue, through the cross section area at the stake profile at an elevation of 2875 *m*, partially compensates for the mass loss of the glacier tongue, which was analysed for the period July 2012 to August 2015 (Paper III, Appx. C, Stocker-Waldhuber and Kuhn (2019)). The surface mass balance is primarily calculated within 50 *m* elevation ranges and thus the balance below 2900 *m* was recalculated to the glacier area below 2875 *m*. A mean subglacial thickness change of -1.45 *m* results as the remainder of the balance of mass loss at the glacier tongue surface and the mass flux to the tongue. This change in thickness includes subglacial melt, changes in the thickness of subglacial sediments and bedrock erosion and exaration. An attempt at estimating the magnitude of the erosion rate of Gepatschferner is in the order of $28 - 31 * 10^3$ *t/a* assuming a density of $1.8 - 2.0$ *t/m³* (e.g. Hilger et al., 2019) at a rate of 1 *mm/a* (e.g. Hallet et al., 1996). An extrapolation to the whole glacier area in the PROSA basin results in an erosion rate of $33 - 37 * 10^3$ *t/a* on the same assumptions. Even though such an estimate is affected by considerable uncertainties, it shows comparable magnitudes to single extreme events, like the rapid evacuation of subglacial sediments during the formation of the funnel-shaped surface depression at the tongue of Gepatschferner (Stocker-Waldhuber et al., 2017).

6. Conclusion

Glacial changes and dynamical processes on different but neighbouring glaciers in the Ötztal Alps (Austria), especially in the Kaunertal and at the tongue of Gepatschferner, were investigated in the framework of this thesis. The aim of these investigations was determining the magnitudes and balancing glacial and subglacial processes as well as their effect on glacier disintegration. The analyses showed the consequence of extreme events on the glacier retreat rates at the example of the formation of a funnel-shaped surface depression at the tongue of Gepatschferner, and examples on other glaciers. This process can be seen as both consequence and accelerator of rapid glacier disintegration. Further, the investigations revealed that beside extreme events, like heavy precipitation and the rapid evacuation of subglacial sediments, especially changes at the glacier tongue of Gepatschferner and the observed mass exchanges at the glacier tongue dominate the runoff regime of the upper river Fagge.

The continuation of long-term monitoring is a challenging task given the wide range of issues, from possible process changes like glacier advances and retreats, to changes in measuring methods, to the financial support of the programs. The importance of such a data basis is clear from the example of glacier flow velocities. With a synopsis of various methods and the basis of multiple high-resolution DEMs, the investigations in the joint project PROSA provide basic information on the magnitudes of different processes, which enhances process understanding and also leads to further refining of methods. The findings from these investigations are valuable for various questions at the interface of humans and the environment. Issues thrown up by glaciological investigations are: the effect of the glaciers on the water budget and thus their impact on water and hydropower management, the influence on tourism and glaciers as prestige objects, effects on glacier ski resorts in winter and summer seasons, consequences of intensifying slope processes due to glacier retreat and degrading permafrost, but also the development of new habitats in the glacier forefield and new glacier river sections as a consequence of rapid glacier disintegration.

In effect, the investigations on and around the tongue of Gepatschferner in PROSA were driven both by scientific curiosity and by the practical demands of regional hydrography to understand sediment transfer and power production. They have advanced our knowledge of and to a degree our management of the processes involved and have served both scientific and practical concerns.

7. Outlook

The ongoing and accelerating glacier disintegration results in the medium term in an increase of glacier meltwater production. In the longer term, increasing glacier retreat rates and consequently the disappearance of the most effective ablation areas leads to a degradation of meltwater production. Increasing temperatures and changes of timing and magnitude of precipitation, “unfavourable” to the glacier, lead to an amplification and acceleration of this process development. Under currently prevailing conditions, the disintegration of the glacier tongue of Geptaschferner up to the area of the icefall zone is likely to occur within the next 10 to 15 years. Due to the specific response time of Gepatschferner, such a glacier retreat is also very likely even under unlikely transient positive mass balance conditions for the glacier. As shown in the hydrological modelling of the runoff characteristics, the peak discharge will shift from mid- to early summer and to a more nival runoff regime. Beside the temperature developments, the key factors for an estimation of future scenarios are the changes in timing and magnitude of precipitation events. An increasing number of stable weather conditions, for example, facilitates the development of extreme weather conditions. Consequently, the fluctuation range of seasonal weather conditions increases, which hampers the estimation of future glacier scenarios.

The continuation of the current measurements of the glacier disintegration and especially the continuation of long-term monitoring enable the investigation of the impact of climate change and changes in atmospheric patterns on the glacier state. One question that arises in this context relates to historic minimum glacier extents and the determination of the age of cold ice, which is currently investigated at Gepatschferner at the Weißsee summit, similar to investigations on Chli Titlis glacier (Bohleber et al., 2018). Modelling of the glacier dynamics within this project in turn requires data on glacier flow velocities from long-term monitoring. In line with these long-term investigations and as additional information on subseasonal variations, the ablation and velocity measurements on Gepatschferner will be continued.

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List of Abbreviations and Variables

Abbreviations

AAR	Accumulation Area Ratio	LIA	Little Ice Age
ACINN	Department of Atmospheric and Cryospheric Sciences	LIAG	Leibnitz Institute for Applied Geophysics
ALS	Airborne Laser Scan	LIDAR	Light Detection and Ranging
AWI	Alfred-Wegener-Institut	LoD	Level of Detection
DEM	Digital Elevation Model	LWS	Liquid Water Storage
DFG	German Research Foundation	MLF	Mittle Low Frequency
DGPS	Differential Global Positioning System	OEZ	Hydrological Model
DInSAR	Differential Interferometric System Aperture Radar	PROSA	Proglacial Systems of the Alps
DoD	DEM of Difference	RTK	Real Time Kinematic
ELA	Equilibrium Line Altitude	STPOS-MABZ ...	South Tyrolean Positioning Service, Reference Station Mals-Malles
ELVIS	Electrodynamic Vibrator System	SW	Schwarze Wand
ESSD	Earth System Science Data	TIWAG	Tiroler Wasserkraft AG
FWF	Austrian Science Fund	TLS	Terrestrial Laser Scan
GI	Glacier Inventory	TSF	Taschachferner
GLONASS	Global Navigation Satellite System	w.e.	water equivalent
GPF	Gepatschferner	WGMS	World Glacier Monitoring Service
GPR	Ground Penetrating Radar	WSF	Weißseeferner
GSSI	Geophysical Survey Systems Inc.	ZAMG	Zentralanstalt für Meteorologie und Geodynamik
HD	Hydrographischer Dienst	ÖAV	Austrian Alpine Club
HEF	Hintereisferner	ÖAW	Austrian Academy of Sciences
IGF	Institute for Interdisciplinary Mountain Research		
IPCC	Intergovernmental Panel on Climate Change		
KWF	Kesselwandferner		

Mathematical Variables

A	Area
B	Net Mass Balance
b	Specific Mass Balance
E	Evaporation
P	Precipitation
R	Runoff
S	Storage
V	Volume

Special mathematical variables and indices are given in the papers (cf. Appx. A to C).

Appendix

A. Paper I

Stocker-Waldhuber, M., Fischer, A., Helfricht, K., and Kuhn, M.: Long-term records of glacier surface velocities in the Ötztal Alps (Austria), *Earth System Science Data*, 11, 705–715, doi: <https://doi.org/10.5194/essd-11-705-2019>, 2019

Abstract

Climatic forcing affects glacier mass balance, which causes changes in ice flow dynamics and glacier length changes on different timescales. Mass balance and length changes are operationally used for glacier monitoring, whereas only a few time series of glacier dynamics have been recorded. Here we present a unique dataset of yearly averaged ice flow velocity measurements at stakes and stone lines covering more than 100 years on Hintereisferner and more than 50 years on Kesselwandferner. Moreover, the dataset contains sub-seasonal variations in ice flow from Gepatschferner and Taschachferner covering almost 10 years. The ice flow velocities on Hintereisferner and (especially) on Kesselwandferner show great variation between advancing and retreating periods, with magnitudes increasing from the stakes at higher elevations to the lower-elevated stakes, making ice flow records at ablation stakes a very sensitive indicator of glacier state. Since the end of the latest glacier advances from the 1970s to the 1980s, the ice flow velocities have decreased continuously, a strong indicator of the negative mass balances of the glaciers in recent decades. The velocity datasets of the four glaciers are available at <https://doi.org/10.1594/PANGAEA.896741>.

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Long-term records of glacier surface velocities in the Ötztal Alps (Austria)

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Abstract. Climatic forcing affects glacier mass balance, which causes changes in ice flow dynamics and glacier length changes on different timescales. Mass balance and length changes are operationally used for glacier monitoring, whereas only a few time series of glacier dynamics have been recorded. Here we present a unique dataset of yearly averaged ice flow velocity measurements at stakes and stone lines covering more than 100 years on Hintereisferner and more than 50 years on Kesselwandferner. Moreover, the dataset contains sub-seasonal variations in ice flow from Gepatschferner and Taschachferner covering almost 10 years. The ice flow velocities on Hintereisferner and (especially) on Kesselwandferner show great variation between advancing and retreating periods, with magnitudes increasing from the stakes at higher elevations to the lower-elevated stakes, making ice flow records at ablation stakes a very sensitive indicator of glacier state. Since the end of the latest glacier advances from the 1970s to the 1980s, the ice flow velocities have decreased continuously, a strong indicator of the negative mass balances of the glaciers in recent decades. The velocity datasets of the four glaciers are available at <https://doi.org/10.1594/PANGAEA.896741>.

1 Introduction

The fluctuation of glaciers has become an icon of climate change, after Agassiz (1847) hypothesized the theory of ice ages, which was then confirmed by Penck and Brückner (1909) and further substantiated with isotope analysis on deep sea sediment and polar ice cores (Hays et al., 1976; Shackleton, 2000) and the theoretical work by Milankovitch (1920). First monitoring efforts focused on recording the changing positions of glacier termini, starting in the 17th century and systematically organized in the late 19th century, for example by the German and Austrian Alpine Club (Fritzsch, 1898; Groß, 2018). In the case of catastrophic glacier advances, as reported several times during the Little Ice Age, for instance, for Vernagtferner in the Ötztal Alps (Nicolussi, 2012), local observers often reported the velocity of terminus advances over short periods. At that stage of development, glaciological theory and

monitoring techniques, the monitoring of horizontal ice flow velocities was already well established for Alpine glaciers. Stone line velocities were recorded at 5 glaciers among 20 glaciers regularly monitored for length changes in the Eastern Alps, for example, at the glaciers of Pasterze (Nicolussi and Patzelt, 2001), Vernagtferner (Braun et al., 2012) or Hintereisferner (Span et al., 1997), or in the Western Alps at Rhône Glacier (Mercanton, 1916; Roethlisberger, 1963) or Mer de Glace (Berthier and Vincent, 2012). At the glaciers Unteraargletscher and Mer de Glace, ice flow was already being measured during the 1840s (Forbes, 1846; Agassiz, 1847).

For Alpine glaciers, monitoring of velocity records received less attention after the turbulent decades of the First and Second World Wars. Development of glaciological programmes focused on hydrological programmes and mass balance programmes, as the understanding of glacier flow

was advanced by deformation measurements on Hintereisferner and in the theoretical work of Finsterwalder (1907) and Hess (1924).

Estimates of the global glaciers' contribution to sea level rise is one of the urgent topics of research (e.g. Jacob et al., 2012; Zemp et al., 2019), and estimates of the state of regional glacier inventories are needed. Glacier flow velocities that can be derived from remote-sensing data are an important parameter that provides essential information on dynamic response, which is part of the mass balance evolution of a glacier. For example, ELA (equilibrium line altitude), which played a major role in large-scale data collections for global climate change, has been observed to be above summits and thus undefined for Eastern Alpine glaciers for much of the last decade (WGMS, 2017).

In this paper, two long-term series and two series of about a decade of ice flow velocities are revisited and compared with classical in situ mass balance measurements (Hoinkes, 1970) and ALS (airborne laser scanning) data (Abermann et al., 2010). On these four glaciers, ice flow velocities are measured in situ at stone lines (horizontal velocities) or at stakes (3-D velocities). The stones and stakes are annually relocated to their original position. Long-term velocity data are recorded annually, shorter time series also reveal seasonal variabilities. The four glaciers are also part of a network of long-term measurements of glacier fluctuations (Groß, 2018); area and volume change have been recorded in inventories from the LIA (Little Ice Age) maximum onwards (Patzelt, 1980; Groß, 1987; Kuhn et al., 2012; Fischer et al., 2015).

This paper presents ice flow velocity records on well-investigated mountain glaciers and their relation to other in situ monitoring parameters. These data can be used for validation of numerical ice flow models and further research on ice flow velocity as a monitoring parameter and climate proxy on various scales.

2 Glacier sites and data

The ice flow velocities have been recorded on four of the largest glaciers in the Ötztal Alps (Austria). Hintereisferner (HEF), Kesselwandferner (KWF), Gepatschferner (GPF) and Taschachferner (TSF) are neighbouring glaciers (Fig. 1) differing in size, aspect and elevation range (Table 1).

HEF, a typical valley glacier, has a long tradition of hydrological, meteorological, geophysical and glaciological investigations (e.g. Blümcke und Hess, 1899; Förtsch and Vidal, 1956; Hoinkes and Steinacker, 1975; Kuhn et al., 1999; Fischer, 2010; Helfricht et al., 2014; Strasser et al., 2018). Ice flow velocities on HEF have been sporadically but almost annually measured at ablation stakes for more than 100 years at stone lines (Span et al., 1997). Line 3 on HEF is the oldest stone line, started in 1895 and lasted until 1985 when the glacier retreated upstream from the location of the profile.

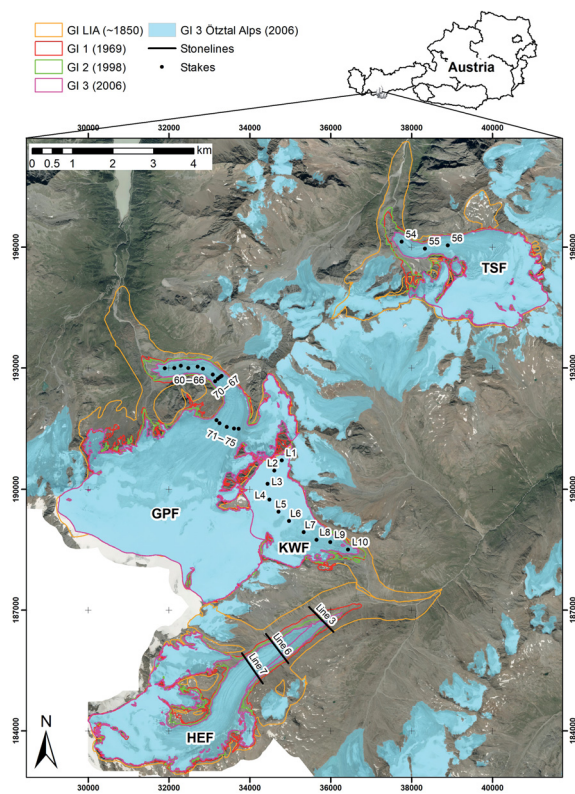


Figure 1. Location of the stone lines (3, 6 and 7) on Hintereisferner (HEF) and stakes on Kesselwandferner (KWF), Taschachferner (TSF) and Gepatschferner (GPF). On Gepatschferner, stakes 60 to 66 are longitudinal stakes from the glacier snout upwards to the first cross-profile including the stakes 67 to 70 (from the orographic right to the left). Stakes 71 to 75 are located in a cross-profile at the root zone of the tongue. The glacier area was taken from the Austrian Glacier Inventories (GI) from the LIA (Little Ice Age) around 1850, GI1 from 1969, GI2 from 1998 and GI3 from 2006 (Fischer et al., 2015). Background: orthophoto from 2015; data source: Land Tirol – <https://www.tirol.gv.at/data/>.

Records at Line 6 were started in 1932/33 and at Line 7 in 2013/14. In situ mass balances have been measured since 1952 (Hoinkes, 1970; Fischer, 2010; Fischer et al., 2013; Strasser et al., 2018).

The investigations on KWF are historically linked to those on HEF (e.g. Kuhn et al., 1985) with the same long-term investigations of length variations since 1884 and mass balances since 1952 (Fischer et al., 2014). The terminus of KWF detached from the tongue of HEF in 1914. KWF is a plateau glacier and covers a small elevation range compared to HEF, GPF and TSF, especially since the terminus retreated to the top of a steep terrain level and detached from the dead ice body at the front of this step in 2012. Velocity measurements were started in 1965 by Schneider (1970) at ablation

Table 1. Geographic location and characteristic numbers of GPF, HEF, KWF and TSF from Austrian Glacier Inventory 3 of 2006 (Fischer et al., 2015) and the year of the start of velocity measurements (meas. since). exp: exposition; sc: accumulation area; sa: ablation area.

name	location	exp. sc	exp. sa	altitude range [m]	area [km ²]	meas. since
GPF	46.85° N, 10.75° E	NE	N	2116–3501	16.62	2009/10
HEF	46.79° N, 10.75° E	E	NE	2436–3715	7.49	1894/95
KWF	46.84° N, 10.79° E	SE	E	2754–3496	3.82	1965/66
TSF	46.90° N, 10.86° E	N	NW	2424–3756	5.71	2009/10

stakes and at accumulation stakes along the centre flow line of the glacier. A comparison between direct glaciological and geodetic measurements on KWF, as well as on HEF, was presented by Fischer (2011). The main outcome of the comparison was that both mass balance datasets generally agree within measurement uncertainties.

GPF is the second largest glacier of the Austrian Alps. The main glacier rests on a wide but hilly plateau and the tongue descends through a narrow valley. After these early mappings (Sonklar, 1860; Finsterwalder, 1928), GPF was subject to geophysical investigations (Giese, 1963), photogrammetric analyses (Keutterling and Thomas, 2006) and is still one of the Eastern Alpine key research sites and has extensive knowledge on its Holocene fluctuations (Nicolussi and Patzelt, 2001). Recently, Gepatschferner became part of a detailed study on geomorphodynamics (Heckmann et al., 2012; Heckmann and Morche, 2019). In this study, the stake network at the glacier tongue was extended from 3 stakes, where velocities have been measured since 2009, to 16 stakes in 2012. TSF is similar to GPF a plateau and valley glacier with a wide accumulation area and a narrow glacier tongue. The stake velocity records on TSF were started together with those on GPF in 2009 at three positions at the glacier tongue.

On both glaciers, GPF and TSF, the positions of the stakes are measured several times during the summer months, allowing a discussion of the sub-seasonal variability. In contrast, the velocity records at HEF and KWF were performed once a year and can be discussed in relation to their long-term mass balance records.

3 Methods

Based on the historical development of geodetic techniques, different methods came into operation on these glaciers during the past century. Trigonometric networks were installed in 1894 on HEF (Blümcke and Hess, 1899) and in 1965/66 on KWF (Schneider, 1970) to determine glacier surface velocities with a theodolite at stone lines on HEF and ablation stakes on both glaciers (Fig. 1). On HEF and KWF, stake velocities were measured using a theodolite and tachymeter until 2009. Since then DGPS (differential global positioning system) has been used. On GPF and TSF, the full series was measured by DGPS (system: Topcon; antennas: Hiper V; software: Magnet Tools).

The velocity records are compared to direct glaciological and geodetic mass balance measurements from Hoinkes (1970), Schneider (1970), Fischer (2010), Fischer et al. (2013), Stocker-Waldhuber et al. (2017) and Strasser et al. (2018) on HEF, KWF and GPF. In these publications, the surface mass balances were derived from stakes and snow pits by using the direct glaciological method (Hoinkes, 1970). Additionally, DEMs (digital elevation models) and DODs (DEMs of difference) from photogrammetric or high-resolution ALS data came into operation to determine volume and elevation changes (Abermann et al., 2010).

3.1 Velocity measurements at stone lines

The method of stone lines (Heim, 1885; Hess, 1904) was only used on HEF at three cross-profiles. The position of several stones and their distance to each other is fixed within a defined cross-profile. The number of stones depends on the glacier width and thus varies in time with any expansion or reduction of the glacier. The position of the stones was measured initially with tachymetric systems and with DGPS since 2009. The stones are flat, with a diameter ranging from 0.15 m to a maximum of 0.3 m. The distance between the original defined position of the stone within the profile and the position in the subsequent year is measured using a measuring tape. The horizontal displacement is calculated in consideration of the elevation change or the slope of the surface at each stone. The stones are then moved to their original position. From 2009, the displacement was calculated from the measured DGPS positions, but the measuring tape is still used for control. The annual velocities at the stone lines are given as the mean annual values of the stones in the profile and thus depend on the number of stones.

Velocity records from ablation stakes complemented earlier data for Line 6 (before 1932/33) and Line 7 (before 2013/14) for periods when the stakes were reinstalled at their original position. The stakes are located at the central flow line of the glacier, thus representing the maximum flow velocity at the profile. A ratio of 80 % between the mean velocity from the stone line and the maximum velocity at stakes located at the centre of profile (Span and Kuhn, 2003) was taken to compare the stake values with the mean values from the stone lines.

3.2 Velocity measurements at stakes

Velocity measurements are performed at ablation stakes and at accumulation stakes on KWF, GPF, and TSF and complement the stone lines on HEF. The position of the stakes and their motion on KWF is measured at the top of the stake and calculated to the lower end of the stake, its base point. This has the advantage that the measured velocity is not affected by surface changes of accumulation or ablation. Figure 2, taken from Schneider (1970), shows the components of the velocity vector (\mathbf{d}) at the base point of the stake within the accumulation area (left side) and the ablation area (right side) between two points in time (t_1 , t_2) depending on submergence (negative value of v) and emergence (positive value of v). This definition coincides with the definition of submergence and emergence in Cogley et al. (2011). The vertical motion can be calculated as the remainder of the absolute elevation change of the surface (Δd) and the accumulation or ablation (Δa) from the elevation change due to the sloping surface (Δh) and the vertical component (Δz) of the velocity vector (\mathbf{d}) (Schneider, 1970). The difference between the actual flow path (\mathbf{d}), which is the length of the velocity vector, and the horizontal motion (Δs), which is the projected velocity, results from the vertical component (Δz). Annual values of the horizontal flow velocity ($\Delta s/a$), as well as the vertical motion values of submergence and emergence, were calculated for 365 d and on the basis of a fixed coordinate system. The horizontal velocity component (Δs) and the vertical component (v) in Schneider (1970) correspond to the definitions of (u) and (w) in Cuffey and Paterson (2010). Upward motion is positive.

The stakes on KWF are reinstalled annually at their initial (xy) position. Redrilling and measurements are conducted with a level rod for exact perpendicular conditions. The reflector or the DGPS antenna is directly mounted to the top of the stake. Therefore, duraluminium stakes with a rigid connection are used on KWF as ablation stakes ($\varnothing = 2$ cm) as well as thicker accumulation stakes with a diameter of 5 cm for the necessary resistance against snow pressure. Tipping over and melting in may lead to errors in measuring the vertical motion. On KWF, tipping over of the stakes is avoided by the use of duraluminium stakes. Wood wool underneath the stake and at the downhill side of the stake protects against melting.

4 Accuracies and uncertainties

The investigations on KWF are accurate to the low centimetre level (0.05 to 0.1 m) for the horizontal and the vertical stake position determined with theodolite and tachymeter. This is possible because of statistical adjustment of the measured positions using resection and intersection techniques and especially the statistical adjustment of the trigonometric network. Further details of the derived errors for this specific dataset can be found in Schneider (1970). In 2009,

DGPS measurements with a RTK (real time kinematic) procedure came into operation. During these measurements, the base-station is located in close proximity to the glacier at fixed points of the trigonometric network (Schneider, 1970; Niederwald, 2009; Weide, 2009; Zauner, 2010), allowing a staking out of the stake position with a comparable accuracy in the low centimetre level. The overall accuracies depend on a proper implementation of the measurement methods. The precision requirements on KWF are in the range of ± 0.05 m per single measurement or at least ± 0.1 m for the period between the two readings for the horizontal and the vertical displacement.

In contrast to the stakes on KWF, ice flow velocities at GPF and TSF are measured at wooden ablation stakes with DGPS and a post-processing procedure, the measured positions refer to the glacier surface. The minimum occupation time for DGPS with post-processing is 10 min but is mostly in the range of 30 to 60 min. The nearest base station, which provides basic data within the GPS and GLONASS satellite system, is located in Malles (STPOS-MABZ, $46^\circ 41' 9.55''$ N, $10^\circ 33' 3.73''$ E, South Tyrol, Italy). The baseline to the stakes on GPF is about 26 km and about 32 km to the stakes on TSF. The accuracies from the post-processing procedure on these glaciers are ± 0.1 m per single measurement or ± 0.2 m for the period between two readings at best. Additionally, the distance to the base station and shading effects of the surrounding topography lead to higher uncertainties for the DGPS measurements in the low decimetre to metre level.

The uncertainty of the stone line measurements on HEF, determined with a measuring tape, can only be estimated. They depend on the measuring distance, surface roughness and possible slipping of stones on the ice surface. The number of stones in the profile varies in time, which leads to a systematic error in the mean velocity of the lines. The number of stones at Line 7 decreased from 19 stones initially to 17 stones and at Line 6 to 4 stones in 2017. The velocities of the stone lines refer to the horizontal component of the velocity vector (Δs) and are calculated from theodolite and tachymeter measurements until 2009 and with RTK-DGPS since then with an absolute error of ± 0.05 m per single measurement. An estimated uncertainty of the mean stone line velocity of 5 % of the annual displacement is higher in contrast to the measurements on KWF due to the possible slipping motion of stones in the profile. The slipping error mainly depends more on the surface slope and the annual surface ablation than on the surface velocity. This means that the higher the ablation rate and the steeper the surface slope, the higher the slipping error. Consequently, this error becomes more important at low velocities (Blümcke and Finsterwalder, 1905).

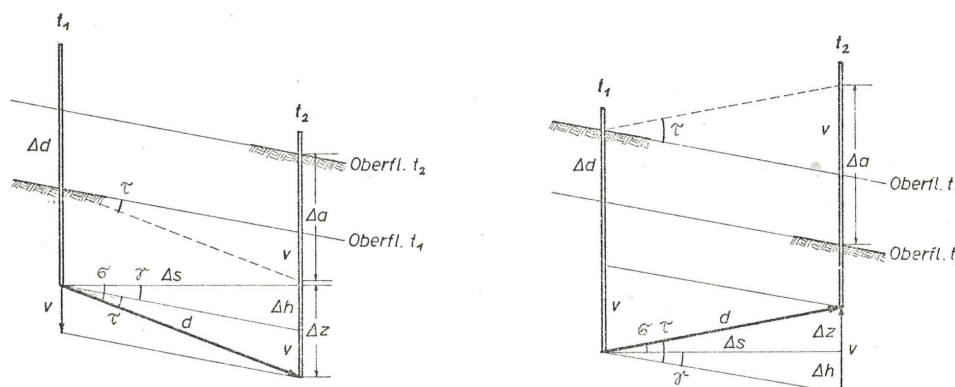


Figure 2. Drawings by Schneider (1970) of the motion of a stake and changes at the glacier surface (Oberfl.) between two time steps (t_1 , t_2) within the accumulation area (left) and the ablation area (right). d : flow path (length of the velocity vector); v : vertical velocity; Δs : horizontal velocity (projected velocity); Δd : absolute surface elevation change; Δa : point mass balance (relative surface elevation change from accumulation or ablation).

5 Results

5.1 Hintereisferner

Three stone line records on HEF display the variation in glacier surface velocities for different periods, for more than 100 years in total (Fig. 3). Three periods with increasing surface velocities were recorded on HEF. The first and most extensive acceleration of surface velocity happened before 1920, with a maximum mean stone line velocity of 125 m per year at Line 3 in 1919 (Hess, 1924). This is 112 m per year above the mean flow velocity of 13 m per year of the long-term average (1895–1985) at this location. The velocity increased to this maximum within a few years and decreased very quickly until 1922, resulting in a small advance of the glacier terminus in subsequent years of around 60 m (Span et al., 1997). The second period was recorded from 1935 to the early 1940s and the most recent one during the 1970s. During that time, the mass balance of the glacier was positive for several years (Fig. 3). Since 1980, surface velocities on HEF have continuously decreased at the stone lines to about 4 m per year in recent years at Line 6 and to about 7–8 m per year at Line 7. This continuous decrease is accompanied by strong negative mass balances in recent decades.

5.2 Kesselwandferner

On KWF, measurements were started in the hydrological year 1965/66, including horizontal and vertical ice flow velocities (Fig. 4 and Fig. 5). These long-term investigations document different glacier states at a longitudinal profile of up to 10 accumulation and ablation stakes. There are two main contrasting periods, the first period from the start of the measurements to 1985 and the second period since then. During the first period, the glacier advanced because of positive mass balances. During that time 75 % of the measured

glaciers in Austria and Switzerland advanced due to positive mass balances as a result of decreasing summer temperatures and increasing annual precipitation (Patzelt, 1985). The surface velocity of the glacier increased but with decreasing magnitudes from the terminus (L10) to the uppermost stake (L1) within the accumulation area. This means an increased velocity gradient along the glacier, with maximum of about 90 m per year at the terminus declining to a few metres per year at the highest elevations. The gradient of the vertical velocities was also large, with a submergence of up to 3 m per year within the accumulation zone to an emergence of up to 5 m per year at the lowermost stake. During that time the ELA (equilibrium line altitude) shifted to lower elevations, which can be seen as the transition from submergence to emergence from stake to stake.

The advancing state of the glacier ended in 1985, followed by a sharp decrease in the surface velocities and a reduction of the velocity gradients along the flow line. The terminus velocity response was large due to the positive mass balances. A significant change in velocity near the ELA at L6 did not occur until negative mass balances occurred around 1985. Submergence transitioned gradually to emergence around 1990 at stakes L8 and L7 and in 2005 at L6, representing a shift of the ELA to higher elevations. During that time, ELA shifted from 3130 m (mean value from 1985 to 1990) to 3214 m during the period 2005–2010, and even above the crest level in 2003 for the first time since the beginning of the mass balance measurements (Fischer et al., 2014; Strasser et al., 2018). At the lowermost stake L10, velocity decreased rapidly to almost zero because of the decreasing mass supply to the terminus. This area became ice free in 2010 (Figs. 4 and 5). The latest positive mass balance occurred in 2015, with an immediate response in the horizontal and vertical velocities.

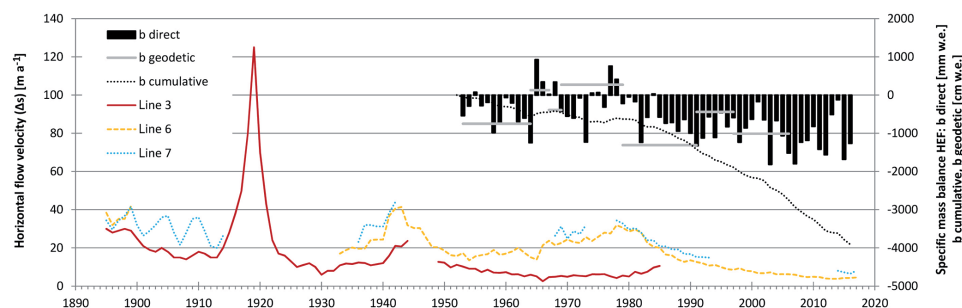


Figure 3. The mean annual velocities of the stones at lines 3, 6 and 7 on Hintereisferner since 1894/95 (= 1895). The data series has been extended since Span et al. (1997) and annual specific surface mass balance (*b* direct) (Strasser et al., 2018; WGMS, 2017; original data: Hess, 1924), as well as the geodetic balances from DODs (*b* geodetic) by Fischer (2011) since 1953. Locations of the stone lines are shown in Fig. 1.

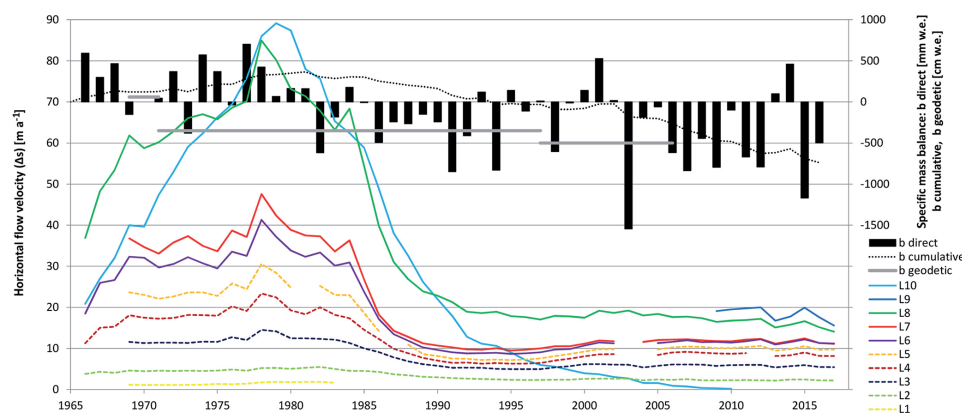


Figure 4. Annual horizontal flow velocities ($\Delta s/a$) at the accumulation and ablation stakes on Kesselwandferner (e.g. the year 2015 refers to the hydrological year 2014/2015) and the specific surface mass balance (*b* direct) (Strasser et al., 2018; WGMS, 2017), as well as the geodetic balances from DODs (*b* geodetic) by Fischer (2011). Locations of the stakes are shown in Fig. 1.

5.3 Gepatschferner and Taschachferner

The measurements of ice flow velocities and ablation on GPF and TSF were started in 2009/10. The stake network on GPF was extended in 2012. During these measurements, interannual velocity fluctuations were small, especially at the three stakes on TSF (54, 55 and 56). At the lowermost Stake 54, the horizontal velocities were less than 10 m per year during the whole period. The two higher-altitude points 55 and 56 returned velocities of 30 to around 40 m per year. The higher values at 55 compared to 56 are caused by topographic effects, with a steepening of the glacier tongue and a narrowing of the cross section from Stake 56 towards Stake 55 (Fig. 6).

On GPF, a general trend of decreasing surface velocities was found at all stakes, with a larger decline in velocity at the terminus than at the upper cross-profile (71–75). At Stake 62, a funnel-shaped surface depression, caused by an evacuation of subglacial sediments due to a heavy precipitation event, led to a spatially limited increase in surface velocity in that

area and a later decrease to almost zero (Stocker-Waldhuber et al., 2017). In total, a general slowdown of velocities at the tongue of GPF was found since the beginning of the measurements.

An example of sub-seasonal fluctuations in surface velocity is given in Fig. 7 for Stake 65 at GPF, which has been measured from 2009 with the least data gaps since then. The velocities are given as mean values per day to make the different time periods of the stake readings comparable. During the winter seasons velocities generally decrease. Maximum values were typically found in August each year, except for the years 2013 and 2014, which had earlier peaks in July. During winter months the elevation change of the surface from geodetic measurements is close to zero or even positive while surface velocity is decreasing. The opposite process is found during the summer season, when the highest surface velocities go along with the most negative elevation change.

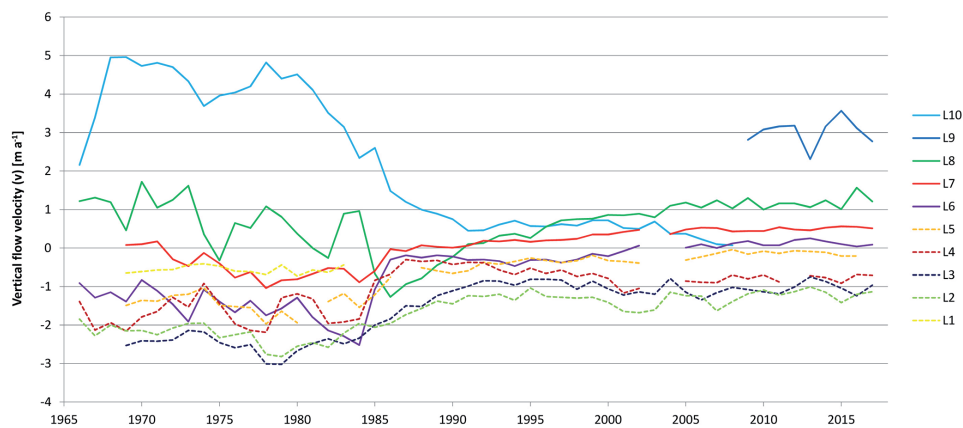


Figure 5. Annual vertical velocities ($\Delta v/a$) at the accumulation and ablation stakes on Kesselwandferner (e.g. the year 2015 refers to the hydrological year 2014/2015). Positive values represent emergence flow, negative ones represent submergence flow. Locations of the stakes are shown in Fig. 1.

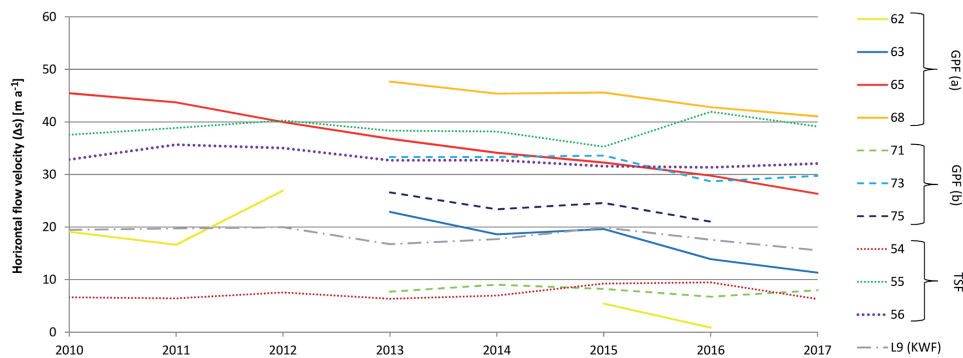


Figure 6. Annual horizontal flow velocities ($\Delta s/a$) on Gepatschferner and Taschachferner and L9 at Kesselwandferner for comparison (e.g. the year 2015 refers to the hydrological year 2014/2015). GPF (a): selection of the longitudinal stakes at the tongue of Gepatschferner. GPF (b): three stakes at the cross-profile. Locations of the stakes are shown in Fig. 1: Stake 71 – orogr. left side; Stake 73 – centre; Stake 75 – orogr. right side.

6 Discussion

The investigations show that the magnitude of the fluctuations of the surface velocities is higher at the ablation stakes compared to those within the accumulation area and highest at the lowermost stakes. This means that changes in observed velocity, especially at ablation stakes, are very well suited for documenting the glacier state, even more so at a fast reacting glacier like KWF. This is supported by a linear regression of annual mean specific balance (b) of the total glacier area of HEF and KWF versus the mean specific balance of their accumulation areas (bc) for the period 1965/66–1999/00 by Span and Kuhn (2003). They found nearly identical correlation coefficients for the two balances, while the standard deviation $\sigma(b)$ was twice as high as $\sigma(bc)$, documenting the higher sensitivity of the ablation areas to mass balance changes of the two glaciers.

On GPF and TSF these measurements were conducted exclusively at stakes at the tongue where the decreasing velocity rates represent the retreating state of the glacier. The decreasing velocities were found especially on GPF, in contrast to TSF, where the flow rates remained almost constant during these investigations. This is caused by the specific topographic conditions of the TSF glacier tongue, which is steeper and shorter, and the terminus is located at a higher altitude compared to the tongue of GPF.

The sub-seasonal fluctuations on GPF (Fig. 7) represent the typical acceleration of the glacier during summer months, which is well known and was, for example, already measured on HEF between the end of July and mid-September from 1900 to 1904 by Blümcke and Finsterwalder (1905). The summer peaks on GPF and TSF were found mainly during August each year. These sub-seasonal fluctuations depend on the drainage network, which is driven by the amount of

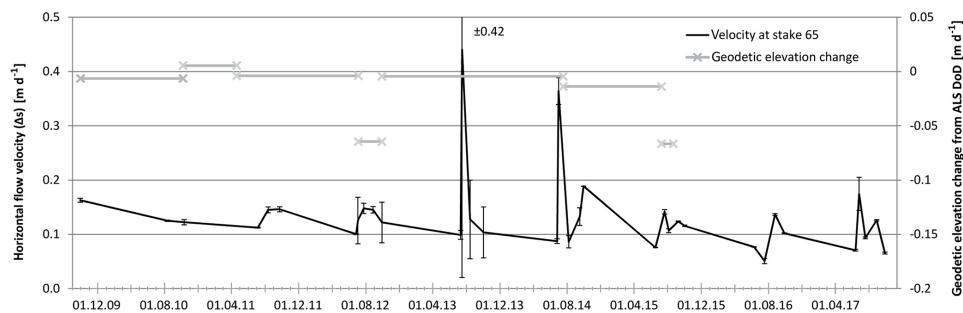


Figure 7. Mean daily horizontal velocities ($\Delta s \text{ d}^{-1}$) at Stake 65 on Gepatschferner between the measurements, as an example of the sub-seasonal fluctuation of surface velocity. The peak in July 2013 shows the highest uncertainty, very likely because of few satellites due to shading effects of the surrounding topography, which depend on the time of the measurements. Additional information is given by the mean elevation change per day from ALS DODs at the position of the stake (data extended from Stocker-Waldhuber et al., 2017).

melt water, seasonal and extreme weather conditions (Iken, 1977; Gudmundsson, 2002). The accuracy of the measurements on GPF varies over time and depends on shading effects of the surrounding topography. For example, the peak in 2013 shows the greatest uncertainty due to topographic shading effects and is thus not representative of the actual surface velocity.

Generally, the glacier surface velocities will be overestimated by stone velocity measurements, especially at low velocities and high ablation rates. This difference is shown by Hess (1924) for the period between 1913/14 and 1921/22 with measured surface velocities at neighbouring stones and boreholes.

7 Data availability

Velocity data of the four glaciers Hintereisferner, Kesselwandferner, Gepatschferner and Taschachferner are available at <https://doi.org/10.1594/PANGAEA.896741> (Stocker-Waldhuber et al., 2018). New data will be added every year.

8 Conclusions

The long-term investigations of the surface velocities at these glaciers document the state of each glacier and its response to a climate signal. Three periods with accelerating velocities caused by positive mass balances were found in the longest time series on HEF. A time shift of the maximum values from higher to lower stone line profiles indicates the response time of the tongue. Despite the increase in surface velocities during these three periods, mass gain on HEF was insufficient for the terminus to advance, except for a small advance during the 1920s. The 1920s peak velocity at Line 3 was also confirmed by measurements at boreholes, stakes and additional stones within the ablation area (Hess, 1924). In contrast to HEF, the terminus of KWF advanced by more than 250 m from the 1970s to the 1980s (Patzelt, 1985; Fis-

cher et al., 2018). KWF presents an immediate response at all profiles concurrently, which means that a mass gain or increase in the thickness within the accumulation area causes an increase in the emergence at the lowermost stakes within 1 year.

During glacier retreat, the transition from submergence to emergence shifts to higher elevations, as was found on KWF from 1986 to the present. As a consequence, the magnitude of the vertical velocities decreases, which leads to increasing retreat rates of the terminus but, at the same time, to an increase in the thickness at higher elevations in case of a positive mass balance. Apart from the effect of the mass balance, according to the continuity equation, local thickness changes can also be caused by convergent or divergent glacier flow.

For the investigated temperate mountain glaciers, ice flow velocity is a glaciological parameter that reacts very quickly to changes in the forcing such as the glacier mass balance variability (Huss, 2012). As conventional parameters like ELA tend to be above the summit for the investigated glaciers under current conditions and specific mass balance is affected by rapid changes in area, long-term monitoring of ice flow provides valuable additional information on the glacier state. Our dataset allows for the development and validation of perspectives on ice flow velocity as monitoring tool.

Author contributions. MSW is responsible for the velocity measurements and data analyses of Hintereisferner, Kesselwandferner and Gepatschferner, prepared the figures and wrote the manuscript. AF is leading the working group, accounts for the maintenance of the long-term monitoring programs and contributed in writing the manuscript. KH is responsible for the velocity measurements and data analyses of Taschachferner. MK initiated the measurements on Gepatschferner and Taschachferner. All co-authors were involved in corrections and additions to the manuscript during the whole review process.

Competing interests. The authors declare that they have no conflict of interest.

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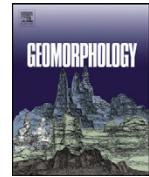
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B. Paper II

Stocker-Waldhuber, M., Fischer, A., Keller, L., Morche, D., and Kuhn, M.: Funnel-shaped surface depressions – Indicator or accelerant of rapid glacier disintegration? A case study in the Tyrolean Alps, *Geomorphology*, 287, 58–72, doi: <https://doi.org/10.1016/j.geomorph.2016.11.006>, 2017

Abstract

Alpine glaciers have been retreating at extreme and historically unprecedented rates. While the general course of regional retreat rates reflects long-term climatic change, individual extreme events are closely related to the geomorphological settings and processes of the specific glacier. Nevertheless, these extreme events also influence the regional means and might be an important feedback mechanism accelerating the response of glaciers to climate change. In 2009, during the recent disintegration of the terminus of Gepatschferner ($46^{\circ}52'30''N$, $10^{\circ}45'25''E$), a shallow circular depression appeared at the glacier tongue with a decrease of surface ice flow velocity to almost nil. In 2015 the area was ice-free. During a heavy precipitation event in August 2012, a subglacial sediment layer of $> 10\text{ m}$ was flushed out, which accelerated the subsidence of the ice surface. The development of this 15 to 30 m deep depression was monitored with a combination of methods in high detail, including direct ablation measurements and a time series of seven high-resolution airborne laser DEMs, plus recordings of ice flow velocity and surface elevation with DGPS. The thickness of ice and sediment layers was measured with vibroseismic soundings in 2012 and 2013. Similar developments were observed at three other glaciers with extreme retreat rates. Our investigation suggests that this mechanism has a major impact on and can be read as an indicator of a nonlinear increased response of glaciers to climate change.



Funnel-shaped surface depressions – Indicator or accelerant of rapid glacier disintegration? A case study in the Tyrolean Alps



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ABSTRACT

Alpine glaciers have been retreating at extreme and historically unprecedented rates. While the general course of regional retreat rates reflects long-term climatic change, individual extreme events are closely related to the geomorphological settings and processes of the specific glacier. Nevertheless, these extreme events also influence the regional means and might be an important feedback mechanism accelerating the response of glaciers to climate change. In 2009, during the recent disintegration of the terminus of Gepatschferner (46°52′30″N, 10°45′25″E), a shallow circular depression appeared at the glacier tongue with a decrease of surface ice flow velocity to almost nil. In 2015 the area was ice-free. During a heavy precipitation event in August 2012, a subglacial sediment layer of >10 m was flushed out, which accelerated the subsidence of the ice surface.

The development of this 15 to 30 m deep depression was monitored with a combination of methods in high detail, including direct ablation measurements and a time series of seven high-resolution airborne laser DEMs, plus recordings of ice flow velocity and surface elevation with DGPS. The thickness of ice and sediment layers was measured with vibroseismic soundings in 2012 and 2013. Similar developments were observed at three other glaciers with extreme retreat rates. Our investigation suggests that this mechanism has a major impact on and can be read as an indicator of a nonlinear increased response of glaciers to climate change.

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1. Introduction

The retreat of mountain glaciers is one of the most prominent and visible indicators of climate change (Vaughan et al., 2013). In the 21st century, retreat rates reached a historically unprecedented level (Zemp et al., 2015). Not all glacier types and sizes are affected similarly and simultaneously by climate change. In the Eastern Alps, apart from regional differences, large valley glaciers are most strongly affected, while smaller glaciers at high elevations retreat more slowly (Abermann et al., 2011). The reason for the higher sensitivity of larger glaciers is the role of ice dynamics: decreasing ice flow velocities reduce the inflow of ice into glacier tongues (Fischer et al., 2013), accelerating thickness loss more than the ablation rates. As, globally, velocity measurements are sparse and time series

are short, the question that arises is whether this mechanism is accompanied by a geomorphological feature allowing a remote-sensing-based detection of such situations. One candidate for such an indicator is circular depressions surrounded by circular crevasses. These depressions with surrounding crevasses have been widely observed, the most prominent one at the Gjalp eruption site on Vatnajökull caused by glacier melt induced by subglacial volcanic activity (Björnsson, 2002). A subglacial lake formed, and lowering of the lake level resulted in subsidence of the glacier surface (Magnusson et al., 2007). Similar geomorphological features are reported by Howat et al. (2015) caused by an outburst of a subglacial meltwater lake beneath the Greenland Ice Sheet. On a smaller scale, a similar depression with circular crevasses formed by an outburst of a subglacial melt water lake was described by Konrad (1998) for a small mountain glacier in the Sierra Nevada. Subglacial drainage systems play an important role in storage and release of water (e.g. Nye, 1976; Funk and Röthlisberger, 1989; Hooke and Pohjola, 1994).

Apart from those depressions related to subsurface energy, surface depressions can also be related to the evolution of supraglacial lakes. There, increased heat flux towards the ice leads to the formation of

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the depression (Huss et al., 2013). In the accumulation area, surface depressions can also be formed by wind erosion (e.g. Lehning et al., 2008; Dadic et al., 2010). The formation of these depressions is not accompanied by the formation of circular crevasses.

Srbik (1937) observed surface depressions with circular crevasses during the collapse of glacier tongues in the Eastern Alps during an earlier period of extreme glacier retreat. In contrast to the above described depressions, these were situated close to the glacier terminus. Tsutaki et al. (2011) found similar geomorphological features during the retreat of the Rhone glacier and recorded surface ablation, ice thickness, surface velocity as well as volume changes during two years of investigating the impact of proglacial lake formation on ice dynamics and glacier evolution. They found an increase in ice flow velocity related to the formation of a proglacial lake, which remained after the ice retreated.

The funnel-shaped depression can thus evolve from different supra-, intra- and subglacial processes. Detailed and quantitative observations of the evolution and processes on mountain glaciers are sparse, but needed for the interpretation of these features.

On the terminus of the extremely retreating Gepatschferner (46°52'30"N, 10°45'25"E, Ötztal Alps), a surface depression evolved during a larger project focusing on comprehensive investigations of the morphodynamics and sediment budgets (e.g. Heckmann et al., 2012). The detailed surveys of surface mass balance, surface elevation, thickness and thickness changes of the glacier and subsurface sediments provided a detailed record of the evolution of this surface depression from the early beginning to the disintegration of the glacier tongue.

Surface mass balance was measured directly, by readings of ablation stakes and results from energy exchange with the atmosphere and mass gain by snow falls (Cuffey and Paterson, 2010). Local thickness changes result not only from surface mass balance but also from englacial and basal mass balance, ice dynamics and basal erosion and deposition of sediment as well as changes in water level in case of subglacial lakes (Cogley et al., 2011). Seven high-precision laser scan DEMs allowed determining the geodetic mass balance by calculating volume changes. These volume changes thus reflect surface mass balance and englacial and basal processes, as reported during the evolution of subglacial lakes. The comparison of directly measured surface mass balance to geodetic mass balance gives an indication of the role of englacial and subsurface processes, which can be validated by changes in ice thickness and subsurface sediment revealed by vibroseismics. The surface ice flow velocity was measured at the ablation stakes with DGPS. Surface elevation between the dates of the LiDAR flights was also recorded with DGPS along profiles across the depression to gain a more detailed picture of the temporal evolution of the depression, giving the first direct and qualitative process study of the formation of a circular depression on the terminus of a mountain glacier. The phenomenon of surface depression, followed by a collapse of the glacier tongue, at Gepatschferner is compared to three similar features at other extremely retreating Eastern Alpine glaciers. Although further data in other regions and for other glacier types are needed, the results can serve as a starting point for a discussion of the interpretation of depressions as indicators for extreme glacier retreats from remote sensing images, where neither repeat imagery nor elevation information is available.

2. Study sites

Gepatschferner is situated in the Ötztal Alps and mainly exposed to the north. The glacier covered an area of 15.6 km² in 2012. Together with the Italian part of the glacier (the Austrian – Italian border follows the ice divide at the plateau), Gepatschferner is the largest glacier of the Eastern Alps. The flow velocity of the tongue is still very high with maximum values of >50 m per year due the large firn area above 2900 m a.s.l. and the massive ice mass is moving

towards a narrow outlet valley where the tongue has an average width of about 300 m down to an elevation of 2200 m a.s.l. The tongue is exposed to the northwest and reaches a thickness of >100 m (Span et al., 2005) and surface velocities of up to 50 m per year before it turns to the west in the lowest part. The surface depression is located at the lowest part of the tongue, where the surface velocity slows down to almost nil (<1 m/a). The depression occurred on the orographic right of the tongue at about 2300 m a.s.l., close to the glacier margin (Fig. 1, Annex A1). The extent of the depression on Gepatschferner and the changes therein are compared to the depressions on the nearby glaciers Mittelbergferner, Sulztalferner and Hintereisferner (Fig. 1).

The surface depression on Mittelbergferner (46°55'50"N, 10°54'8"E, Pitztal Alps) is located directly at the snout of the glacier (Annex A2). The glacier itself is a typical valley glacier and covered an area of 9.9 km² in 2006. The smallest of the four glaciers is Sulztalferner (47° 0'35"N, 11° 4'50"E, Stubai Alps), with an area of 3.7 km² in 2006, the funnel occurred at the very flat part of the glacier tongue (Annex A3). The depression on Hintereisferner (46°48'35"N, 10°46'55"E, Ötztal Alps) is also located close to the terminus (Annex A4). Hintereisferner is a typical valley glacier and covered an area of 7.5 km² in 2006. All of these glaciers showed extreme retreat rates in recent years (Fischer et al., 2013). Information about the extent of the glaciers is given by the Austrian glacier inventories (Patzelt, 1980; Groß, 1987; Lambrecht and Kuhn, 2007; Kuhn et al., 2012; Fischer et al., 2015).

3. Methods

3.1. Airborne laser scans

DoDs (DEM of Difference) between multiple high-resolution ALS (Airborne Laser Scan) data (Abermann et al., 2010; Wheaton et al., 2010) were calculated and revealed elevation changes (resulting from basal and surface melt, ice flow and changes of subglacial sediments). DEMs with a grid size of 1 × 1 m were generated from the mean elevation value of the point clouds and are available for the years 2006, 2009, 2010, 2011, two datasets in 2012 and 2014 within an area (circle) of 80 m radius around the centre of the depression. The basis for a calculation of DoDs is, first, the same resolution of each grid and, second, the same reference system (in this study: ETRS89 UTM 32N). An exact overlay of the individual cells of each raster is a basic requirement for calculating raster differences. The DoDs were calculated with ArcGis software by using the tool 'minus (spatial analyst)'.

Given the size of the depression, the area of interest was defined as a circle (A_c) with a radius of 80 m (below referred to as '80 m circle') around the maximum elevation change (centre of the depression) for the period 01.09.2006–18.07.2014 as a reference area for the definition of the depression. The size of the depression (A_d) is defined as the area within a boundary of 20% higher elevation changes than the mean elevation change within the whole 80 m circle (Δh_c). Since there is no similar study in the literature, tests with different threshold values were made. The value of a mean elevation change plus 20% was chosen to separate increased elevation changes at the depression area from the range of elevation changes of the surroundings, which in turn allows a comparison of the different DoDs. So the depression is defined as the area where elevation decreased by >20% of the average decrease observed in the 80 m circle. Values higher or lower than 20% either excluded too much of the depression area or included even surrounding features. In addition, area and volume changes were calculated for the whole period (01.09.2006–18.07.2014), based on a depression with a $\Delta h_c + 5\%$ boundary (* in Tables 1,2). The area between the depression and the defined boundary of the 80 m circle is defined as the ring (A_r) and represents the area outside the depression. Subglacial changes within the area of

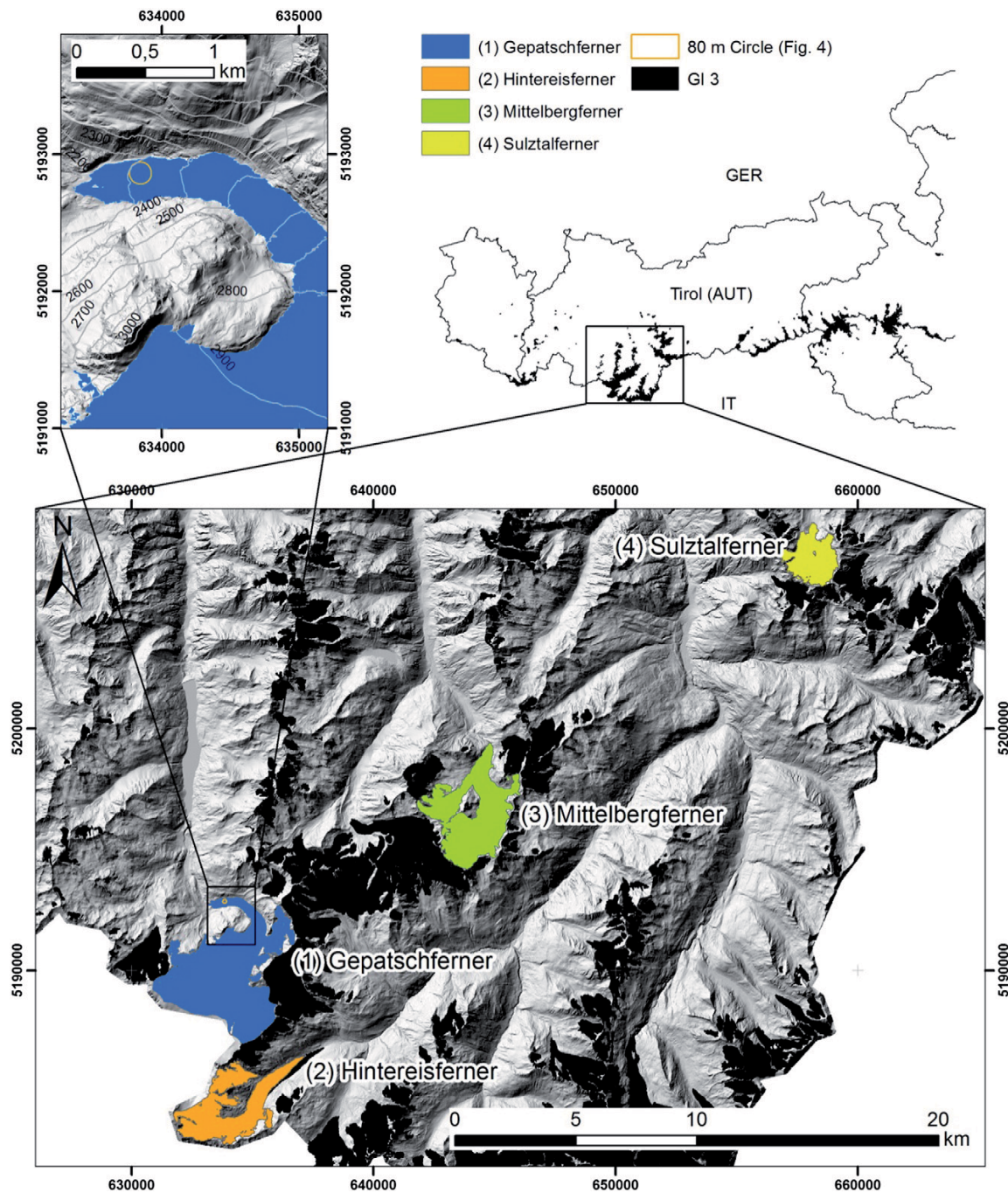


Fig. 1. Overview of the locations of Gepatschferner (1), Hintereisferner (2), Mittelbergferner (3), and Sulztalferner (4) and the location of the depression on Gepatschferner at the 80 m circle (Fig. 4) (background: Hillshade 2006). GI3: Third Austrian Glacier Inventory (Fischer et al., 2015).

the depression ($\overline{\Delta h_c} + 20\%$ and $\overline{\Delta h_c} + 5\%$) were calculated from the total volume changes within the depression (ΔV_d) less the volume changes calculated with a mean elevation change of the ring (Δh_r) but related to the area of the depression (A_d). The information of mean volume changes per day was chosen to make the different timescales of the ALS periods comparable.

3.2. Surface mass balance

Direct (glaciological) mass balances (Cuffey and Paterson, 2010) have been recorded at the tongue of Gepatschferner since 2009 with the help of ablation stakes. One of the stakes was installed very close to the later surface depression, which first became evident as a shallow

Table 1

Mean elevation changes within the 80 m circle ($\overline{\Delta h_c}$), the ring ($\overline{\Delta h_r}$) and the depression ($\overline{\Delta h_d}$), as well as the maximum elevation change within the depression. A_d : Area of the depression ($\overline{\Delta h_c} + 20\%$). A_r : Area of the ring (the area between the 80 m circle and the beginning of the depression in Fig. 4). Area of the circle: 20,073 m². * calculated for the depression $\overline{\Delta h_c} + 5\%$.

Period			A_r (m ²)	A_d (m ²)	$\overline{\Delta h_c}$ (m)	$\overline{\Delta h_r}$ (m)	$\overline{\Delta h_d}$ (m)	Δh_d max. (m)
30.09.2009	–	18.07.2014	18,392	1681	–28.8	–27.7	–39.9	–47.0
28.09.2012	–	18.07.2014	17,754	2319	–11.4	–10.7	–16.6	–22.6
04.07.2012	–	28.09.2012	17,567	2506	–6.2	–5.8	–9.4	–15.4
07.10.2010	–	04.07.2012	17,859	2214	–4.7	–4.5	–6.5	–7.8
30.09.2009	–	07.10.2010	17,916	2157	–6.4	–6.2	–8.5	–9.5
01.09.2006	–	30.09.2009	$\Delta h_d < (\overline{\Delta h_c} + 20\%)$		–20.4			
01.09.2006	–	18.07.2014	18,978	1095	–48.9	–48.1	–63.5	–68.8
01.09.2006	–	18.07.2014	16,723*	3350*	–48.9	–47.2*	–57.3*	–68.8

deepening at the end of 2009. The ablation was measured and the position of the stake was reinstalled regularly until 2014. In 2013, a new stake was installed outside the depression.

3.3. Vibroseismics

Vibroseismic investigations came into operation as part of a field campaign to investigate the thickness of subglacial sediment layers on the tongue of Gepatschferner. Measurements with the ELVIS vibrator source (Eisen et al., 2010; Polom et al., 2013) at 71 geophones on a profile length of 142 m within a sweep of 10 s in a frequency range between 30 Hz and 240 Hz were performed in April 2012 and repeated in April 2013 (30 Hz–160 Hz) at the same locations marked with DGPS. The processing of the vibroseismic data was done with ‘SPW’ (Seismic Processing Workshop) software separated into pre-processing, signal enhancement, velocity analysis and stacking, post stack processing and the depth conversion and migration. The depth conversion from the signal travel time is based on the calculation of the ‘Dix’ velocities on a depth interval of 0.1 m. The seismic section was interpreted in relation to the surrounding topography and the DGPS measurements at the bottom of the depression. The verification of the interpretation of the bedrock topography was done in 2015 as the depression became ice free (Annex A5).

3.4. DGPS measurements

Surface elevation and the positions of the ablation stakes were recorded with DGPS (Gepatschferner: Topcon Hiper V; Hintereisferner: Trimble Zephyr 2). The elevation change was calculated with a DoD.

The depression on Hintereisferner was subject to investigations using DGPS and DoDs (Haberkorn, 2011). The DoD of this area was recalculated (Annex A4). On Sulztalferner the depression occurred after the latest available DEM, therefore the size and temporal development is estimated from terrestrial and aerial photos.

3.5. Errors and accuracy

The accuracy of the direct stake measurements is assumed to be ± 0.01 m of each reading and ± 0.02 m for the period between the readings. The extrapolation of the ablation to the surrounding area reduces the accuracy of specific mass balance to ± 0.1 m w.e. (Kuhn et al., 1999).

The vertical uncertainty of the DGPS measurements varies in time and depends on the processing methods (Monteiro et al., 2005). On Gepatschferner, the accuracy with post-processing was ± 0.1 m at its best. With the further development of the depression and shading effects, the uncertainty of the point measurements was ± 1.5 m at its worst, giving a range of ± 0.2 m to ± 3 m for the elevation changes determined with DGPS. Note that the accuracy of the direct stake reading refers only to the surface ablation. The accuracy of the DGPS measurements refers to the total elevation change at the stake, which is important with respect to the DEM surface.

For the DoDs the vertical accuracy is ± 0.4 m or ± 0.2 m for each DEM (Bollmann et al., 2011). The ALS surveys of 2012 and 2014 were aimed at higher point densities (10 points/m²) and thus higher accuracies of the raster DEMs, which should be in the range of ± 0.04 m for the DoD.

Information on the accuracy of vibroseismic soundings using a shear-wave vibrator is problematic for the profile at the surface depression and can only be estimated due to the missing information of the shear-wave velocities for subglacial sediments, the bedrock and the unknown but expected high complexity of the surrounding topography and because of the limited length of the profiles, especially in 2013. An accuracy of 10% of the ice thickness or ± 5 m at the profile on Gepatschferner seems a plausible estimate and is confirmed by the verification of the interpretation in 2015 (Annex A5).

4. Results

4.1. Mass balance and ice flow velocity

The surface velocity at the stake decreased between 2009/10 and 2013/14, during the first years the velocity was about 16 m per year,

Table 2

Volume change per day within the 80 m circle (ΔV_c), the ring (ΔV_r), the depression (ΔV_d) as well as a calculated subglacial volume change per day. *calculated for the depression $\overline{\Delta h_c} + 5\%$.

Period			Days	ΔV_c [m ³]	ΔV_r [m ³]	ΔV_d [m ³]	ΔV_d subglacial [m ³]
30.09.2009	–	18.07.2014	1752	–330	–291	–38	–12
28.09.2012	–	18.07.2014	658	–348	–289	–59	–21
04.07.2012	–	28.09.2012	86	–1447	–1185	–274	–105
07.10.2010	–	04.07.2012	636	–148	–126	–23	–7
30.09.2009	–	07.10.2010	372	–345	–299	–49	–13
01.09.2006	–	30.09.2009	1125	–364	$\Delta h_d < (\overline{\Delta h_c} + 20\%)$		
01.09.2006	–	18.07.2014	2877	–341	–317	–24	–6
01.09.2006	–	18.07.2014	2877	–341	–274*	–67*	–12*

Table 3

Distance [m] and horizontal flow velocities [cm/d] of the ablation stake between each position along the cross-profile (Fig. 2).

Position	Distance [m]	Velocity [cm/d]	Position	Distance [m]	Velocity [cm/d]
1 – 2	8.1	7	8 – 9	7.9	3
2 – 3	16.0	5	9 – 10	0.1	2
3 – 4	Relocated		10 – 11	0.9	4
4 – 5	3.8	6	11 – 12	Relocated	
5 – 6	10.5	4	12 – 13	0.3	1
6 – 7	2.4	6	13 – 14	8.7	1
7 – 8	3.0	7			

decreasing to 10 m per year in 2011/12 and to almost nil with <1 m per year in 2013/14 (Table 3). The positions 3 and 4 (Fig. 2) belong to the same date (11.08.2010) as the stake was reinstalled up-glacier close to its original position.

The ablation at the stake decreased with time, as the steep ice walls of the funnel shaded the bottom of the depression. 1.09 m of ice melt was recorded during the presence of the supraglacial lake, in contrast to 3.26 m of ice melt during the same period at the stakes outside the sink, a reduction of 66% of the surface ablation under a large water column and shading effects.

4.2. Volume changes

In order to quantify the magnitude of the elevation changes as the depression developed, the DEM of 2006 was chosen as the reference before the onset of the deepening. Mean volume changes per day were calculated for the area within a radius of 80 m around the centre of the depression since 01.09.2006 (Figs. 3,4). The flight dates of the ALS campaigns are shown in Fig. 3 together with the mean values of each period. The elevation and volume change rates are given in Table 1 and Table 2. The mean volume change per day between

01.09.2006 and 18.07.2014 is $-341 \pm 2 \text{ m}^3$ within the 80 m circle, which corresponds to a mean elevation change of $-48.9 \pm 0.2 \text{ m}$ between the two dates. The maximum value, which is located in the middle of the depression, amounts to $-68.8 \pm 0.2 \text{ m}$ during the same period (01.09.2006–18.07.2014). The period in summer 2012 (04.07.2012–28.09.2012) shows a strongly negative value of $-1447 \pm 9 \text{ m}^3$ per day for the whole area, corresponding to a mean elevation change of $-6.2 \pm 0.1 \text{ m}$ within 86 days. The maximum change of the surface height was $-15.4 \pm 0.1 \text{ m}$ during the same period (04.07.2012–28.09.2012). The subglacial volume change, by separating the volume changes between the depression and a mean elevation change of the ring related to the area of the depression, amounts to $-105 \pm 6 \text{ m}^3$ per day between 04.07.2012 and 28.09.2012.

4.3. Thickness of ice and basal sediment

About half of the vibroseismic profile in 2012 lies in the depression (the location of the profile is shown in Fig. 4a). In 2013 the measurements were limited to the lower part of the profile, which is located outside of the sink, because of the steepness of the depression and the supraglacial lake. The interpretation of the vibroseismic sections of 2012 and 2013 shows the bedrock and subglacial sediment layers (Figs. 5,6). The lines 1 and 2 represent the glacier surface measured with DGPS at each Geophone in 2012 and 2013; the dots mark the bottom of the depression in August 2013 and June 2014 measured with DGPS. The bedrock of the interpretation of 2012 and 2013 is represented by the lines 3 and 4. The interpretation of the vibroseismic sections was done with respect to the point measurements at the bottom of the depression and the proximity of the glacier margins and gives a maximum ice thickness of $48 \pm 5 \text{ m}$ in 2012 and sediment layers with a maximum thickness of $20 \pm 5 \text{ m}$.

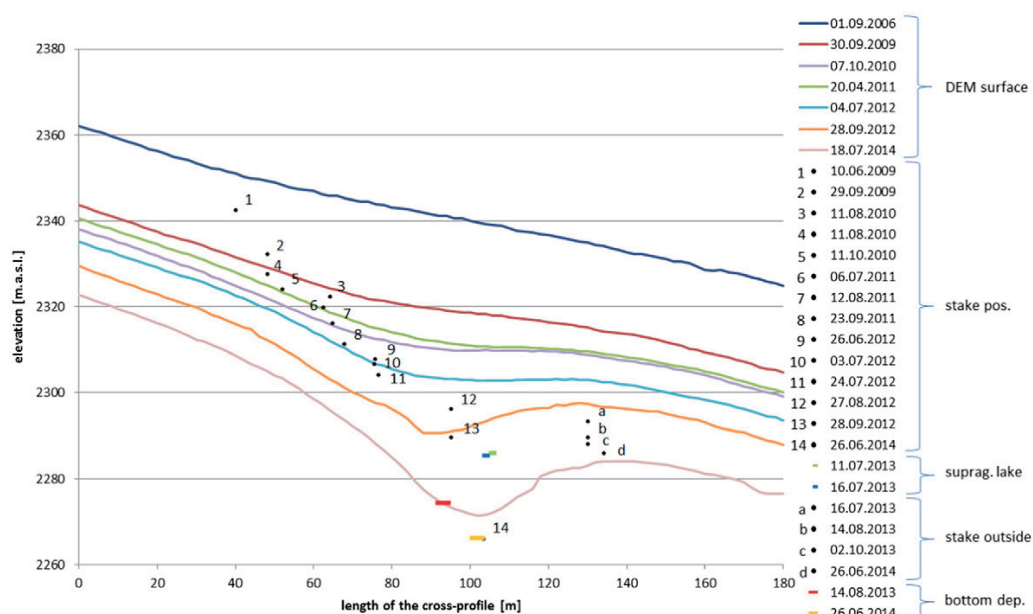


Fig. 2. Elevations of the DEMs along the cross-profile (shown in Fig. 4) and position of the stakes, the elevation of the supraglacial lake and the bottom of the depression as well as the position of a new stake outside the depression. The positions of the ablation stake and additional measurements with DGPS along the profile show the ongoing development until 2014.

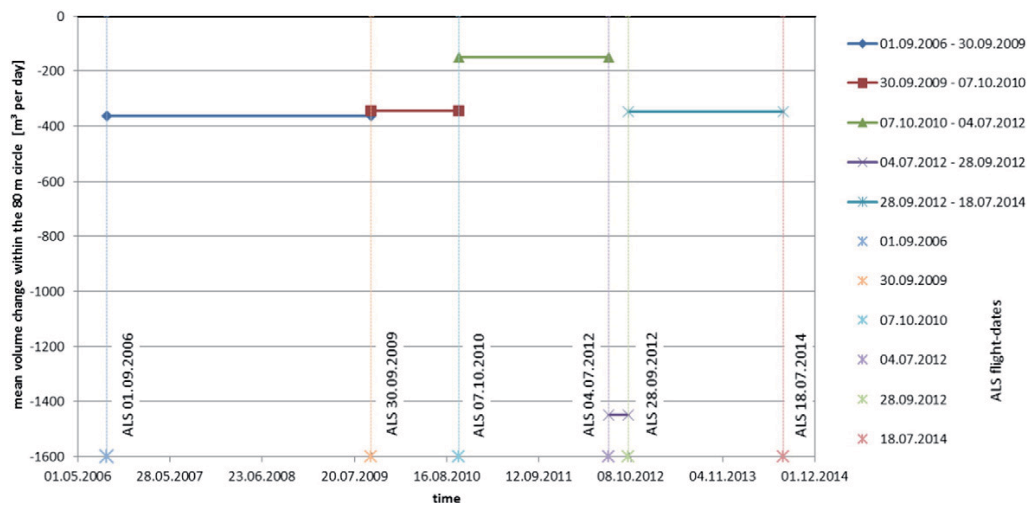


Fig. 3. Mean volume changes per day of the DoDs (DEM of Difference) between the different ALS flights within the 80 m circle (20,073 m²).

4.4. Comparison of geodetic and direct measurements

For a comparison of changes from DoDs and direct stake readings and DGPS measurements, the different time periods must be taken into account. Mean daily change rates were calculated for the DoDs (Table 2). The height differences of the ablation stake to the surface of the DEM in 2006 along the cross-profile (Figs. 2,4) between each measurement date are shown in Fig. 7. The height difference of the DEM 2006 surface to the supraglacial lake and to the bottom of the depression is also shown in Fig. 7. The maximum subsidence, calculated for the stake measurements, was 16.6 ± 1.5 cm per day for one month (27.08.2012–28.09.2012) with a starting point just after the heavy precipitation event.

4.5. Heavy precipitation event

The acceleration of the sink process started after a heavy precipitation event on 25.08.2012, with a maximum flood at 1:00 am on 26.08.2012 and a peak discharge of $47.3 \text{ m}^3 \text{ s}^{-1}$ (mean discharge 2012: $3.42 \text{ m}^3 \text{ s}^{-1}$) at the gauging station Gepatschalm in the forefield of Gepatschferner (Baewert and Morche, 2014). Precipitation was measured at two weather stations, Gepatschalm and Weißsee, which are located about 3 km and 3.5 km away from Gepatschferner. Between 06:30 pm (25.08.2012) and 01:15 am (26.08.2012), the measured precipitation amounted to 37.6 mm and 38.1 mm at the two stations.

4.6. Supraglacial lake

During the winter months 2012/13 a supraglacial lake filled the depression (Annex A1), indicating the closure of the drainage system during winter months (e.g. Stenborg, 1965). The surface level of the lake was also measured with DGPS in July 2013 and returned variations of up to 0.5 m within 1 day. Between 17.07.2013 and 14.08.2013 the lake emptied and the bottom topography was surveyed with DGPS (Fig. 2) representing the depth of the funnel-shaped surface depression at its maximum depth. The difference between the lake surface on 16.07.2013 and the bottom on 14.08.2013 was -11.6 ± 1.6 m (estimated water volume: $1250 \pm 200 \text{ m}^3$, diameter surface: ca. 15 m, diameter bottom ca. 8 m).

5. Discussion

The shallow deepening started in 2009 and slowly progressed until August 2012, with subsequent acceleration of the sink process. The process is indicated by the decrease in surface elevation, shown along a cross section in Fig. 2. The DEM in 2006 shows no surface depression and the slope was nearly constant along the profile. In July 2014 a distinct depression is visible (Fig. 2). For the calculation of the depth of the depression, the lowest elevation within the depression is compared to the elevation of a straight line extrapolating a constant inclination of the ice surface in the surrounding of the depression. In July 2014 the lowest point of the depression was 26 m lower than the flat surface extrapolated from the surrounding slope. The cross section, defined at the beginning of the measurements, did not in the end run across the deepest point of the depression. The ablation stake at position 14, which was drilled at the deepest point, was about 6 m lower than the lowest point of the profile. All other stakes were located within the profile, showing a continuous deepening of the depression at variable speed.

Surface elevation changes result from surface mass balance as well as from basal and englacial processes and from ice dynamics. To confine the contribution of basal and englacial processes to the total volume change, surface mass balance can be estimated from the stake measurements. The recorded ablation rates are lower than 10 cm/day. The daily subsidence rates are similar to the ablation at all times, apart from the summer of 2012, when subsidence was several times the ablation.

In contrast to increased flow velocities reported by Tsutaki et al. (2011), we found a decrease of the surface velocity from seven to 1 cm per day over time, apart from the period with the extreme precipitation event (Table 3). The stake at position 12 was measured shortly after the extreme precipitation event documented by the precipitation records. The subsidence as well as the horizontal ice flow velocity in this period was the highest recorded (Fig. 2). As surface mass balance did not show significant changes, a significant impact on the subsidence can be attributed to the internal and subglacial changes. The relocation of the glacier river (Annex A6) and significant changes in the proglacial morphology (Baewert and Morche, 2014) are other indications of basal processes causing sediment erosion. The results of the vibroseismic measurements exclude changes in water and air content beneath the ice.

During the presence of the supraglacial lake, the surface ablation of the water-covered ice surface was reduced. This reduction can be explained with the reduced incoming short wave radiation due to shading

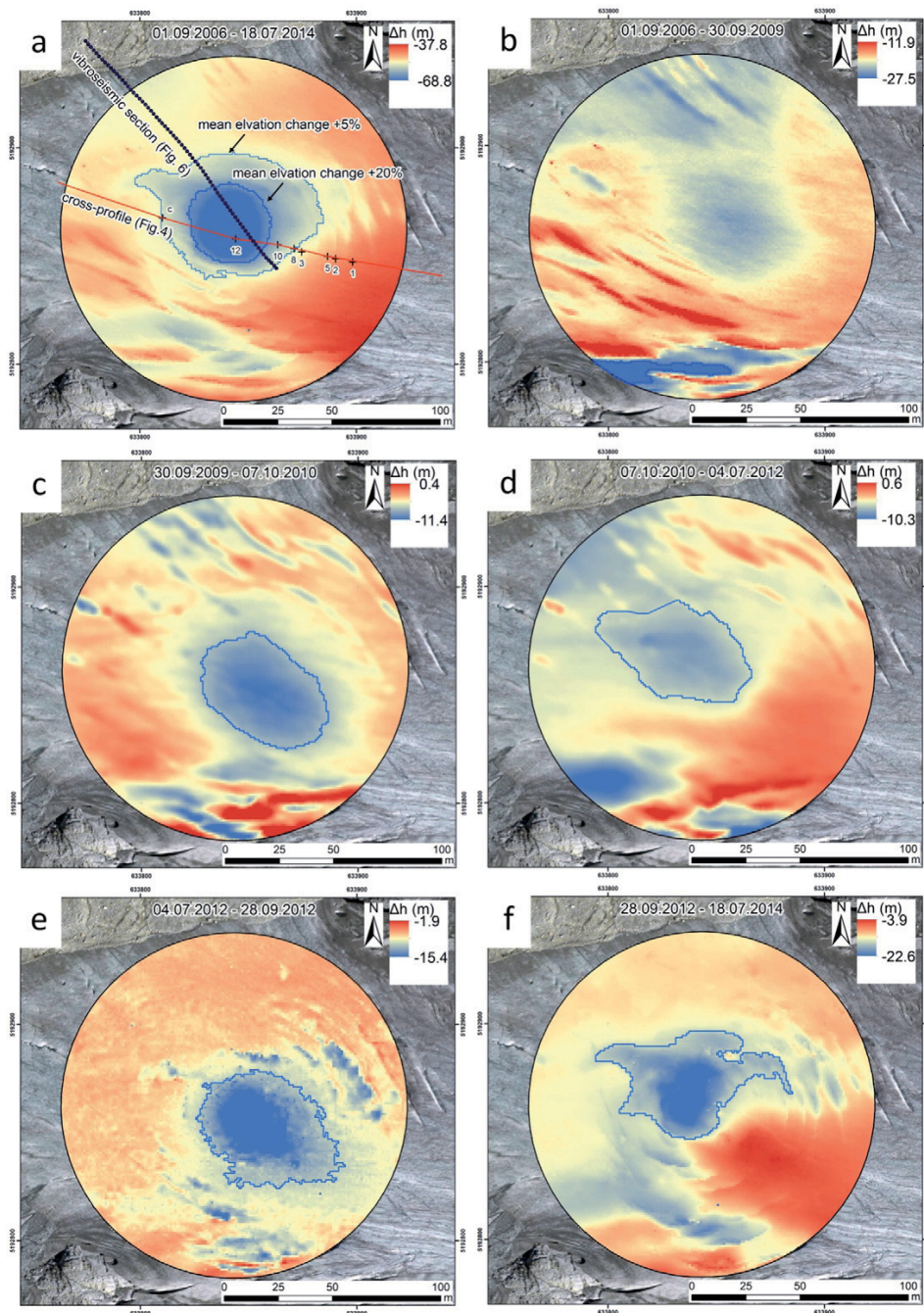


Fig. 4. DoDs (DEM of Difference) between 01.09.2006 and 18.07.2014 within the 80 m circle on the tongue of Gepatschferner (Fig. 1). The location of the ablation stakes at the cross-profile (Fig. 2) through the depression is shown as well as the location of the vibroseismic profile (Fig. 6).

at the lake by steep ice walls. The increased surface ablation measured at the supraglacial lake on Glacier de la Plaine Morte by Huss et al. (2013) might result from different radiative settings.

The vibroseismic data are interpreted on the assumption of different substrates with different signal velocities. The complex topography and interference from multiple reflections from the surrounding slopes introduce additional uncertainty. Discussing these becomes even more

important at the short profile in 2013. In July 2015 the bottom of the depression became ice-free and even the subglacial meltwater channel became visible at the back of the depression as well as a solid rock in front of it (Annex A5).

A time series of images shows the development of the geometry of the funnel since 27.08.2012 (Annex A1) as well as the 3D model of the DEM since 2006 (Annex A7). This confirmed the vibroseismic

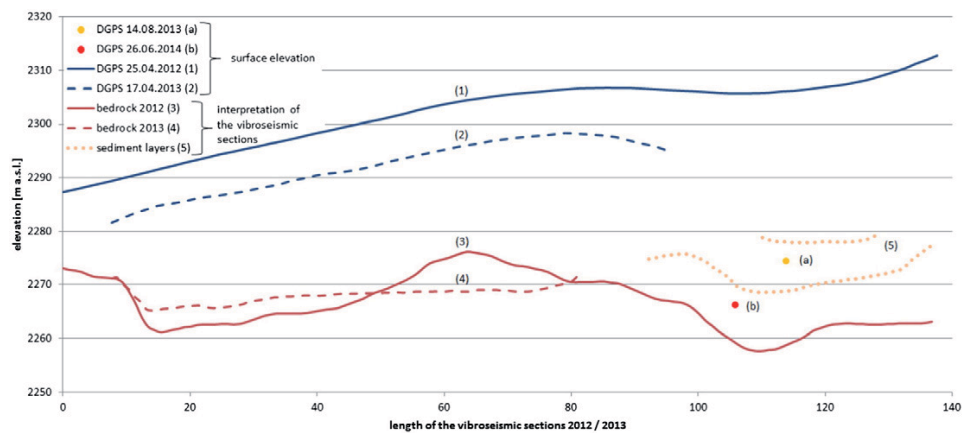


Fig. 5. Interpretation of the vibroseismic sections (3, 4) in 2012 and 2013 (location s. Fig. 4a). The lines 1 and 2 show the glacier surface measured with DGPS at each Geophone in 2012 and in 2013. The bottom of the surface depression measured with DGPS is given as dots (a, b), the location of sediment layers of 2012 as dotted lines (5).

interpretation. The remaining ice-thicknesses were plausible regarding the ongoing retreat of the tongue ([Annex A6](#)). The thickness of the subglacial sediment layers fits with the magnitude of the elevation change during the sink process. Based on the accuracy of the measurements, a remaining error of $\pm 10\%$ (max. ± 5 m) for the bedrock and the sediment layers has to be taken into account. The displacement of a subglacial meltwater channel during a heavy precipitation event and the evacuation of subglacial sediments were earlier reported by [Haeberli \(1980\)](#) and [Warburton \(1994\)](#). The dislocation is also possible with respect to the complex topography which becomes ever more evident as the tongue retreats further (picture in [Annex A6](#)).

5.1. Comparison with depressions at other glacier tongues

Since the year 2000, the retreat of Gepatschferner has clearly been above the average of the surveyed Austrian glaciers ([Fischer et al., 2013; Annex A8](#)). Between 2013 and 2015, Gepatschferner was one of the glaciers with the largest absolute length losses, amounting to about 100 m per year. The extreme retreat rates occurred simultaneously with the depression. As a first check if the formation of depressions could be considered a geomorphological feature intrinsically linked to rapid retreats or even a mechanism behind large retreat rates, we analysed depressions at three other glaciers.

The funnel at the snout of Mittelbergferner ([Annex A2](#)) had a diameter of approximately 250 m and the elevation changed continuously in total to about -80 m within 9 years (DoD 1997–2006) in contrast to -28 m at the surrounding area of the tongue during the same period, leading to a difference of more than five meters per year. The specific topography with a bedrock sill in the front, lateral water inflow of the main meltwater discharge of a neighbouring glacier and technical measures by actors from a glacier ski resort to reduce snow and ice ablation ([Olefs and Fischer, 2008](#)) at the terminus reinforced the formation of this depression. The length change of Mittelbergferner is not surveyed annually, but the loss of glacier length can be estimated from the glacier inventories ([Fischer et al., 2015](#)) at about -20 m per year (from 1997 to 2015) and therefore also above average.

On Sulztalferner ([Annex A3](#)) a sink developed in 2007 on the very flat part of the tongue shortly after a steep slope and another sink in 2008 in the immediate proximity of the first one. Each of them developed within one year, with an elevation change of about 20–30 m and diameters of up to 125 m. The main process of the formation of these depressions was triggered by the subglacial drainage system, lateral inflow and the formation of subglacial lakes, which became visible with the ongoing retreat. In 2011 the whole area became ice free. Sulztalferner showed its largest length changes in 2005 and 2007.

On Hintereisferner ([Annex A4](#)) a shallow depression became visible in 2004 and has developed continuously since. The DoD of 26.09.2003–

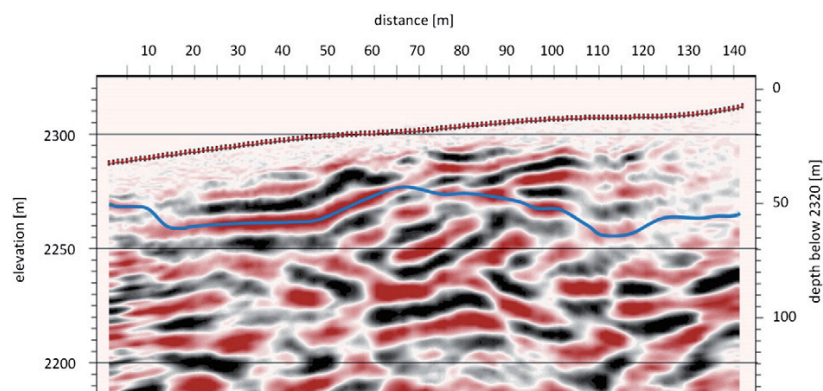


Fig. 6. Interpretation of the bedrock topography on the seismic section in 2012.

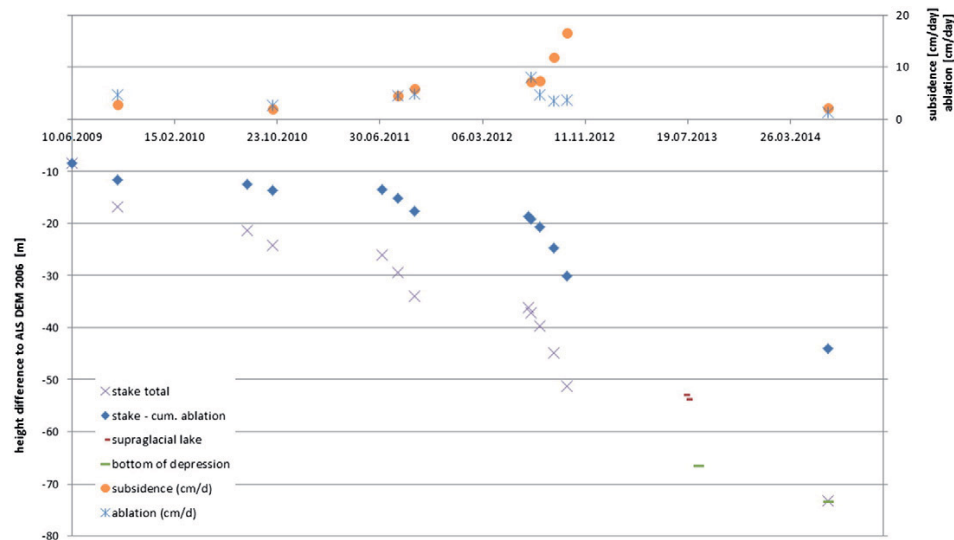


Fig. 7. Height differences of the stakes, the supraglacial lake and the bottom of the depression, compared to the ALS DEM of 2006 (left y-axis). 'Stake total': total difference between the stake elevation and the surface of the DEM 2006; 'stake – cum. ablation': 'stake total' minus the cumulative ablation. Lowering of the stake and ablation at the stake between each period per day (right y-axis).

30.09.2009 shows maximum elevation changes of -34 m within the depression in contrast to -28 m during the same period at the surrounding area calculated with the DoD, DGPS and ablation stake measurements (Haberhorn, 2011), which leads to a difference in the surface lowering of 1 m per year between the depression and the surrounding area for six years. The maximum elevation change in the whole region between 2580 m a.s.l. and 2620 m a.s.l. was -36.1 m and was found on the orographic right of the tongue as a deep meltwater channel began to form (Annex A4). The depression is still far from the terminus and Hintereisferner shows the lowest retreats of all glaciers.

What all of these depressions have in common is the location on glacier tongues close to the terminus where surface velocities are low and decreasing. The depressions are surrounded by circular crevasses indicating the subsidence. In all the depressions formation began with a slow progress in the early stage, except the depression on Sulztalferner, which developed within one year as part of the collapse of the flat part of the tongue during a phase when the tongue was separated from the upper part of the glacier.

All three funnels observed are underlain by rivers that move sediments at a higher rate. Temporary accumulation may then easily be eroded by water input following a heavy precipitation event. On Mittelbergferner and Sulztalferner the thermal heat delivered by lateral inflow and direct glaciological investigations. A slow but steady evolution of the depression on Gepatschferner was followed by a rapid increase of the formation after a heavy precipitation event. The acceleration peaked with a subsidence of 16.6 ± 1.5 cm per day for one month (27.08.2012–28.09.2012) and resulted in a depression with a maximum depth of about 30 m. The acceleration very likely

forced by the erosion of subglacial sediments during a flood event in August 2012.

The history of the retreat of Gepatschferner has been measured and documented in more detail than that of other Alpine glaciers, especially at the surface depression. Short-term measurements were performed on the tongue of Hintereisferner, while observations indicate similar behaviour of the funnels on Mittelbergferner and Sulztalferner. Their tongues still move at considerable speed and transport ice over an altitudinal range in the order of 1000 m. In that sense, while they are retreating, they are still actively adjusting to a changing climate. What we measured and observed on the tongue of Gepatschferner is thus applicable to other large, active, but retreating, glaciers and to their forefield. The situation is different with glaciers of a small altitudinal range and low flow velocities. We conclude that altitude range, subglacial water flow or later water inflow are essential criteria for the emergence of funnels on glacier tongues. Whether the occurrence of depressions can be considered an indicator of extreme retreat can only be verified after further investigations on other glaciers.

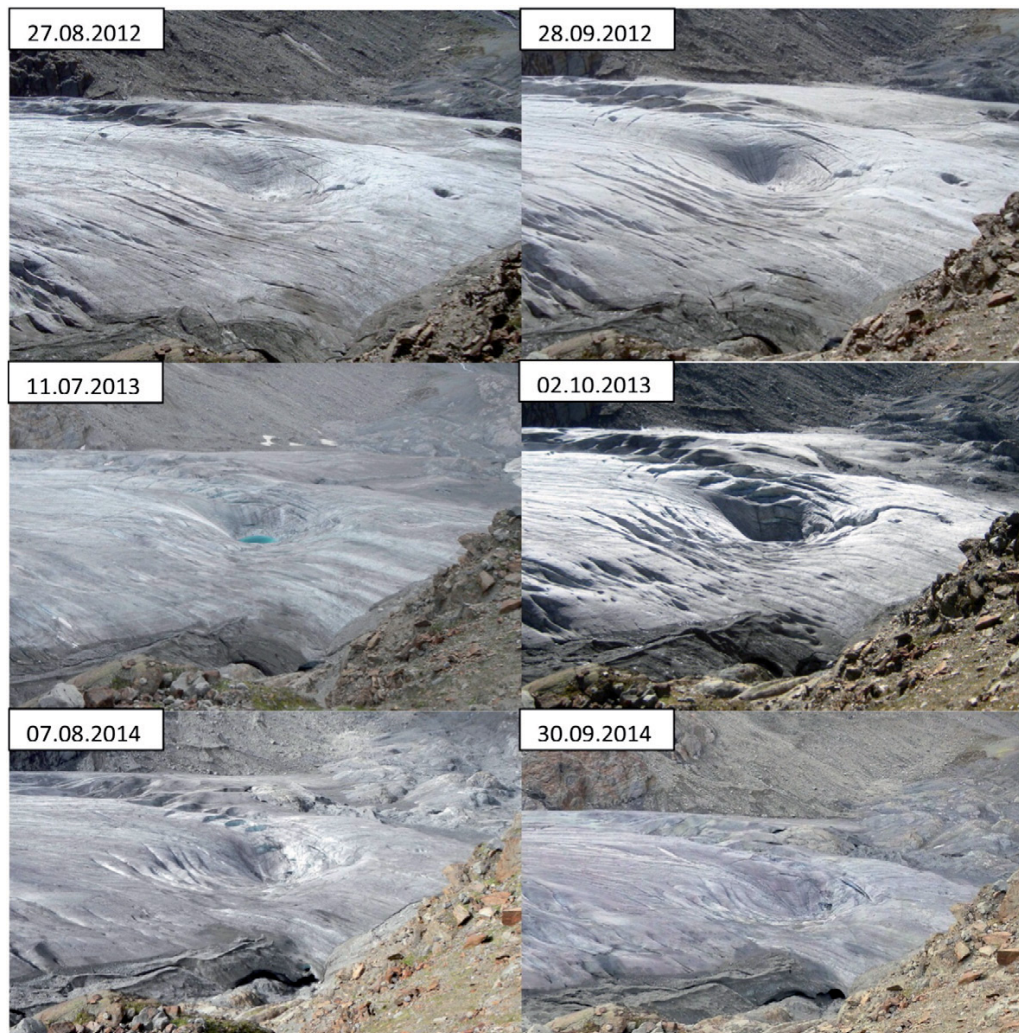
Acknowledgement

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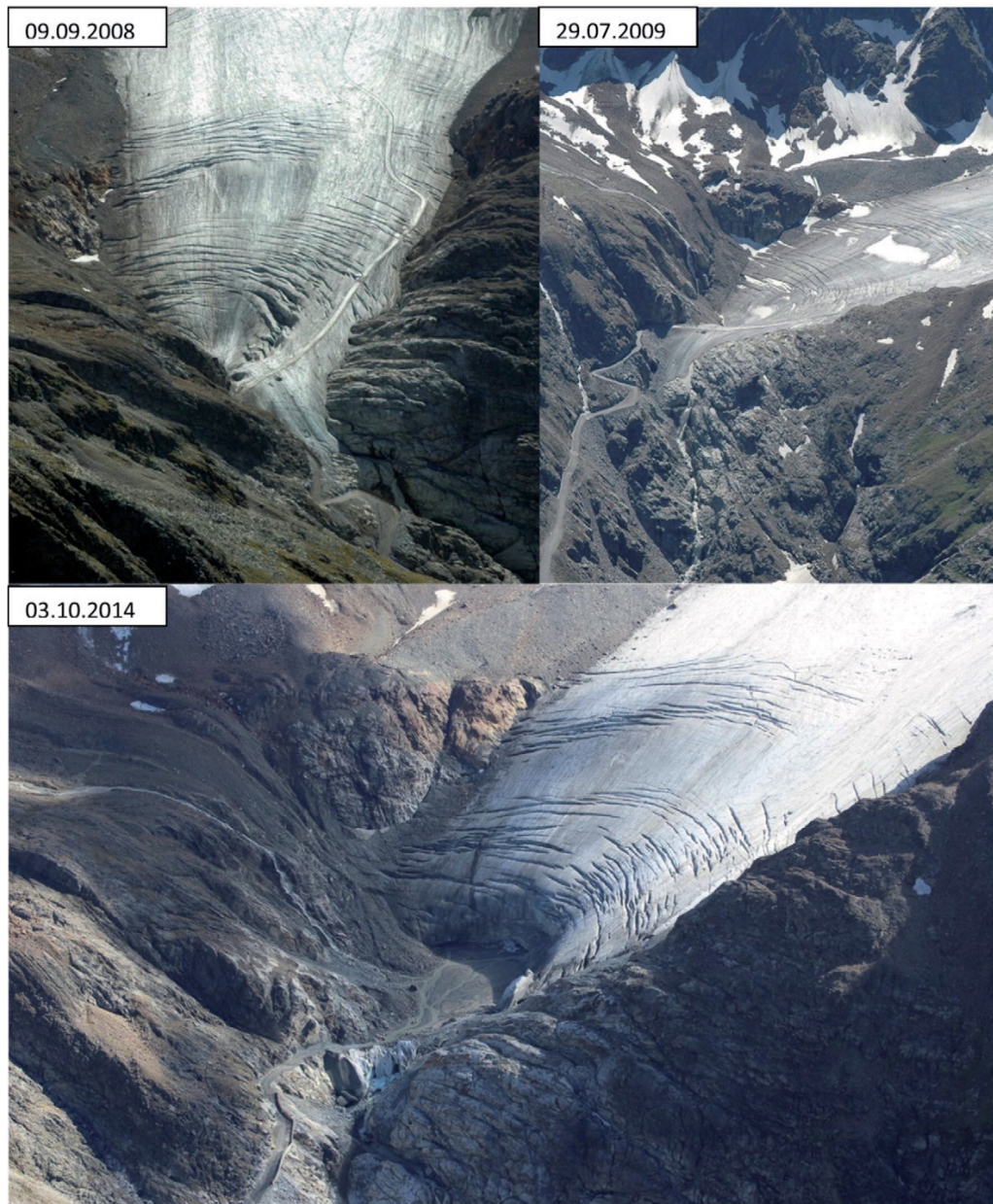
6. Conclusion

In this paper we traced the development of a deep funnel-shaped surface depression on the tongue of Gepatschferner on the basis of high resolution ALS data, DGPS measurements, vibroseismic soundings and direct glaciological investigations. A slow but steady evolution of the depression on Gepatschferner was followed by a rapid increase of the formation after a heavy precipitation event. The acceleration peaked with a subsidence of 16.6 ± 1.5 cm per day for one month (27.08.2012–28.09.2012) and resulted in a depression with a maximum depth of about 30 m. The acceleration very likely

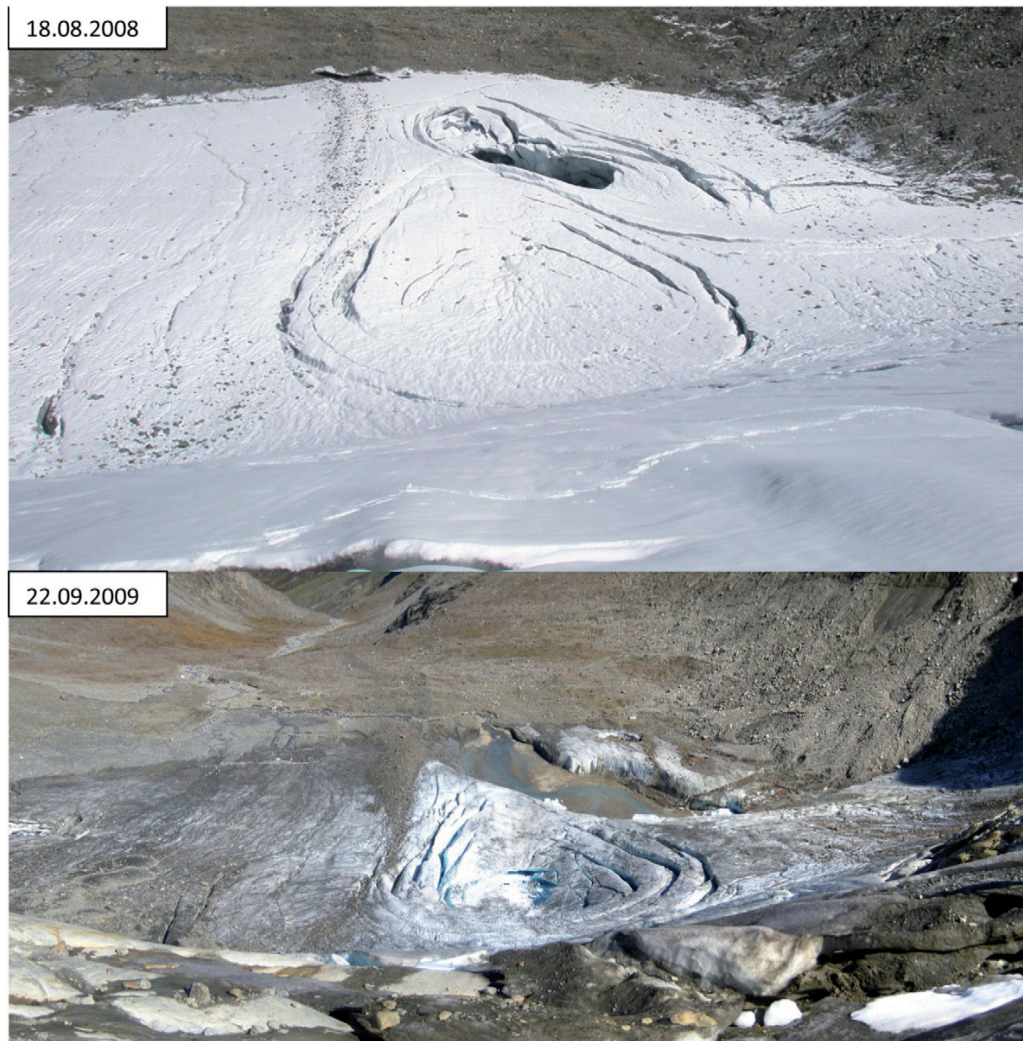
Appendix A. Annex



A1. Time series of the formation of the depression on Gepatschferner.

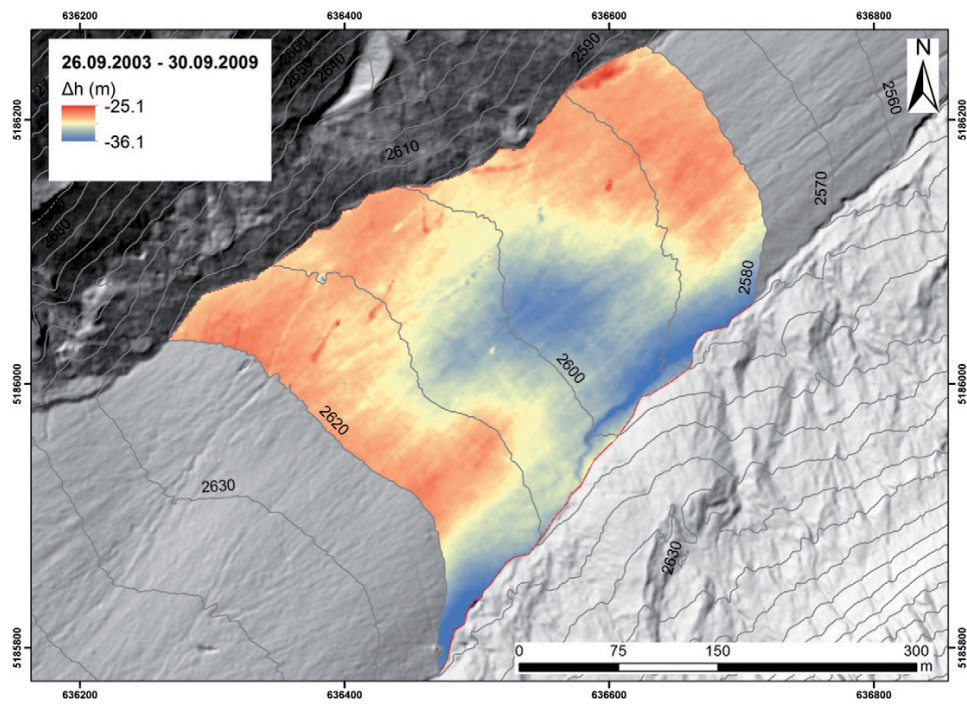


A2. Depression at the snout of Mittelbergferner (Photograph 2009: M. Olefs).

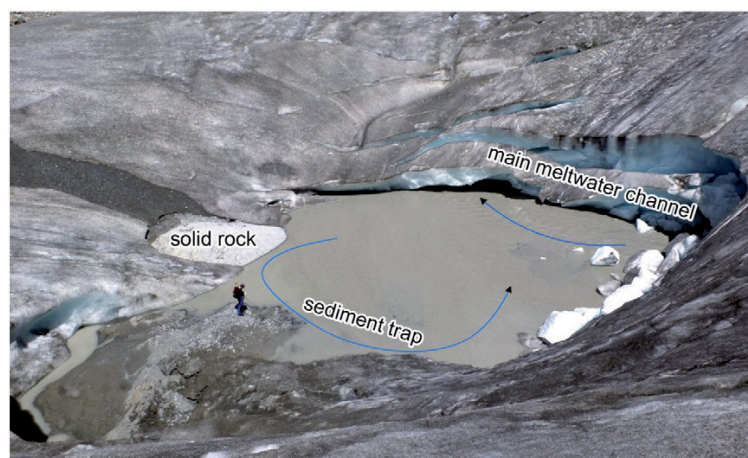


A3. Depressions on the flat tongue on Sulztalferner (Photographs: M. Olefs).

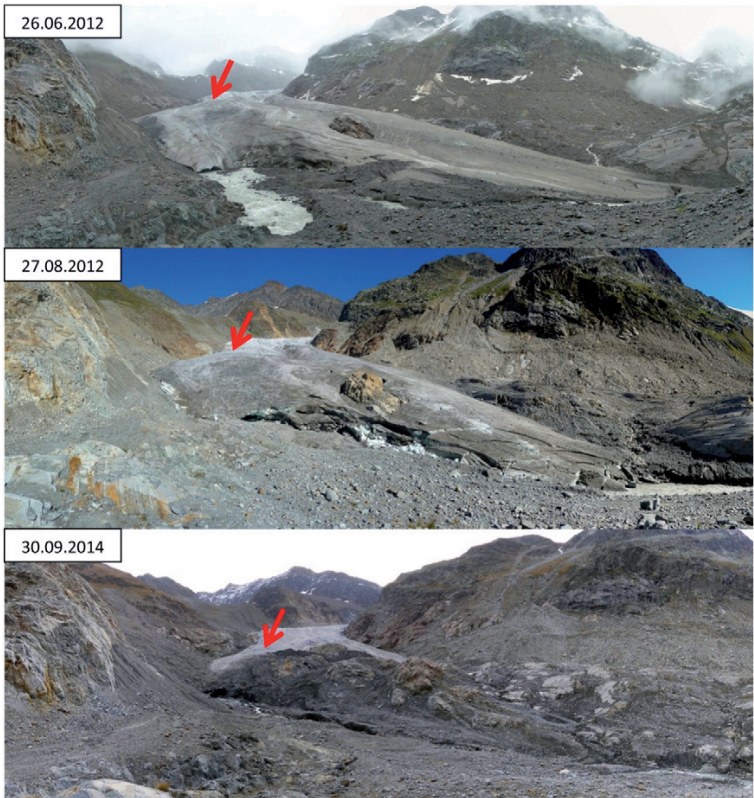
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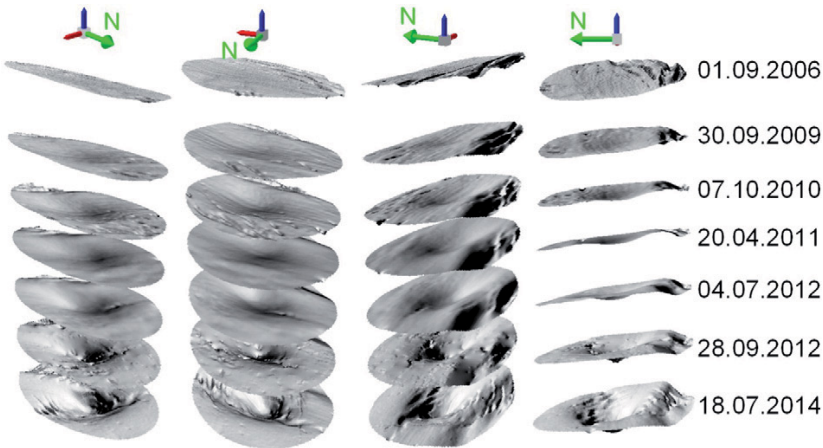
A4. DOD (DEM of Difference) 26.09.2003–30.09.2009 of the depression on Hintereisferner (Haberkorn, 2011).



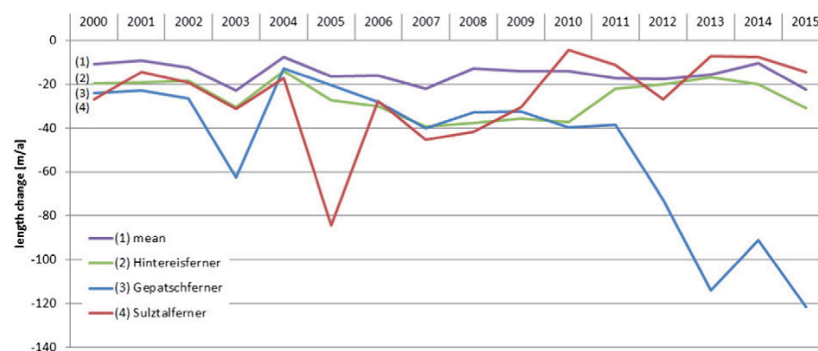
A5. Bottom of the depression (21.07.2015).



A6. Retreat of the tongue and dislocation of the main channel due to the flood event (26.08.2012). Arrow: surface depression.



A7. 3D Model of the depression on Gepatschferner within the 80 m circle for each ALS flight date, displayed with a constant offset.



A8. Length change per year of the glacier terminus of Gepatschferner, Sulztalferner and Hintereisferner. The mean refers to all Austrian glaciers which are subject to length change measurements (Fischer et al., 2013).

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C. Paper III

Stocker-Waldhuber, M. and Kuhn, M.: Closing the balances of ice, water and sediment fluxes through the terminus of Gepatschferner, in: Geomorphology of proglacial systems. Landform and sediment dynamics in recently deglaciated Alpine landscapes, edited by: Heckmann, T., Morche, D., Springer, Cham, doi: https://doi.org/10.1007/978-3-319-94184-4_5, 2019

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Abstract

The terminus of Gepatschferner ($46^{\circ}52' N$, $10^{\circ}46' E$) was subject to detailed glaciological investigations in the joint project PROSA. Both direct and geodetic methods were applied. Specifically, ice surface lowering measured at ablation stakes determined mass loss at the glacier surface, ice surface velocity was measured directly at the same stakes with differential GPS, and geodetic radar and vibroseismic soundings came into operation to investigate ice thickness and thickness of subglacial sediments. Multiple high-resolution airborne laser scanning (ALS) surveys document total volume changes. In contrast to a differentiated examination of the balances of ice water and sediments, the combination of these balances was an appropriate approach for investigating glacier mass exchanges and identifying dominant processes within the glacial system. The calculation or estimate of the fluxes of ice, water and sediments entering the narrow terminus at an elevation of 2875 *m* and leaving it at the glacier snout at 2200 *m* was based on glacier motion, surface and basal melt rates and on the lateral mass transport to the glacier from rock face and moraine bedrock erosion recorded from repeated terrestrial laser scans. In the course of the investigations on Gepatschferner, multiple rockfall events and the rapid evacuation of subglacial sediments were observed. The highest mass fluxes within the glacial system of Gepatschferner were associated with these extreme or episodic events, which exceeded the normal annual processes by multiple orders of magnitude. The relevant geophysical processes in this study period were thus not representative of long-term averages, if these ever existed. They did, however, display an interesting spectrum of naturally occurring situations. In that period, the mean velocity through the cross section at 2875 *m* was 22.5 *m* per year. Below that profile, the ice loss at the terminus corresponds to a mean surface lowering of 3.61 *m* per year between 2012 and 2015.

5. Closing the Balances of Ice, Water and Sediment Fluxes Through the Terminus of Gepatschferner.

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Abstract

The terminus of Gepatschferner (46°52'N, 10°46'E) was subject to detailed glaciological investigations in the joint project PROSA. Both direct and geodetic methods were applied. Specifically, ice surface lowering measured at ablation stakes determined mass loss at the glacier surface, ice surface velocity was measured directly at the same stakes with differential GPS, and geodetic radar and vibroseismic soundings came into operation to investigate ice thickness and thickness of subglacial sediments. Multiple high-resolution airborne laser scanning (ALS) surveys document total volume changes. In contrast to a differentiated examination of the balances of ice water and sediments, the combination of these balances was an appropriate approach for investigating glacier mass exchanges and identifying dominant processes within the glacial system. The calculation or estimate of the fluxes of ice, water and sediments entering the narrow terminus at an elevation of 2875 m and leaving it at the glacier snout at 2200 m was based on glacier motion, surface and basal melt rates and on the lateral mass transport to the glacier from rock face and moraine bedrock erosion recorded from repeated terrestrial laser scans. In the course of the investigations on Gepatschferner, multiple rockfall events and the rapid evacuation of subglacial sediments were observed. The highest mass fluxes within the glacial system of Gepatschferner were associated with these extreme or episodic events, which exceeded the normal annual processes by multiple orders of magnitude. The relevant geophysical processes in this study period were thus not representative of long-term averages, if these ever existed. They did, however, display an interesting spectrum of naturally occurring situations. In that period, the mean velocity through the cross section at 2875 m was 22.5 m per year. Below that profile, the ice loss at the terminus corresponds to a mean surface lowering of 3.61 m per year between 2012 and 2015.

5.1 Introduction

Changes in glacier mass can be quantified with geodetic, hydrological and direct glaciological measurements (Hoinkes 1970; Cuffey and Paterson 2010). A combination of such measurements and investigations (Hubbard and Glasser 2005) is the basis for an approach to close the respective balances of ice, water and sediments. Estimating the magnitudes of each term of the balancing approach helps to separate dominant processes from less important ones and their contribution to

the ongoing change of proglacial systems under conditions of rapid deglaciation (Heckmann et al. 2012). This chapter is based on the idea of conceptualizing a connection between the budgets of ice, water and sediment and their seasonal variation within a glacial system on the basis of state-of-the-art measurements. Surface and total mass balance measurements at several glaciers in the Alps and their production of meltwater have been investigated for a long time (e.g. Hoinkes 1970; Thibert et al. 2008; WGMS 2012; Fischer et al. 2013) as well as the fluvial sediment transport and the transport of suspended solids in the glacial stream (e.g. Gurnell and Clark 1987; Hofer 1987; Warburton 1990; Chaps. 12 and 13). Likewise, measurements of glacier surface velocity have a long history (Span et al. 1997; Span and Kuhn 2003) and provide important information about glacier dynamics (Van der Veen 2013). Geophysical methods offer a wide range of possibilities for investigating glaciological issues such as physical properties of ice or the internal structures of glaciers, ice thickness distribution and bedrock topography or subglacial sediments (Hauck and Kneisel 2008). The potential of Airborne Laser Scanning (ALS) data for glaciological questions has been demonstrated in several publications (e.g. Abermann et al. 2010; Bollmann et al. 2011; Helfricht et al. 2012) and can be taken as one of the most important databases for direct and indirect investigations. Carrivick et al. (2015) show that combining multiple methods yields insights into glacier evolution. Gepatschferner, located in the Kaunertal in the Ötztal Alps (46°52' N, 10°46' E), is the second biggest glacier of the Eastern Alps (Patzelt 1980; Groß 1987; Lambrecht and Kuhn 2007; Kuhn et al. 2012) and extended over 16.4 km² in 2006, 15.6 km² in 2012 (Fischer et al. 2015) and 15.3 km² in 2015. It was subject to a wealth of measurements in past decades. Length changes of the glacier terminus have been measured since 1856 (e.g. Fritzsche 1898; Fischer 2016). Seismic investigations were carried out between 1953 and 1958 (Förtsch et al. 1955) and were continued in 1960 and 1961 (Giese 1963); ice thickness measurements with ground penetrating radar were conducted in 1996 (Span et al. 2005). Changes in length, area and volume between 1850 and 2006 were calculated by Hartl (2010). Since 2012, the glacier is part of a catchment where detailed investigations of geomorphodynamics have been carried out (Heckmann et al. 2012; Chap. 1). The glaciological measurements in this study are mainly confined to the terminus, defined as the glacier below 2875 m, except calculations of area, elevation and volume changes from ALS data, which are calculated for all glacier areas. Detailed investigations on the terminus of the glacier focus on surface melt, surface velocities, ice thickness and the thickness of subglacial sediments. With a synopsis of these measurements at the terminus of Gepatschferner, an approach to close the balances of ice, water and sediments is given in the first part of this chapter. That means, we need to know how much ice is flowing into the glacier terminus at 2875 m surface elevation, what is the balance of accumulation and of ice melt at the terminus below, how much water enters the terminus from above and what is the run-off from the glacier, how much sediment reaches the terminus from above and from the lateral slopes and how much leaves the glacier as bedload and as suspension in the river. In the second part, we attempt an estimate of the magnitudes of the turnover volumes.

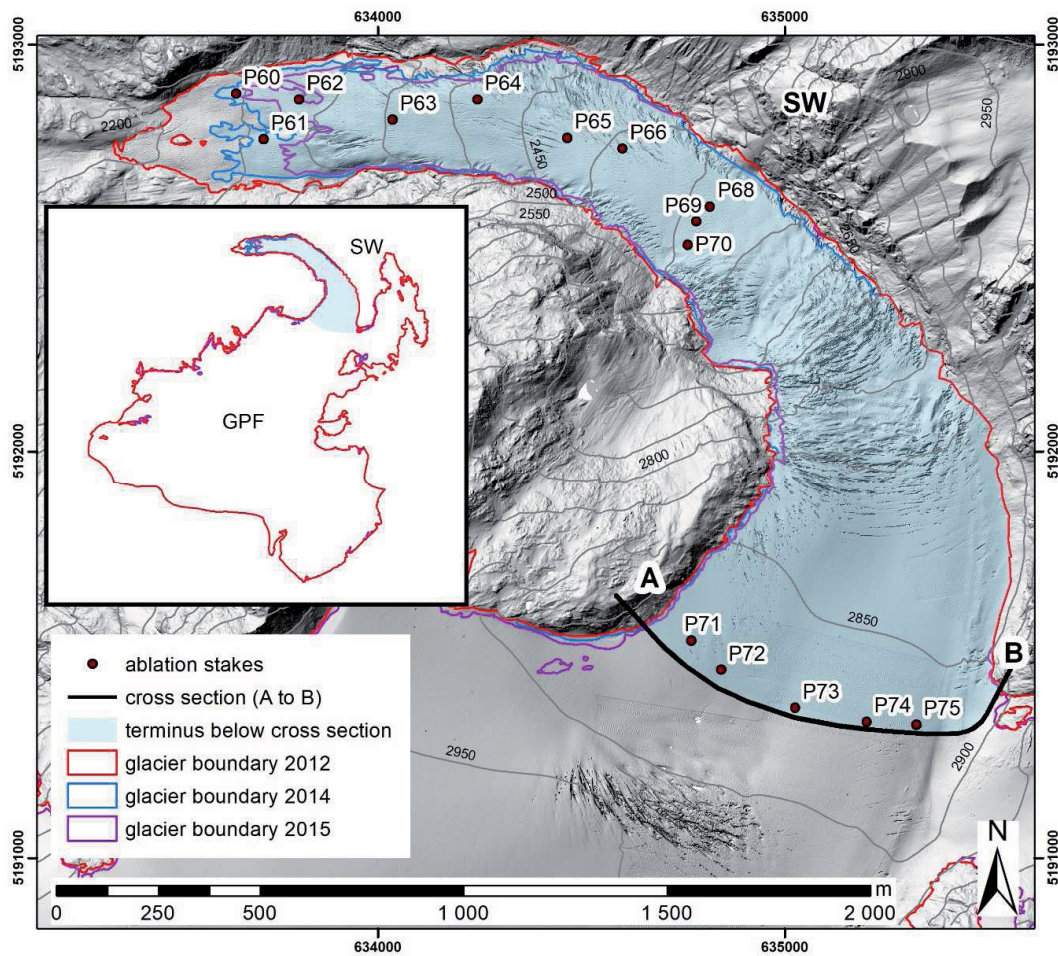


Fig. 5.1: Position of ablation stakes at the terminus of Gepatschferner 2014 and glacier boundaries 2012, 2014 and 2015 as well as the cross section at the root zone of the terminus between point A and B. Hill shade dated July 2012. Inset: the entire Gepatschferner (GPF) on orthophotograph (data source: Land Tirol – data.tirol.gv.at). SW: Schwarze Wand.

5

5.2 Methods

High-resolution airborne laser scans (Abermann et al. 2010) are fundamental databases to arrive at distributed surface elevation changes and to georeference measurements of ablation, glacier motion, ice thickness and thickness of subglacial sediments. In this study, ALS data from 04.07.2012 and 22.08.2015 are used; they set the time frame of the balances. The digital elevation models (DEMs) were aggregated as mean values from the ALS point clouds on a raster size of 1x1 m. Gaps were closed by a stepwise resampling using a bilinear interpolation. The DEMs, which are the basis of the calculations, aim at a vertical accuracy of ± 0.2 m for each DEM and ± 0.4 m for the DEM of difference (DoD) (Bollmann et al. 2011), which is in the same order as the basal change rates. An additional DEM is available from orthophotographs from 18.07.2014. Differential Global Positioning System (DGPS) measurements and direct stake readings were carried out on the glacier terminus at 15 stake positions (Fig. 5.1). Five of the stakes are located at a cross section in the root zone of the terminus at an elevation of 2875 m. Additionally, vibroseismic measurements (Eisen et al. 2010) were carried out

at the terminus of Gepatschferner in 2012, 2013 and 2014 to investigate the thickness of subglacial sediment layers. A DEM of the glacier bed is provided by Span et al. (2005). It was produced by interpolating between ground penetrating radar (GPR) measurements. The mean hydrological balance was calculated with a semi-distributed, conceptual model (Kuhn and Batlogg 1998, 1999; Kuhn 2000, 2003; Kuhn et al. 2016) for the period 2006/07–2014/15, based on the geodetic total glacier mass balance and measured values of temperature and precipitation. The model provides monthly values of basin precipitation, snow cover, glacier mass balance and run-off, separated into meltwater and rain for 100 m elevation bands partly verified by the basin run-off measured at Gepatschalm gauging station, situated at 1900 m. Bedload transport and the transport of suspended solids are measured directly in the proglacial river at the glacier snout (Fig. 5.2; see details in Chap. 13). The lateral mass flux from adjacent hillslopes to the glacier surface was calculated from ALS and terrestrial laser scanning (TLS) data (Fig. 5.2; see details in Chaps. 9, 11).

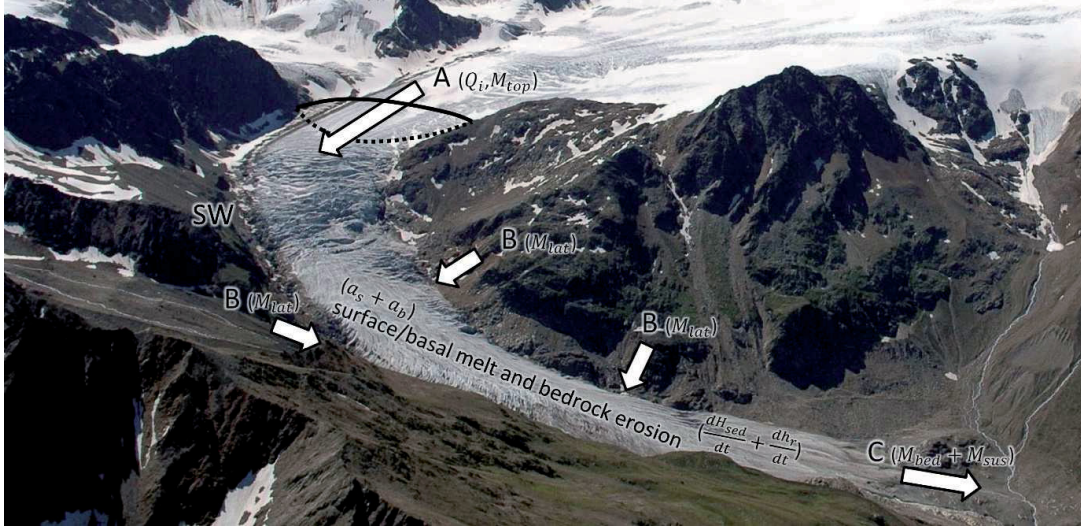


Fig. 5.2: Photograph of the terminus of Gepatschferner. A: transport of ice and sediments through the cross section to the terminus (Eqs. 5.3, 5.4, 5.11); B: lateral mass transport on to the terminus from rock slopes and moraines (Eq. 5.11); C: bedload transport and transport of suspended solids within the glacial stream (Eq. 5.11); SW: Schwarze Wand.

5.2.1 Ice and water fluxes

Several factors contribute to elevation changes of the glacier surface over time ($\partial h_s / \partial t$) at a specific point, including the ablation on the surface (a_s), basal melt (a_b), thickness changes of the subglacial sediment layer ($\partial H_{sed} / \partial t$) and bedrock ($\partial h_r / \partial t$) erosion, advection of ice thickness ($u * \partial H_i / \partial x$), convergence or divergence of ice ($H_i * \partial u / \partial x$). Englacial and subglacial water is seasonally stored, mostly in the matrix of sediments and ice, and has negligible changes from year to year (Jansson et al. 2003). At any point (x, y) on the glacier surface

$$\frac{\partial H_i}{\partial t} = (a_s + a_b) - \frac{\partial Q_i}{B \partial x} \quad 5.1$$

$$\frac{\partial Q_i}{B \partial x} = \frac{\partial}{\partial x} (\bar{u} * H_i) = H_i \frac{\partial \bar{u}}{\partial x} + \bar{u} \frac{\partial H_i}{\partial x} \quad 5.2$$

The flux of ice to the terminus (Q_i) through a cross section (C) at a mean glacier width (B) and the mean ice thickness (H_i) at the root zone of the terminus depends on the velocity of ice (\bar{u}), which is the sum of the mean deformation velocity (\bar{u}_d) and the mean velocity of basal sliding (\bar{u}_b).

$$Q_i = B * H_i (\bar{u}_d + \bar{u}_b) \quad 5.3$$

$$Q_i = C * \bar{u} \quad 5.4$$

The volume of ice (V_i) stored in the terminus in relation to the area (A) each year is

$$V_i = Q_i - (a_s + a_b) * A \quad 5.5$$

5 from the glaciological method, equivalent to

$$V_i = \frac{\partial H_i}{\partial t} * A \quad 5.6$$

from the geodetic method. This means that the amount of subglacial melt (a_b) can be inferred in metres of ice per year as

$$a_b = \frac{Q_i}{A} - a_s - \frac{\partial H_i}{\partial t} \quad 5.7$$

where H_i , a_s and a_b are means over the entire terminus, and

$$\frac{\partial H_i}{\partial t} = \frac{\partial h_s}{\partial t} - \frac{\partial H_{sed}}{\partial t} \quad 5.8$$

10 where h_s is determined from ALS and H_{sed} from seismic soundings. The densification of snow or firn can be neglected at the terminus, except for a minor volume change due to closing crevasses, and also because the cross section is located within the ablation zone; thus, the density of ice (ρ_i) is kept constant, giving a straightforward way of converting volume to mass fluxes. The conventional glaciological mass balance measurements refer indeed to the weighed mass of snow where accumulation is concerned. All other measurements, i.e. ablation, changes of surface elevation, ice
15 flow velocity and sediment thickness, are measured in terms of metres. This is why we prefer to express the balance terms of thickness (H [m]), volume (V [m^3]), volume fluxes per year (Q [m^3/a]) and volume flux densities per year ($[m^3/m^2a]$, which is equivalent to mean velocities horizontally or to accumulation or ablation vertically, in metres per year). Only in those cases where several components (ice, water, sediments) are involved do we refer to mass fluxes per year ($[kg/a]$ or
20 water equivalent (w.e.) per year [m w. e./a]). Mass losses at the terminus can be calculated from the absolute values of surface and subglacial ablation ($a_s + a_b$) over the terminus area (A). The 'remaining' ice of the specified area corresponds to the storage of ice (S [m w. e.]).

$$S = Q_i \frac{\rho_i}{\rho_w} - (a_s + a_b) \frac{\rho_i}{\rho_w} * A \quad 5.9$$

The storage of water (S) in the form of glacier ice (Jansson et al. 2003) is the connection to the hydrological balance of precipitation (P), runoff (R) and evaporation (E).

$$S = P - R - E \quad 5.10$$

25 5.2.2 Sediment fluxes

The mass flux of the bedload transport (M_{bed}) and the transport of suspended solids within the glacial stream to the snout of the glacier (M_{sus}) equals the thickness changes of the subglacial sediments ($(\partial H_{sed}/\partial t)\rho_{sed}$) of the terminus area (A), the flux of sediments from the firn area to the terminus (M_{top}) and the lateral input to the glacier from landslides and rockfalls of the surrounding

slopes (M_{lat}). Neglecting bedrock erosion, the thickness change is a result of the divergence in the sediment transport. Assuming a stationary case, the terms of mass fluxes are balanced by thickness changes of the subglacial sediments (s. Table 5.1).

$$M_{bed} + M_{sus} = M_{top} + M_{lat} - \frac{\partial H_{sed}}{\partial t} \rho_{sed} * A \quad 5.11$$

5.2.3 Balancing approach

The absolute elevation of the glacier surface above sea-level (h_s) depends on the elevation of the bedrock topography (h_r), the thickness of ice (H_i), the thickness of subglacial sediments (H_{sed}) and of liquid water (H_w) and changes in time. In this case, bedrock erosion is neglected, so the bedrock topography does not change. Likewise, annual changes of englacial and subglacial water are neglected.

$$h_s = h_r + H_{sed} + H_i + H_w \quad 5.12$$

$$\frac{\partial h_s}{\partial t} = \frac{\partial H_{sed}}{\partial t} + \frac{\partial H_i}{\partial t} \quad 5.13$$

Of the terms in Eqs. 5.12 and 5.13, h_s is determined from ALS data, h_r from GPR data, H_{sed} from seismic data, H_i follows from Eq. 5.12 if H_w is neglected, because englacial water does not change the surface elevation and subglacial water is mostly contained within the sediment matrix.

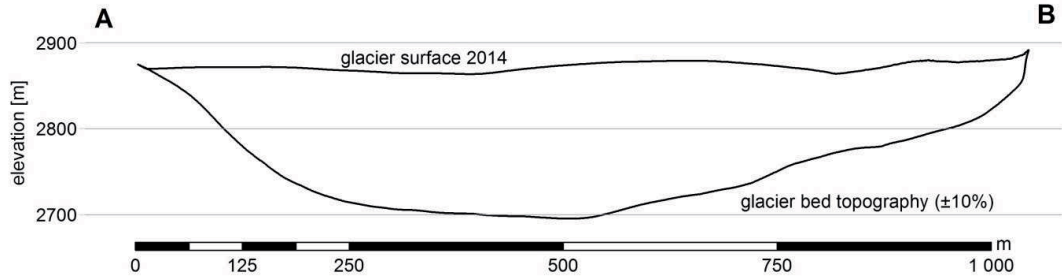


Fig. 5.3: Vertical cross section from point A to point B (Fig. 5.1) between the glacier surface 2014 and the interpolated glacier bed topography calculated from ice thicknesses values determined by ground penetrating radar with an estimated uncertainty of $\pm 10\%$ by Span et. al. (2005).

5.3 Estimating magnitudes of the fluxes

At a cross section at the root zone of the terminus, at an elevation of 2875 m, the mean ice thickness is about 100 m and the maximum ice thickness 150 m. The cross-sectional area (C) between the bed topography and the ice surface represented in the DEM 2014 is 125,547 m² (Fig. 5.3). Between 2012 and 2015, the cross-sectional area varied by only 2-3% to the sectional area of 2014. Maximum ice surface velocities were found at the central stakes 'P73' and 'P74' (Fig. 5.1) of the cross-profile at the centre flow line of the glacier, with 35 m per year as a mean value between 2012 and 2015. The mass flux of ice to the terminus (Eq. 5.3) is thus calculated from the cross-sectional area of 2014 and the maximum velocity at the central stake. The mean velocity through the section is taken as approximately 64% of the maximum ice surface velocity (Span and Kuhn 2003). So the mean annual velocity through the section is 22.5 m per year, or 67.6 m for the period (04.07.2012-22.08.2015),

which leads to a total volume gain of the terminus of 8,489,060 m³, or 6.20 m/m² during the period, calculated for the 1.369 km² area of the terminus in 2014. For the investigated three-year period, the geodetic determination of the change in surface elevation of the terminus out of the DoD is -10.84 m of ice. The direct investigations at the glacier surface by stake readings returned a specific surface balance of the terminus of -15.59 m of ice within three years (04.07.2012-22.08.2015). From Eq. 5.1, the subglacial changes are -1.45 m for this period or about -48 cm per year as the remainder of the DoD, the mass gain due to the specific mass flux of ice to the terminus and the specific surface mass balance. The basal rate of change of -0.48 m per year consists of the basal melt rate and minor contributions of the bedrock erosion. A comparison of the uncertainty of each term of the ice mass balance of the terminus reveals different orders of magnitude. The uncertainty of the surface mass balance measured with the direct glaciological method (Hoinkes 1970) is assumed to be smaller than 0.1 m of ice per year (Kuhn et al. 1999). The surface velocities measured with DGPS aim at a horizontal precision of a few centimetres (Monteiro et al. 2005) and are in the range of ± 0.2 m per year at the cross section on Gepatschferner. The variation in the maximum surface velocity per year at the cross section during the three years of stake measurements was $\pm 5\%$ and affects the basal change rate by about ± 0.11 m. The uncertainty of GPR measurements and the bedrock topography at the cross section is an order of magnitude higher and can only be estimated. However, we assume that about 10% of the given ice thickness should be a good approximation. In the case of Gepatschferner, a calculation with $\pm 10\%$ of the mean ice thickness within the cross section at the root zone of the terminus leads to a calculated range of the basal change rate at the terminus between -0.28 and -0.69 m per year. Water storage within an Alpine catchment can be separated into liquid water and ice components. Within a highly glaciated catchment, the dominant storage of liquid water is within snow or firn (Kuhn et al. 2016), but those components are not as significant for total run-off as the volume of ice. For the whole catchment, the storage term of the hydrological balance (Eq. 5.10) equates the ice mass loss of the glacier. This negative part of the specific glacier mass balance between 2006/07 and 2014/15 amounts to -314 mm w.e. (water equivalent) per m² and year or 18% of the total headwater run-off. By calculating the specific contribution of the terminus relative to the whole catchment area, the negative balance of the terminus of Gepatschferner amounts to -107 mm w.e. per year. So the terminus below 2875 m makes a specific contribution of about 6.1% to the total run-off. A model run with higher temperatures (+2 °C) and constant glacier area shows a significant increase of 36% in the meltwater production (Kuhn et al. 2007). An assumed reduction of the ice-covered area until 2050 due to higher temperatures still leads to an increase of 27% of the total run-off. The bedload transport and the transport of suspended solids within the proglacial stream (see details in Chap. 13) represent the mass loss or export from a catchment and thus lead to a mean surface lowering in the order of magnitude of millimetres to centimetres per year (Carrivick et al. 2013). The sediment mass originates from active rock slopes, moraines and from subglacial bedrock erosion. However, only a small part of the surrounding steep slopes and moraines provide a lateral mass transport directly on to the surface of the terminus of Gepatschferner. Most of the material from active rock slopes (>40°) is deposited on moraines, and often, the material from moraines is transported underneath the terminus at the

peripheral zones (see details in Chap. 11). On Gepatschferner, the very active rock slope Schwarze Wand is responsible for most of the deposited material on the glacier surface, with approximately 66,000 tons a year between 2012 and 2015 (see details in Chap. 9). Such active rockfall zones or comparable ‘extreme’ events exceed the average transport processes many times over. On Alpine glaciers, a ‘final’ deposition of solid rocks in the glacier forefield, which were previously deposited on the glacier surface, is delayed by the glacier motion and/or retreat by up to several hundred years (Span et al. 1997). In the case of Gepatschferner, solid rocks from the Schwarze Wand, deposited at the central flow line of the glacier, will arrive in the forefield of the glacier in approximately 30 years under present conditions of glacier motion and the present extent of the terminus. Given retreat rates of the terminus of about 100 m per year between 2012 and 2015 (Fischer 2016), the transport time to the forefield can be assumed as approx. 10 years. Material from rock faces or moraines deposited on dead ice bodies has not been taken into account, because these regions are dynamically almost decoupled from the terminus itself. The distribution and thickness of subglacial sediment layers at specific profiles was investigated with vibroseismic soundings on the terminus of Gepatschferner. In one profile at the lowermost part of the glacier, a sediment trap measured maximum thicknesses of 20 ± 5 m. During a heavy precipitation event (Baewert and Morche 2014), the subglacial sediment layers were flushed out rapidly, resulting in an increased deepening process of a surface depression (Stocker-Waldhuber et al. 2017). In contrast to this extreme event, the specific erosion of the glacier should be in the order of magnitude of millimetres up to a few decimetres per year (Hallet et al. 1996). The volume of sediments evacuated during the extreme event mentioned above would be in the same order of magnitude as a specific erosion rate of a few centimetres per year in relation to the area of the terminus. The glacier area further up the terminus (Gepatschferner >2875 m) was not taken into account because the sediment transport from the firn area is unknown. However, the estimated magnitude of the sediment production from bedrock erosion of the whole Gepatschferner is assumed to be in the range of 10^4 - 10^6 m³ per year, with a calculated range of specific erosion rates of about one millimetre to a five centimetres per year (c.f. Chap. 17).

Table 5.1: Measured, calculated and estimated quantities within the PROSA catchment with respect to the balancing approach to the terminus of Gepatschferner.

measured quantities		
glacier area of Gepatschferner 2015	15.281±0.23	km ²
terminus area 2014 (< 2875 m)	1.369±0.03	km ²
cross section area (2875 m), bedrock to surface 2012	0.128±0.01	km ²
cross section area (2875 m), bedrock to surface 2015	0.122±0.01	km ²
mean ice thickness cross section	100±10	m
max. ice thickness at cross section	150±15	m
max. velocity on cross section surface	35±0.2	m/a
max. thickness of subglacial sediment layers (Stocker-Waldhuber et. at. 2017)	20±5	m
min. surface melt rate at the terminus	-1.14±0.10	m/a
max. surface melt rate at the terminus	-8.72±0.10	m/a

calculated and estimated quantities (04.07.2012-22.08.2015)

mean velocity through the cross section per year	22.5	m/a
ice volume flux to the terminus	8.489	10 ⁶ m ³
mean specific ice mass gain of the terminus	6.20	m
mean elevation change at the terminus (DoD)	-10.84	m
mean specific surface mass balance at the terminus	-15.59	m
subglacial changes at the terminus (basal melt and bedrock erosion)	-1.45	m
hydrological balance based on Kuhn et. al. 2016 (2006/07-2014/15)		
mean specific annual glacier mass balance	-868	mm w.e.
mean annual storage of the catchment; negative part of the glaciers	-314	mm w.e.
mean annual catchment runoff	1740	mm
contribution of the glaciers to the total runoff	18	%
contribution of Gepatschferner terminus to total runoff	6.1	%
lateral contribution of Schwarze Wand	66000	t/a
estimated transport duration at central flow line	10 - 30	a
estimated sediment production of Gepatschferner	10 ⁴ - 10 ⁶	m ³ /a
mean erosion Gepatschferner 2012-2015 (assuming: 1 mm, $\rho = 2500 \text{ kg/m}^3$)	38618	t/a

5.4 Conclusions

The balancing approach presented here aims at combining measured quantities and magnitudes only estimated on an annual basis. A regionalized analysis of each parameter should be taken into account and is as important as the separation of periodic/annual from episodic processes. On Gepatschferner, the glaciological measurements are mainly confined to the terminus or even more specific locations, such as the vibroseismic investigations at the surface depression. On the terminus, we found from geodetic investigations that the mean surface lowering from 04.07.2012 to 22.08.2015 was -10.84 m. In contrast, the directly measured surface ablation of -15.59 m within the same period is largely compensated by the ice mass flux to the terminus, calculated out of surface velocities and ice thickness data, which leads to a gain of 6.20 m. The remainder of this balance suggests a basal change rate of -0.48 m per year. These basal changes consist of subglacial ice melt and the erosion of sediments and the bedrock. However, the three-year time window is a snapshot that may be short compared to the recurrence of extreme events. Thus, an extrapolation of the measured and calculated changes and processes to the whole glacier area remains problematic, as indicated by examples of 'extreme' or episodic events, which are multiple orders of magnitude higher than changes within 'normal' daily or annual cycles, like the rockfalls on Schwarze Wand or the rapid evacuation of subglacial sediment layers during a heavy precipitation event.

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List of variables and indices

variables

a	ablation
A	area
B	glacier width
C	cross section
E	evaporation
h	elevation
H	thickness
M	mass flux
P	precipitation
Q	volume flux
R	run-off
S	storage
t	time
u	velocity
V	volume

indices

b	basal
bed	bedload
d	deformation
i	ice
lat	lateral
r	bedrock
s	surface
sed	sediment
sus	suspension
top	from the area above 2875 m to the terminus
w	water

D. Mass Balance Tables GPF Below 2900 m

Table D.1.: Annual mass balances per altitude zones (mean of the 50 m elevation range) at the tongue of Gepatschferner below 2900 m. (cf. Tab. 4.1)

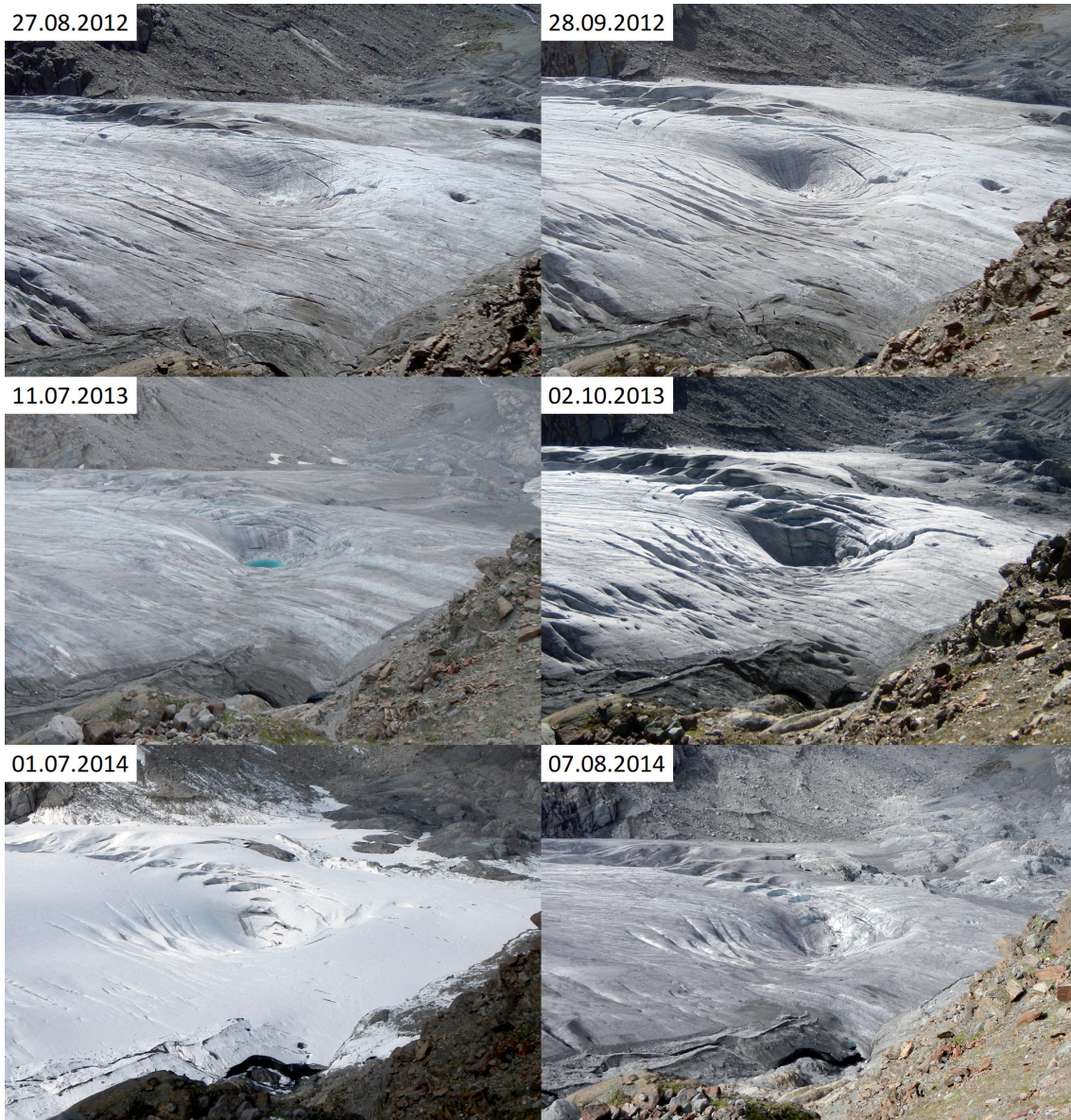
glaciological year 2011/2012				glaciological year 2012/2013			
<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]	<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]
2175	0.002	-18.2	-7750	2175	0.005	-40.6	-7750
2225	0.035	-260.0	-7428	2225	0.037	-280.1	-7568
2275	0.057	-392.7	-6869	2275	0.062	-419.0	-6784
2325	0.060	-354.6	-5925	2325	0.054	-328.7	-6079
2375	0.048	-311.8	-6546	2375	0.047	-269.9	-5750
2425	0.059	-366.4	-6250	2425	0.061	-343.2	-5609
2475	0.072	-450.9	-6238	2475	0.072	-370.5	-5114
2525	0.073	-425.2	-5857	2525	0.072	-315.0	-4363
2575	0.071	-391.5	-5517	2575	0.073	-271.1	-3738
2625	0.072	-400.3	-5555	2625	0.069	-241.2	-3519
2675	0.033	-177.7	-5436	2675	0.034	-119.8	-3542
2725	0.058	-306.7	-5250	2725	0.057	-184.8	-3256
2775	0.079	-379.5	-4784	2775	0.089	-278.6	-3144
2825	0.257	-916.6	-3573	2825	0.262	-748.7	-2854
2875	0.484	-1111.5	-2297	2875	0.486	-845.2	-1740

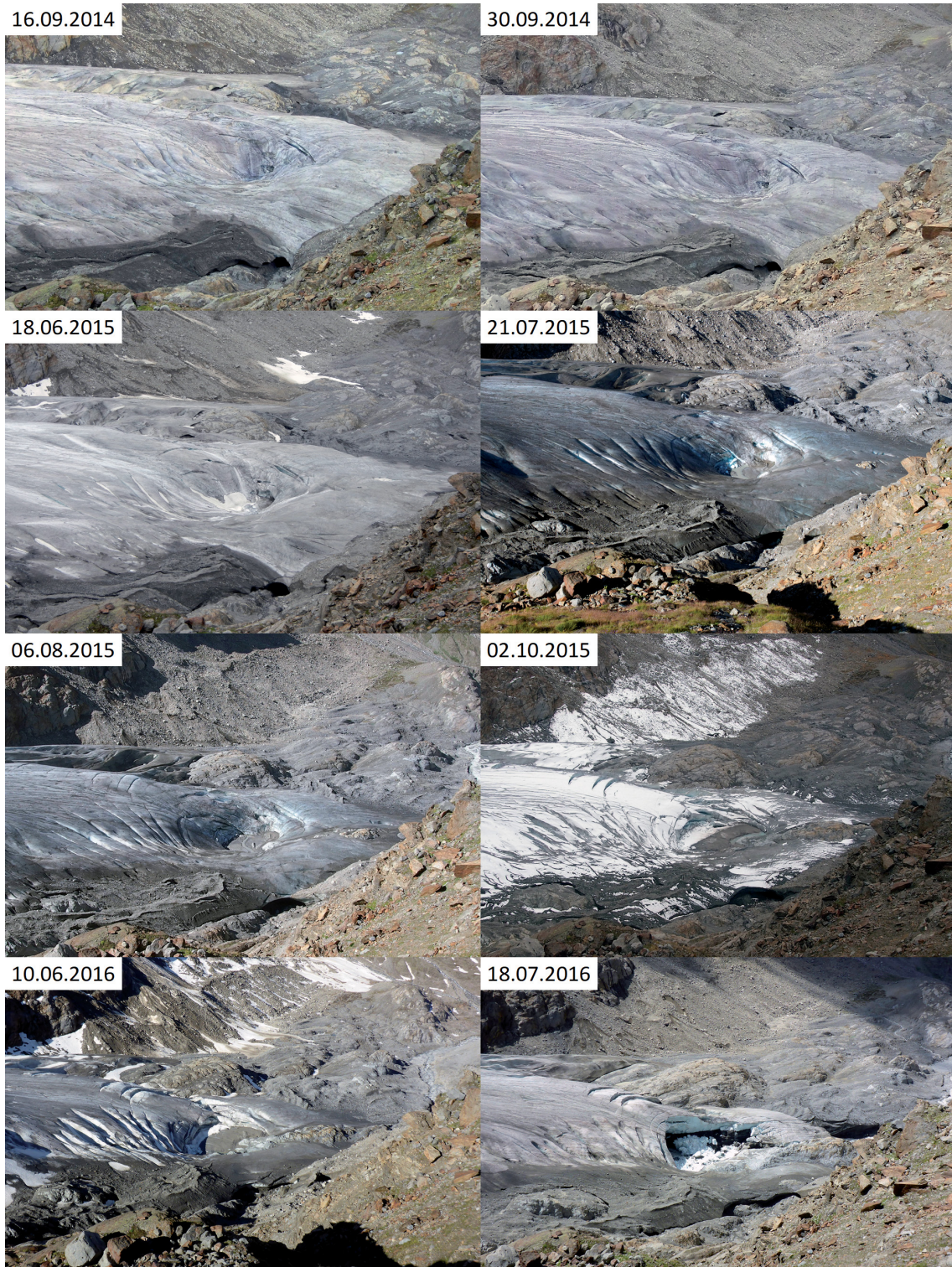
glaciological year 2013/2014				glaciological year 2014/2015			
<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]	<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]
2225	0.007	-38.6	-5250	2225	0.001	-8.4	-7750
2275	0.048	-252.2	-5217	2275	0.030	-236.3	-7750
2325	0.042	-238.4	-5655	2325	0.037	-285.2	-7750
2375	0.038	-228.1	-6018	2375	0.035	-261.4	-7530
2425	0.055	-324.0	-5864	2425	0.053	-386.0	-7250
2475	0.066	-294.0	-4487	2475	0.061	-415.2	-6754
2525	0.069	-257.3	-3712	2525	0.068	-385.1	-5667
2575	0.064	-247.8	-3878	2575	0.071	-379.8	-5380
2625	0.064	-237.9	-3690	2625	0.059	-292.6	-4926
2675	0.030	-108.4	-3657	2675	0.031	-140.8	-4536
2725	0.058	-193.6	-3312	2725	0.063	-266.9	-4250
2775	0.083	-239.8	-2879	2775	0.085	-361.8	-4250
2825	0.263	-550.0	-2093	2825	0.269	-1038.2	-3863
2875	0.480	-687.2	-1431	2875	0.473	-1484.8	-3142

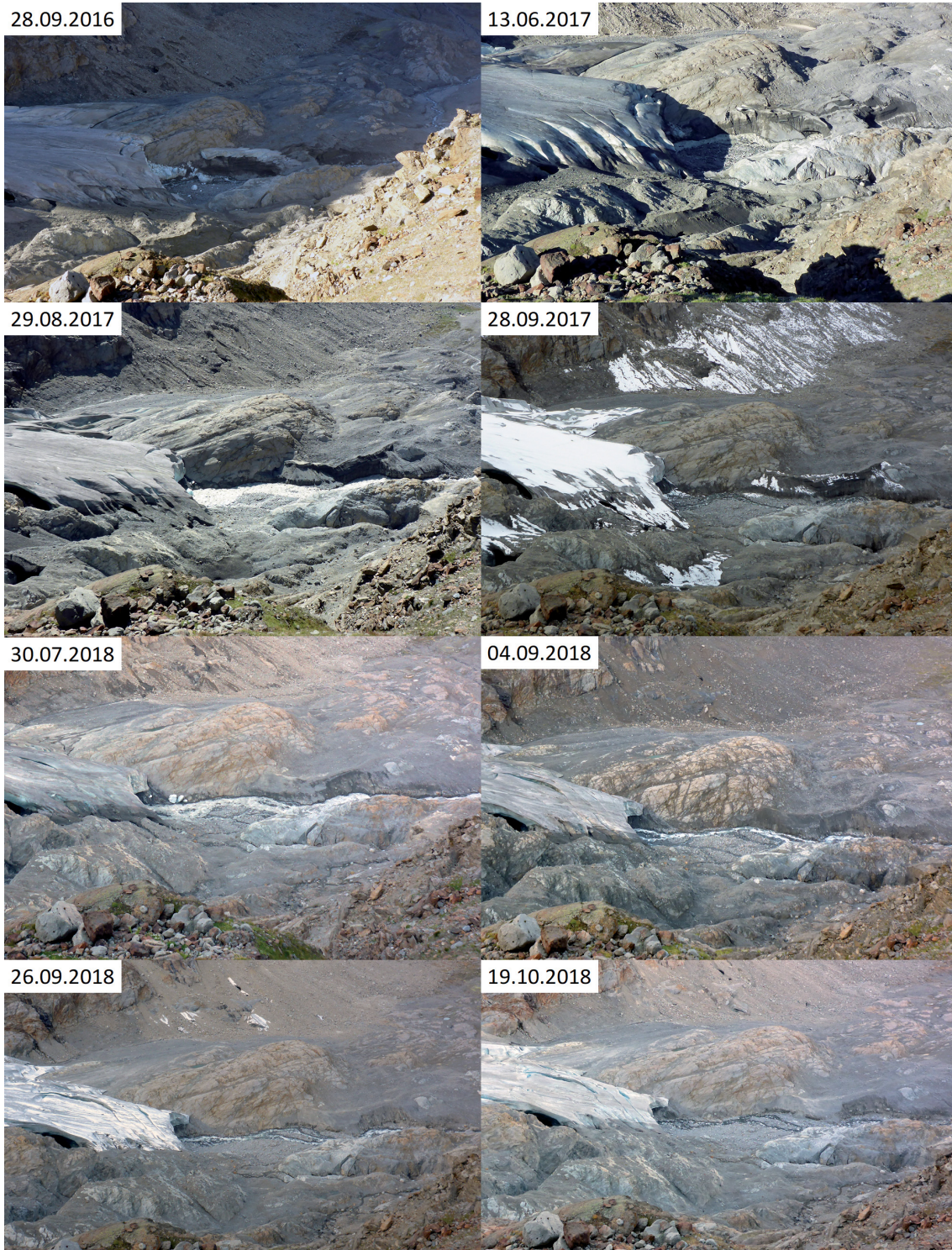
glaciological year 2015/2016				glaciological year 2016/2017			
<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]	<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]
2225	0.001	-9.0	-8250	2225	0.001	-9.0	-8250
2275	0.030	-244.8	-8029	2275	0.030	-251.5	-8250
2325	0.037	-268.1	-7284	2325	0.037	-292.7	-7954
2375	0.035	-235.1	-6773	2375	0.035	-255.5	-7361
2425	0.053	-341.4	-6413	2425	0.053	-363.8	-6834
2475	0.061	-326.2	-5306	2475	0.061	-398.3	-6478
2525	0.068	-289.9	-4266	2525	0.068	-383.7	-5646
2575	0.071	-244.5	-3464	2575	0.071	-348.5	-4936
2625	0.059	-191.0	-3216	2625	0.059	-279.3	-4703
2675	0.031	-100.0	-3222	2675	0.031	-146.2	-4709
2725	0.063	-198.0	-3153	2725	0.063	-271.4	-4322
2775	0.085	-251.1	-2949	2775	0.085	-344.8	-4050
2825	0.269	-737.9	-2746	2825	0.269	-933.7	-3474
2875	0.473	-943.0	-1995	2875	0.473	-1370.3	-2900

glaciological year 2017/2018			
<i>zone</i>	<i>A</i> [km^2]	<i>B</i> [$10^3 m^3$]	<i>b</i> [mm]
2225	0.001	-9.5	-8750
2275	0.030	-266.8	-8750
2325	0.037	-314.2	-8538
2375	0.035	-292.4	-8422
2425	0.053	-430.0	-8077
2475	0.061	-424.4	-6903
2525	0.068	-394.5	-5805
2575	0.071	-388.2	-5499
2625	0.059	-313.3	-5274
2675	0.031	-147.4	-4750
2725	0.063	-295.3	-4702
2775	0.085	-382.4	-4492
2825	0.269	-1061.6	-3950
2875	0.473	-1586.8	-3358

E. Repeat Photos Funnel-shaped Depression







F. Repeat Photos Glacier Tongue Gepatschferner

26.06.2012



04.07.2012



25.07.2012



27.08.2012



28.09.2012



11.07.2013



14.08.2013



02.10.2013



26.06.2014



01.07.2014



06.08.2014



16.09.2014



30.09.2014



18.06.2015



05.08.2015



09.09.2015



02.10.2015



10.06.2016



19.07.2016



25.08.2016



28.09.2016



13.06.2017



19.10.2018



13.06.2017



26.06.2017



19.07.2017



29.08.2017



28.09.2017



12.06.2018



30.07.2018



26.09.2018



19.10.2018



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