Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-153
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 8 January 2019
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Open Access Earth System Science Data Discussions

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

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Abstract. Climatic forcing affects glacier mass balance and ice flow dynamics on different time scales, resulting in length changes. Mass Balance and length changes are operationally used for glacier monitoring, whereas only a few time series of glacier dynamics have been recorded. With more than 100 years of measurements of ice flow velocities at stakes and stone lines on Hintereisferner and more than 50 years on Kesselwandferner, annual velocity and glacier fluctuation records have similar lengths. Subseasonal variations of ice flow velocities have been measured on Gepatschferner and Taschachferner for nearly a decade. The ice flow velocities on Hintereisferner and especially on Kesselwandferner show great variations between advancing and retreating periods, with magnitudes increasing from the highest to the lowest 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 data sets of the four glaciers are available at https://doi.pangaea.de/10.1594/PANGAEA.896741.

1 Introduction

The fluctuation of glaciers has become an icon of climate change, after Penck and Brückner (1909) established the theory of ice ages, later confirmed by isotope analysis on polar ice cores and theoretically explained by Milankovitch. 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. 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, with 5 glaciers with stone line velocity records 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 Rhone glacier (Mercanton, 1916; Roethlisberger, 1963) or Mer de Glace (Berthiere and Vincent, 2012).

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For Alpine glaciers, monitoring of velocity records received less attention after the turbulent decades of the First and Second World War. 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).

Nowadays, when estimates of the global glaciers' contribution to sea level rise is one of the urgent topics of research (e.g. Jacob et al., 2012), and estimates of the state of large glacier ensembles are needed, glacier flow velocities, as potentially remote-sensing based glacier parameters, provide important additional information especially when conventional mass balance parameters fail. For example ELA, which played a major role in large-scale data collections on 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, four long time series of ice flow velocities are revisited and compared with classical in situ mass balance measurements (Hoinkes, 1970) and ALS data (Abermann et al., 2010). On these four glaciers, flow velocities are measured in situ at stone lines (horizontal velocities) or at stakes (3D velocities), with stakes annually set back to their original position. Long-term velocity data are recorded at annual resolution, shorter time series also reveal seasonal variabilities. The four glaciers are also part of a net of long-term measurements of glacier fluctuations (Groß, 2018); area and volume change have been recorded in inventories from LIA maximum onwards (Patzelt, 1980; Groß, 1987; Kuhn et al., 2012; Fischer et al., 2015). Without further discussion of the potential and limitations of different remote-sensing sensors and techniques, this paper focuses on presenting ice flow velocity records on well investigated mountain glaciers and their relation to other in situ monitoring parameters.

2 Glacier sites and data

The ice flow velocities have been recorded on four of the largest glaciers in the Ötztal Alps. Hintereisferner (HEF), Kesselwandferner (KWF), Gepatschferner (GPF) and Taschachferner (TSF) are neighbouring glaciers (Figure 1) but differ in size, aspect and elevation ranges (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 measured at ablation stakes but almost annually 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 behind the location of the profile. 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. Velocity measurements at this plateau glacier were started in 1965 by Schneider

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(1970) at ablation and 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 made by Fischer (2011).

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 early first mappings (Sonklar, 1860; Finsterwalder, 1928), GPF was subject to geophysical investigations (Giese, 1963), photogrammetric analyses (Keutterling and Thomas, 2006) and is one of the Eastern Alpine key research sites, with 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 three stakes, where velocities have been measured since 2009, to 16 stakes in 2012. 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 position of the stakes is measured several times during summer months, allowing a discussion of the 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 (Figure 1). On HEF and KWF, stake velocities were measured using a theodolite and tachymeter until 2009, when DGPS measurements came into operation. On GPF and TSF, the full series was measured by DGPS.

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 (Airborne Lase Scan) 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 used only 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 since 2009 with DGPS. 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

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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. 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 at ablation and accumulation stakes are used on KWF, GPF, 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 its base point. The base point is the lower end of the stake. This has the advantage that the measured velocity is not affected by surface changes of accumulation or ablation. Figure 2 by Schneider (1970) shows the components of the velocity vector (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 (t1, t2) 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) or from the elevation change due to the sloping surface (Δh) and the vertical component (Δz) of the velocity vector (d) (Schneider, 1970). The difference between the actual flow path (d), which is the length of the velocity vector, to the horizontal motion (Δs), which is the projected velocity, results from the vertical component (Δz). Annual values of the horizontal flow velocity (Δs/a) as well as the vertical motion values of submergence and emergence were calculated for 365 days. The horizontal velocity component (s) and the vertical component (v) in Schneider (1970) correlate to the definitions of (u) and (w) in Cuffey and Paterson (2010).

4 Accuracies and uncertainties

The investigations on KWF aim at very high accuracies, which are in the lower cm-level for the horizontal and the vertical stake position determined with theodolite and tachymeter. Beside the instrumental properties, these accuracies can be achieved by the statistical adjustment of the resection and intersection and especially the statistical adjustment of the trigonometric network (Schneider, 1970). In 2009, DGPS measurements with RTK (real time kinematic) procedure came into operation. During these measurements, the base-station is located in close proximity to the glacier at fix-points of the trigonometric network, allowing a staking-out of the stake position with a comparable accuracy in the lower cm-level. The overall accuracies depend on a proper implementation of the measurement methods. The precision requirements on KWF are in the range of ±5 cm per single measurement or at least ±10 cm for the period between the two readings for the horizontal and the vertical

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displacement. The stakes are reinstalled annually at their initial (xy) position. Redrillings and measurements are conducted with a rod level for exact perpendicular conditions. The reflector or the DGPS antenna is directly mounted to the top of the stake. Therefore duraluminium stakes with rigid connection are used on KWF as ablation stakes (Ø = 2 cm) and thicker accumulation stakes with a diameter of 5 cm for the necessary resistance against snow pressure.

In contrast to the stakes on KWF, ice flow velocities at GPF and TSF are measured at wooden ablation stakes with DGPS and post-processing procedure, the measured positions refer to the glacier surface. The minimum occupation time for DGPS with post-processing is 10 minutes but is mostly in the range of 30 to 60 minutes. The nearest base station, which provides basic data within the GPS and GLONASS satellite system, is located in Malles (STPOS-MABZ, 46°41'9.55" N, 10°33'3.73" E, South Tyrol, Italy). The linear distance 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 ±10 cm per single measurement or ±20 cm for the period between two readings at its 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 lower decimetre to metre-level. Stake positions are measured several times during summer seasons, allowing a comparison of shorter, sub-seasonal time scales.

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 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. 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.

5 Results

5.1 Hintereisferner

Three stone line records on HEF display the variation of glacier surface velocities for different periods, in total for more than 100 years (Figure 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 velocity of more than 120 m per year in 1919 (Hess, 1924). This acceleration caused a small advance of the glacier terminus in subsequent years. 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 (Figure 3). Since 1980, surface velocities on HEF have continuously decreased at the stone lines to about 4 m per year in the most 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 the most recent decades.

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5.2 Kesselwandferner

On KWF measurements were started for the hydrological year 1965/66, including horizontal and vertical flow velocities (Figure 4 and Figure 5). These long-term investigations document different glacier states at a longitudinal profile of up to ten accumulation and ablation stakes. There are two main contrasting periods, the first one from the start of the measurements to 1985, and the second period since then. During the first period the glacier was in an advancing state because of positive mass balances. During that time 75% of the measured glaciers in Austria and Switzerland presented positive length changes, caused by positive mass balances as a result of decreasing summer temperature 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 a large velocity gradient along the glacier, with maximum annual velocities of about 90 m per year at the terminus, in contrast with 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 of the surface velocities and a reduction of the velocity gradients. Negative vertical velocities became gradually positive around 1990 at stakes L8 and L7, in 2005 at L6 and in 2016 at L5, representing a shift of the ELA to higher elevations. The latest positive mass balance occurred in 2015, with an immediate response in the horizontal and vertical velocities. At the lowermost stake L10, velocity decreased rapidly to almost nil because of the decreasing mass supply to the terminus. This area became ice-free in 2010.

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 (Figure 6).

On GPF a general trend of decreasing surface velocities was found at all stakes, with higher rates from the stakes at the upper cross-profile (71-75) to the terminus. 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 of surface velocity in that area and a later decrease to almost nil (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 subseasonal fluctuations in surface velocity is given in Figure 7 for stake 65 at GPF, which has been measured from 2009 with least data gaps since then. The velocities are given as mean values per day to make the different time periods

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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 with earlier peaks in July. A comparison with the geodetic elevation change at the stake shows an expected inverse process. During winter months the elevation change of the surface 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.

6 Discussion and 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. Therefore responses of velocity fields are more sensitive to climate forcing than terminus fluctuations for this glacier. In contrast to HEF, the terminus of KWF advanced by more than 250 m from the 1970s to the 1980s (Patzelt, 1985; Fischer et al., 2018). KWF presents an immediate response at all profiles concurrently, which means that a mass gain or increase of the thickness within the accumulation area causes an increase of the emergence at the lowermost stakes within one 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 of 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.

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 even higher at the lowermost stakes. This means that velocity measurements, 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.

The subseasonal fluctuations on GPF (Figure 7) represent the typical acceleration of the glacier during summer months, which is well known and was, for example, already measured on HEF from 1900 to 1904 by Blümcke and Finsterwalder (1905). The

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accuracy of the measurements on GPF varies over time and depends on shading effects of the surrounding topography. The peak in 2013 shows the greatest uncertainty and is thus not representative for the actual surface velocity. The peaks look like jerky movements of the glacier but cannot be clearly identified as such.

For the investigated temperate mountain glaciers, ice flow velocity is a glaciological parameter that reacts very quickly to changes in the forcing. As conventional parameters like ELA tend to be above summit for the investigated glaciers under current conditions and specific mass balance is affected by rapid changes in area, monitoring of ice flow can be recommended as additionally surveyed parameter at mountain glaciers. Modern methods like DGPS and remote sensing need only limited extra effort, so that this should be feasible and increases the information available on the currently quickly receding mountain glaciers in a transient state.

Data availability

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

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

Maintaining long-term monitoring is always a challenging task and requires financial support and the help of numerous people, to whom we would like to gratefully express our thanks. Terminus variations of the glaciers and the velocity records on HEF relate to the annual measurements of the Austrian Alpine Club. Mass balance terms are provided by the World Glacier Monitoring Service (WGMS) and the Institute of Atmospheric and Cryospheric Sciences (ACINN). Research (project PROSA) on GPF was funded by DFG (SCHM 472/16-1, SCHM 472/17-2 and BE 1118/33-3) and FWF (I 894-N24 and I 1646-N19) and funding continues from glacier ski resort Kaunertaler Gletscher GmbH and Tiroler Wasserkraft AG (TIWAG), which also supports the measurements on TSF. We want to thank H. Schneider who started the velocity records on KWF and continued them for more than 50 years. These records are now supported by the non-profit organisation Glacier and Climate. We want to thank B. Scott for editing the English.

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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 [km²]	meas. since
GPF	46.85°N, 10.75°E	NE	N	2068-3535	16.62	2009/10
HEF	46.79'N, 10.75°E	E	NE	2399-3715	7.49	1894/95
KWF	46.84°N, 10.79°E	SE	E	2698-3496	3.82	1965/66
TSF	46.90°N, 10.86°E	N	NW	2208-3756	5.71	2009/10

Figure Captions

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 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 – data.tirol.gv.at.

Figure 2: Drawings by Schneider (1970) of the motion of a stake and changes at the glacier surface (Oberfl.) between two time steps (t1, t2) 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: relative surface elevation change from accumulation or ablation.

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

Figure 4: Annual horizontal flow velocities (Δs/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). Location of the stakes s. Figure 1.

Figure 5: Annual vertical velocities (Δv/a) at the accumulation and ablation stakes on Kesselwandferner (e.g. the year 2015 refers to the hydrological year 2014/2015). Positive values are defined as emergence flow, negative ones as submergence flow. Location of the stakes s. Figure 1.

Figure 6: Annual horizontal flow velocities (Δs/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

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the tongue of Gepatschferner. GPF (b): Three stakes at the cross profile; location s. Figure 1: 71: orogr. left, 73: centre, 75: orogr. right.

Figure 7: Mean daily horizontal velocities (Δs/day) at stake 65 on Gepatschferner between the measurements as an example of the subseasonal 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 depends 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)).

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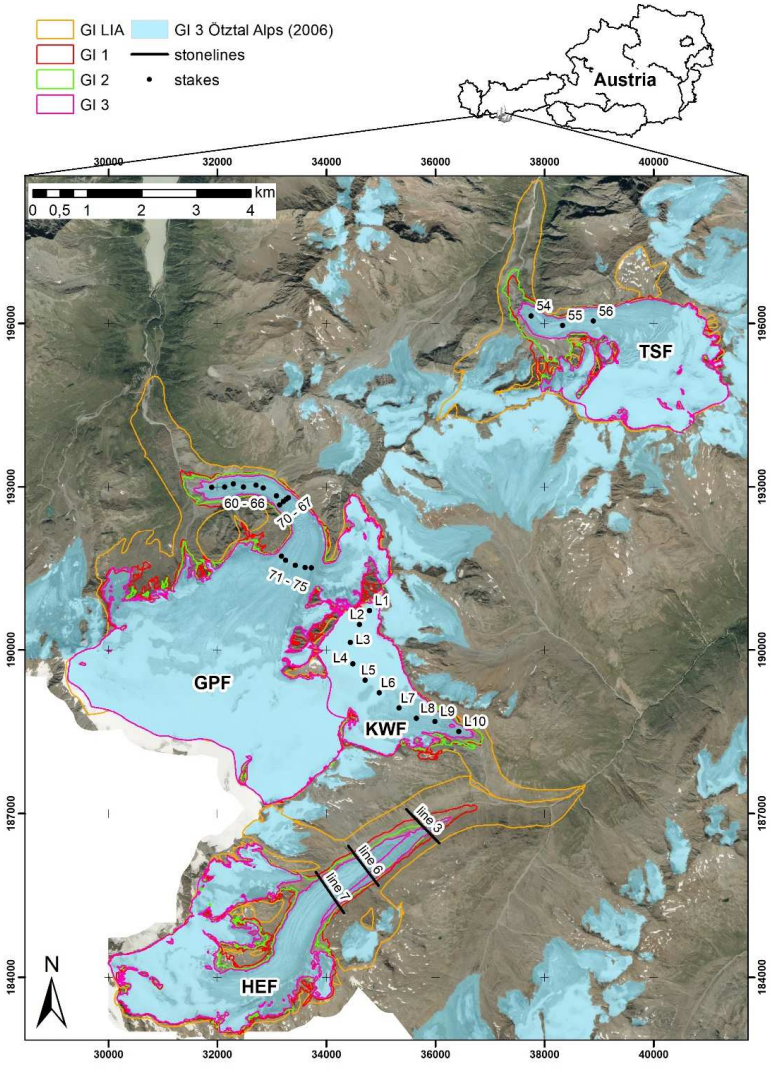

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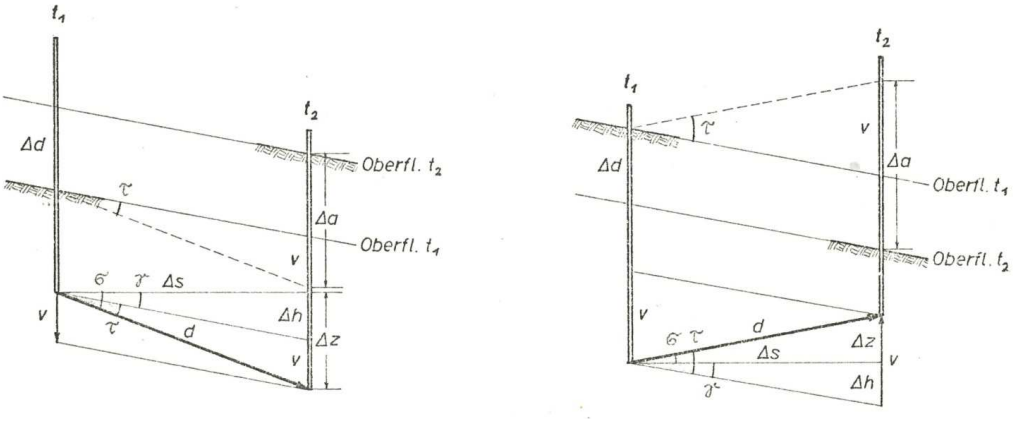

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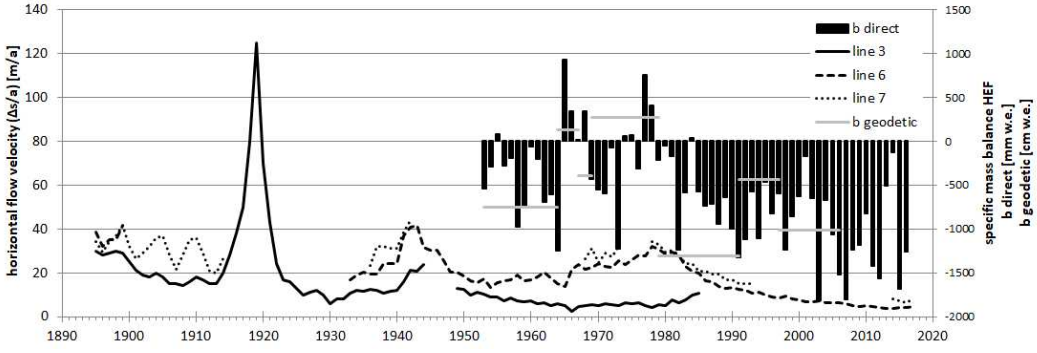

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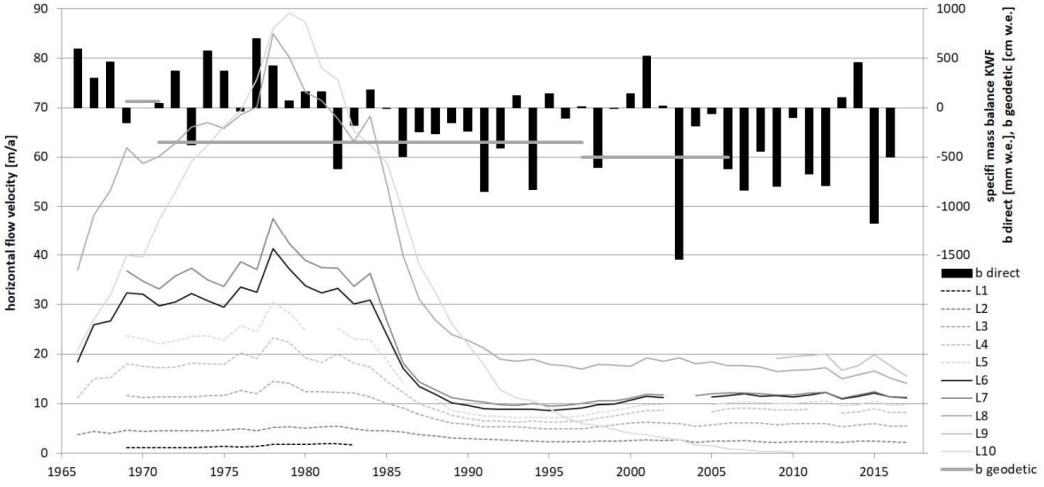

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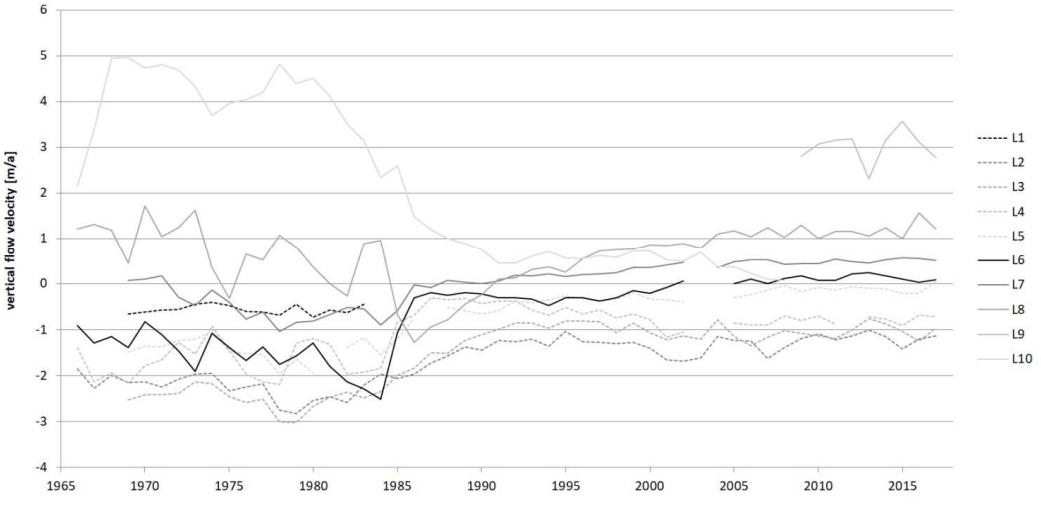

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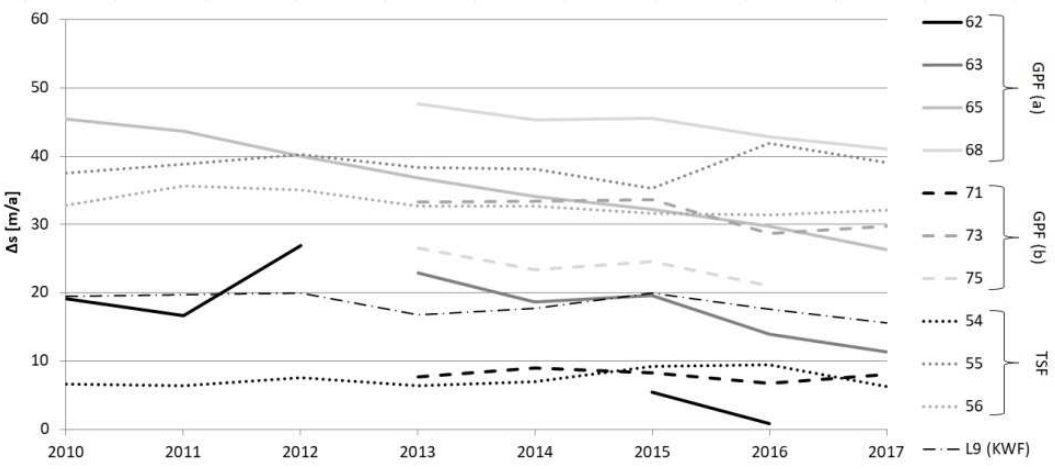

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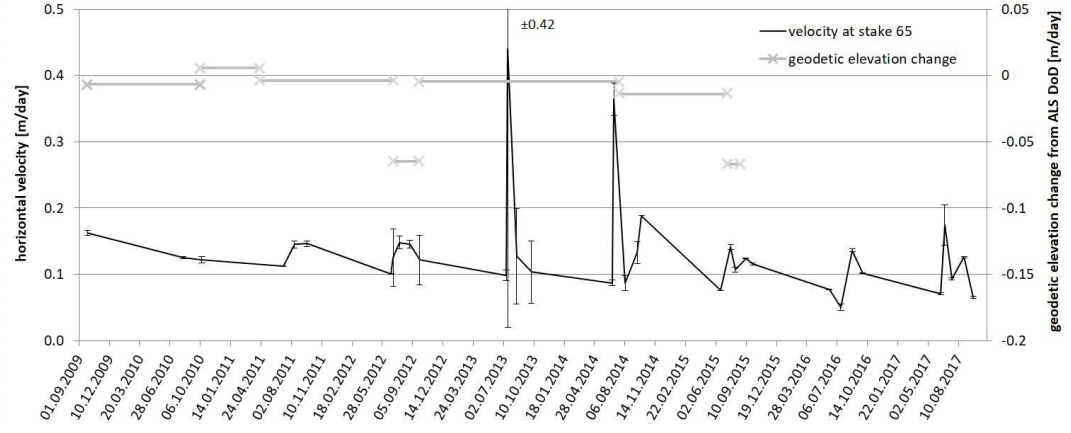

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