

Answers of the authors are formatted with indents:

**Topical Editor Decision: Publish subject to minor revisions (review by editor) (17 Apr 2019) by**

Reinhard Drews

Comments to the Author:

Dear authors,

thank you for responding to the reviews in detail. The reviewers have raised some important points, and the revised manuscript has certainly improved. There is no doubt that you have compiled an important dataset, that deserves publication as it is outstanding particularly regarding the temporal coverage. However, I am not yet convinced by structure and presentation of the paper. Below you will find a long list of editorial and structural changes that I suggest. I am not a native english speaker myself, and I don't require that all editorial remarks are put into practice.

However, particularly section 4 and section 6 require revision in terms of ordering, clarity, and succinctness. Details of the GNSS measurements are not yet clear to me, and also the derivation of errors (and their temporal variability) is not rigorously enough described for a paper in ESSD.

Note that none of my comments require further data analysis, and I echo the reviewer's judgement that the dataset is scientifically meaningful. Another round of revisions with a focus on clear structure and presentation style will give this dataset the framework it deserves.

Kind regards, Reinhard Drews

Thank for your comments and especially your detailed suggestions which helped us to improve the manuscript. Our editorial office did another language check, and we added the suggested information.

General Comment: Please provide a version including track-changes next time.

Please find the track-change version at the end of this response

P1, l3: Suggestion of rephrasing: "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 subseasonal variations of ice flow from Gepatschferner and Taschachferner covering almost 10 years."

Done, as suggested

P1, l 13 - Awkward opening sentence with "established", "confirmed", "later confirmed" and "explained". Suggestion: "...after Aggassiz (1847) hypothesized the theory of ice ages, which was then confirmed by Penck and Brückner (1909) and further substantiated with isotope analysis on polar ice cores (REF?) and theoretical work by Milankowitch (REF?)"

Done, as suggested and we added the three references:

Hays, J.D., Imbrie, J., and Shackleton, N.J.: Variations in the Earth's Orbit: Pacemaker of the Ice Ages, *Science*, 194 (4270) 1121-1132, 1976.

Milankovitch, M.: *Théorie Mathématique des Phénomènes Produits par la Radiation Solaire* (Gauthier-Villars, Paris), 1920.

Shackleton, N.J.: The 100,000-Year Ice-Age Cycle Identified and Found to Lag Temperature, Carbon Dioxide, and Orbital Eccentricity, *Science*, 289 (5486), 1897-1902, 2000.

P1, l15: The monitoring efforts in the 17th and 19th century require a reference, or at least some details on who and where.

We added the information on the measurements of the Austrian Alpine Club

Fritsch, M.: *Verzeichnis der bis Sommer 1896 in den Ostalpen gesetzten Gletschermarken*. Verlag des Deutschen und Österreichischen Alpenvereins, Wien, 1898

P1, l 20: Split than sentence up into two. It is unnecessarily convoluted.

Done

P2, l 8: Replace Jacob et al., 2012 with more recent Zemp et al, 2019?

We added Zemp et al. 2019

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., and Cogley, J.G. (2019): Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 568, 382-386, doi:10.1038/s41586-019-1071-0

P2, l 8: Again a compound-complex sentence structure containing two add-ons with “which” and one inset with “, and estimates ... ,”. This needs to be disentangled because it is unnecessarily hard to read.

Splitted into two sentences

P2, l 10: “For example ELA..” -> “For example, ELA...”

Done

P2, l 14: I think “ALS” is more commonly referred to as “Airborne Laser Scanning” (not Scan)

Done

P2, l16: “at annual resolution” -> “annually”

Done

P2, l16: Make two sentences. Second one “The stones advect with ice flow ( i.e. recording ice-flow in a Lagrangian system). The stakes, on the other hand, are relocated every year to their original position (i.e. recording ice-flow in an Eulerian system).

We added: The stones and stakes are annually relocated to ....

P2, l17 “net” -> “network” and then later “from THE Little Ice Age onwards” .

Done

P2, l20 Remove “Without further discussion....” and start with “This paper presents ice-flow velocity records on well ....”

Done

Close the introduction with one sentence on how this data can be applied (maybe as a baseline dataset for using glacier length/velocity as proxy for climate change over centennial timescales ?)

Added: This data can be used for validation of numerical ice flow models and further research on ice flow velocity as monitoring parameter and climate proxy on various scales.

P2, l 24: “Ötztal Alps (Austria)” later, “that differ” -> “differing”

Done

P2, l 30 “behind” > “upstream”

Done

P3, l 8: What was the main outcome of this comparison?

Added: The main outcome of the comparison was that both mass balance data sets generally agree within measurement uncertainties.

P3, l 19: several measurements during summer do not allow discussion of seasonality (but sub-seasonal variations during summer or variability between different summers).

We changed to “sub-seasonal”

P3, l26 “. After than DGPS was used.”

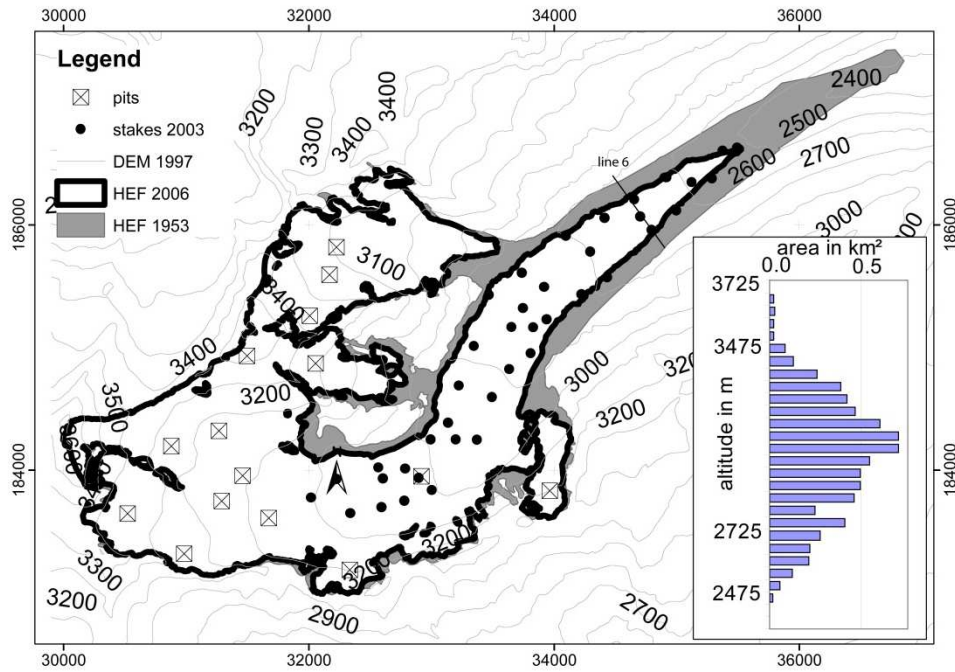
Done

P4, l10 Ok, forget my previous comment about Lagrange and Euler, but I hope you see how this was written confusingly.

cf. comment above

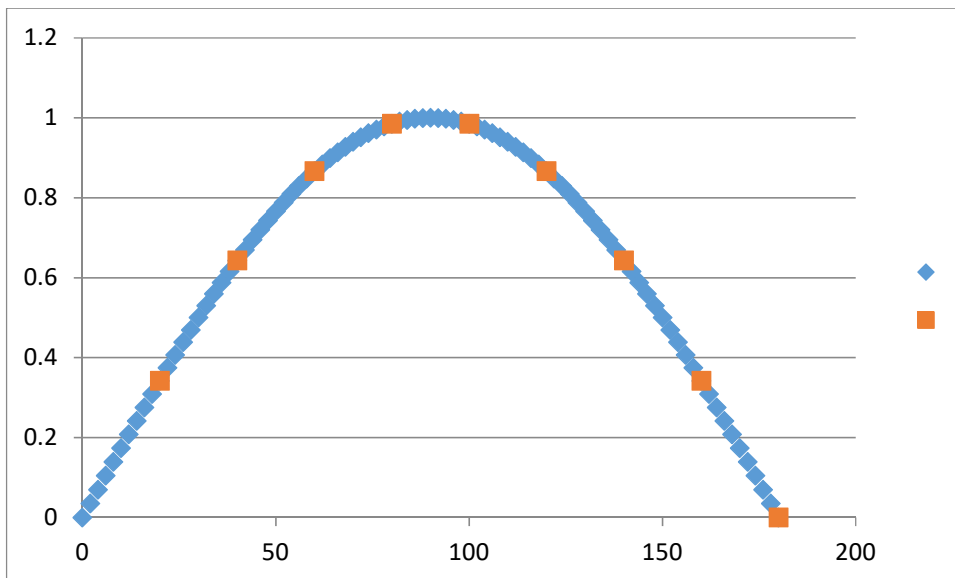
P4, l11 : What is the approximate lateral variation in a stone line, and why do you “only” report the average value? Also “depends on the number of stones” is correct but does not give credit to the reviewer comment (referring to a statistical bias) nor to the lateral variability (simply speaking, if all stones are located at the same place the mean does not depend on the number of stones). Rephrase and add details.

The approximate lateral variation in a stone line depends on the variation of the glacier width. The stones are positioned equidistant within the cross profile. If the glacier shrinks, thus the number of stones decrease. As evident from the Figure below, the glacier width at line 6 at Hintereisferner shrunk by about 50 % between 1953 and 2006.



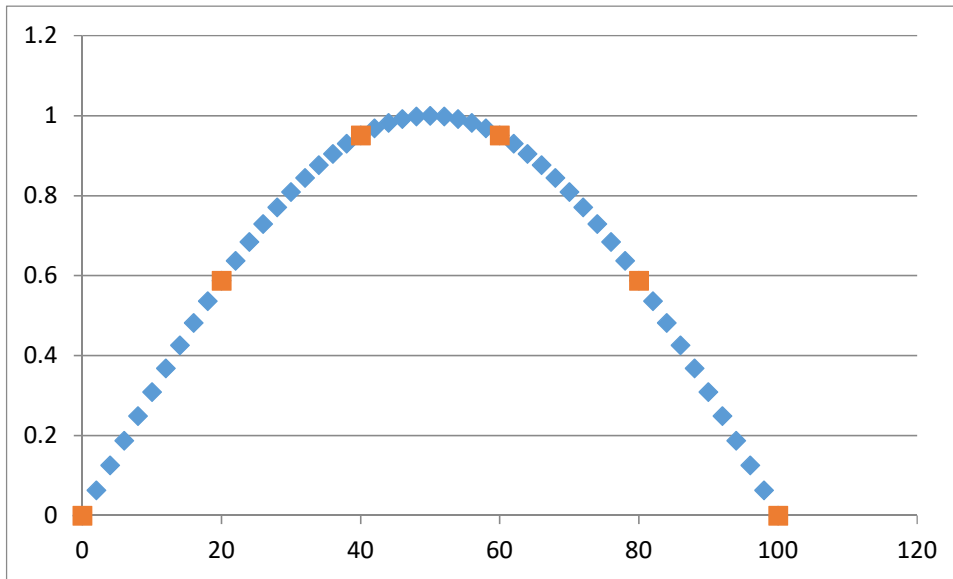
The stones are positioned with a distance of 25 m each along a straight line (cross-profile). So we can expect to cover the range of velocity variability by sampling at these equidistant locations.

Regarding the statistical bias: Mathematically speaking, we can do a simple model presuming a sinus function of velocity:



The mean of the dense sampling (2m) data is 0.6295, the mean of the less dense sampling (20m) data is 0.6301, so the difference is 0.09% only.

In this example, the glacier shrinks from 180 to 100 m.



Sampling still is equistant (20 m. orange), but the number of measurement points reduced as distance between sampling points is constant and total length reduced. Now the constant sampling rate of 20 m gives a mean of 0.512, i.e. 22% error. The velocity curve is smoother than the sinus, the velocity at the glacier boundaries are >0, and maximum velocity reduces when the profile length decreases counteracting the effect of reducing samples in terms of relative error.

length	distance	number points	mean	difference	percent
180	2	91	0.62956002		
180	20	9	0.63014242	-0.00058241	-0.09251008
100	2	51	0.62393169		
100	20	6	0.51294726	0.11098443	21.6366162

P4 I15: It is unclear to me where this ratio comes from, why it was used for comparison and what the take away message is.

The 80% refers to the maximum velocity at the centre flow line of the glacier. This means 80% of the stake velocity is comparable to the mean velocity of the profile as found by Span and Kuhn 2003.

P4. L 24: Whether velocities are positive or negative depends on your choice of coordinate system (some people to z vertically downwards). Be precise here and don't outsource such conventions to an external reference. Also add "relative to the surface" for emergence/submergence velocities.

We calculate with a fix coordinate system, velocities from the lowest point of the stake upwards are positive. This is given in the text: P4 L27 and P5 L3

P4, I 30 "correlate" -> "correspond"

Done

P5 , I 1 “Aim at high accuracies” ? Rephrase: Measurements done with theodolites and tachymeters are accurate to the lower cm-level. This is possible, because of statistical adjustment .... Also add: Further details on the derived errors for this specific dataset can be found in Schneider, 1979.

We rephrased this part

P5 , I 1 I admit that I don't know what “resection” means in this context and my online translation tool only finds medical terms. Please rephrase or explain for the wider ESSD audience.

Resection and intersection means „Rückwärts- und Vorwärtseinschneiden“. We added „... of the measured positions using resection and intersection techniques...“

P5 I 7 what is “staking-out” ?

Staking-out means the locating of a given position (Abstecken)

P5 I 1: First: Collecting all uncertainties in one section is a good idea. However, then this section should only contain this and details of the individual methods (e.g. what stakes are used, the use of wood wool, what rigid connections were used, where the base station was located and so on) should be transferred to the sections 3.1- 3.2. Second: This section needs more structure. What I expect here (given the section heading) would be something like:

Measurements based on theodolites and tachymeters are with XX cm. This depends on a,b,c and details can be found here. Differences between the observed glaciers are a,b,c :

Measurements based on DPGs are within XX cm. This depends on a,b,c. Differences between the observed glaciers are a,b,c.

So for KWF you used your own base station and for GPF & TSF a base station in Italy. Why?

For KWF, the fix points for the reference station are in use since 1962. There is no such network for GPF and TSF, and the station in Italy is near (and was installed much later than 1962, so that it was no option for KWF).

P5, I19 State-of-the art GNSS base stations should receive not only GPS and GLONASS, but also Galileo, Beidou and so on. Is there a reason why you specifically mention GPS and GLONASS ?

Yes, that's true, but so far only the GPS and GLONASS systems were used within the time series presented here. With the ongoing monitoring Galileo will be included.

P5 I20 “linear distance” – “baseline”

Done

P5, I25 what is the order of magnitude for observe sub-seasonal velocities in summer, and how do these relate to the errors of up to 1 m?

The errors of up to 1m are caused by shading effects, which depend on daytime due to the changing satellite coverage. On short timescales a great error from one measurement can be greater than the velocity, or the calculated distance between two readings. Sentence deleted

P5, 25 The use of RTK – DGPS is unclear to me. RTK to me means “real-time kinematic” and requires a radio-link between base station and rover (I doubt this was the case when using the base station in

Malles). Also, why would you use RTK for measuring the stake positions? Wouldn't it be better to determine the position in the post-processing? Why is the stake position required in real-time?

RTK-DGPS is used on KWF and needed because of the exact relocation (staking-out) of the stakes at their initial positions as this position is fixed. The post-processing procedure is used on GPF and TSF.

Following up on this: I am not convinced by the details given regarding the DGPS data. Additionally to the confusion whether the position was determined during post-processing or in real-time, it is also unclear to me what processing scheme has been applied. For example, how did you get the position of your own local base station? In my experience those details are not unimportant when aiming for an absolute horizontal precision of less than 5 cm. Moreover, there is no distinction between errors in horizontal and in vertical direction. Shouldn't it be more difficult to get the vertical displacement? If all of these points result in smaller errors compared to other sources (e.g. the tilt of the stakes, or slipping of stones) this is ok but should be explicitly stated and quantified.

We added the information on the post-processing procedure and added references on the fix points of the local base stations.

Niederwald, T.: Festpunktbestimmung mit GPS für Gletscher-Monitoring-Projekte in den Öztaler Alpen (Tirol), Master thesis, Hochschule für Angewandte Wissenschaften, FH München, Fakultät für Geoinformation, 2009.

Weide, S.: Estimating the Height Accuracy of Airborne Laser Scanning with GPS and Calculation of Glacier Movement at Hintereisferner, Master thesis, Hochschule für Angewandte Wissenschaften FH München, Fakultät für Geoinformation, 2009

Zauner, R.: Glaziologische Analyse der Gletscheroberfläche am Blockgletscher Äußeres Hochebenkar, Hintereisferner und am Kesselwandferner (Öztaler Alpen), Bachelor thesis, Hochschule für Angewandte Wissenschaften FH München, Fakultät für Geoinformation, 2010.

p.5 | 30: GPS measurements should be characterized with an absolute error. 5 % is additional useful information but requires the local flow velocity for context.

Added: with an absolute error of  $\pm 0.05$  m per single measurement

Section 4 is important, but it is currently too unstructured and partially also unclear. This needs to be revised.

P6, | 10 Suggestion add: This is XX m/a (or XX %) above the mean flow velocity measured at this location.

Done

P6 | 20 "During the first period, " (comma) and then later "advanced" (instead of "was in an advancing state")

Done

P6 | 21 “presented positive length changes” sounds complicated. Why not “advanced”?

We changed to: “... advanced due to positive...”

P6 | 32 would it be better to say “Submergence transitioned to emergence around 1990...”

Done, as suggested

P8 | 11 “and highest ant the lowermost stakes”

Done

Section 6 has a quite narrative character and I am not a friend of merging Discussions and Conclusions. Many people only read abstract and conclusion of a paper (and they tend not read the conclusions if they are intertwined with discussion elements). Consider taking these two sections apart, and provide a succinct conclusion emphasizing the uniqueness of your dataset and possible applications.

We splitted section 6 into two sections

P8 | 26: That the accuracy of measurements depends on topographic shading has already been mentioned above. Also it is not quantified. I wonder if this statement is important enough to be repeated in the conclusion.

It is unclear to me, why the “peak in 2014” for GPF has the highest uncertainty. What event in time makes this measurement less certain than the others? Section 4 estimates errors at GPF to be within pm 20 cm “at its best”. I don’t see how this explains the variability in errors shown in Figure 7.

This peak was caused by topographic shading effects, we added this information

P 8 | 28: The term “jerky movement” requires a reference (Goldthwait ?). This is another somewhat speculative sentence which is ok in a discussion but misplaced in a conclusion.

Sentence deleted

P 8 | 31: “As conventional...” is this sentence complete? After reading it multiple times I think I understand that “ELA” and “specific mass balance” are other glaciological parameters to characterize a glaciers, but you find them less well suited compared to the ice-flow velocity.

We added: “... long-term monitoring of ice flow provides valuable additional information on the glacier state.”

P 8 | 30 “extra effort” compared to what?

deleted

I apologize, but the meaning of the last paragraph is opaque to me. Please rephrase. I suggest ending the paper with your main finding, uniqueness and further applications of your dataset. Keep it succinct.

changed



# 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 time scales. 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 subseasonal variations of ice flow from Gepatschferner and Taschachferner covering almost 10 years. 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 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 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 Agassiz (1847) ~~established~~ hypothesized the theory of ice ages, which was then confirmed by Penck and Brückner (1909), later confirmed by and further substantiated with isotope analysis on deep sea sediment and polar ice cores (Hays et al., 1976; Shackleton, 2000) and the theoretically explained work by Milankovitch (1920). First monitoring efforts focused on recording the changing positions of glacier termini, starting in the 17<sup>th</sup> century and systematically organized in the late 19<sup>th</sup> century, for example by the German and Austrian Alpine Club (Fritzsich, 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. ~~with Stone line velocities were recorded at 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 Rhonegletscher (Mercanton, 1916; Roethlisberger, 1963) or Mer de Glace (Berthier and Vincent, 2012). At the glaciers Unteraargletscher and Mer de Glace, ice flow was already 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 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 e~~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. ~~g~~Glacier flow velocities which 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 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, 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 (3D velocities). ~~with~~The stones and stakes are annually ~~set back~~relocated to their original position. Long-term velocity data are recorded ~~at annual resolution~~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).

~~Without further discussion of the potential and limitations of different remote sensing sensors and techniques,~~ This paper ~~presents focuses on presenting~~ice flow velocity records on well investigated mountain glaciers and their relation to other in situ monitoring parameters. This data can be used for validation of numerical ice flow models and further research on ice flow velocity as 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) ~~that differing~~ in size, aspect and elevation ranges (Tab. 1).

- 5 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-upstream from~~ the location of the profile.
- 10 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,

- 15 GPF and TSF, especially since the terminus retreated to the top of a steep terrain level and detached from the dead ice body in the front of this step in 2012. Velocity measurements were started in 1965 by Schneider (1970) at ablation 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 data sets generally agree within measurement uncertainties.](#)

- 20 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
- 25 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. 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 summer months, allowing a
- 30 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.

5 ~~Since then~~~~After than~~ when DGPS (Differential Global Positioning System) ~~measurements came into operation~~~~was~~~~have 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,

10 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

15 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 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

20 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 depends on the number of stones.

25 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, 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~~ ~~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 ( $t_1$ ,  $t_2$ ) 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 ( $\Delta d$ ) and the accumulation or ablation ( $\Delta a$ ) or from the elevation change due to the sloping surface ( $\Delta h$ ) and the vertical component ( $\Delta z$ ) 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 ( $\Delta s$ ), which is the projected velocity, results from the vertical component ( $\Delta z$ ). 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 days and on the basis of a fixed coordinate system. The horizontal velocity component ( $s$ ) and the vertical component ( $v$ ) in Schneider (1970) ~~correlate~~ ~~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. Redrillings 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 rigid connection are used on KWF as ablation stakes ( $\varnothing = 2$  cm) and 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, a 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 in.

### 4 Accuracies and uncertainties

The investigations on KWF ~~aim at very high accuracies, which are accurate to in~~ the lower cm-level (0.05 to 0.1 m) for the horizontal and the vertical stake position determined with theodolite and tachymeter. ~~Beside the instrumental properties, these accuracies can be achieved by the~~ ~~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 on the derived errors for this specific dataset can be found in (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 (Schneider, 1970; Niederwald, 2009; Weide, 2010; Zauner, 2010), 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  $\pm 0.05$  cm per single measurement or at least  $\pm 0.10$  cm for the period between the two readings for the horizontal and the vertical

displacement. ~~The stakes are reinstalled annually at their initial (xy) position. Redrillings 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 rigid connection are used on KWF as ablation stakes ( $\varnothing = 2$  cm) and thicker accumulation stakes with a diameter of 5 cm for the necessary resistance against snow pressure. Tipping over and melting in~~  
5 ~~may lead to errors in measuring the vertical motion. On KWF, a 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 in.~~

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  
10 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~~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  $\pm 0.10$  cm per single measurement or  $\pm 0.20$  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.

15 ~~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 number of stones in the profile varies in time, which leads to a systematic error to the mean velocity of the lines. The number of stones  
20 at Line 7 decreased from initially 19 stones 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 ( $\Delta s$ ) and are calculated from theodolite and tachymeter measurements until 2009 and with RTK-DGPS since then with an absolute error of  $\pm 0.05$  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 on the  
25 surface slope and the annual surface ablation and depends less on the surface velocity. This means, 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). ~~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.~~

## 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 (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 ~~more than 1205~~ 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 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.

### 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 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~~ advanced because of positive mass balances. During that time 75% of the measured glaciers in Austria and Switzerland ~~presented positive length changes, caused by~~ advanced due to 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 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 of 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. ~~Negative vertical velocities became~~ Submergence transitioned gradually to emergence positive 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 nil because of the decreasing mass supply to the terminus. This area became ice-free in 2010 (Fig. 4 and Fig. 5). The latest positive mass balance occurred in 2015, with an immediate response in the horizontal and vertical velocities.

### 5.3 Gepatschferner and Taschachferner

5 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  
10 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 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  
15 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 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. During winter  
20 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.

## 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. 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  
30 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~~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 subseasonal 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 subseasonal fluctuations depend on the drainage network which is driven by the amount of 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~~ the peak in 2013 shows the greatest uncertainty due to topographic shading effects 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.~~

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 Conclusion

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; 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.

For the investigated temperate mountain glaciers, ice flow velocity is a glaciological parameter that reacts very quickly to changes in the forcing as, for example, the glacier mass balance variability (Huss, 2012). 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, long-term monitoring of ice flow provides valuable additional information on the glacier state. Our data set allows to develop and validate perspectives on ice flow velocity as monitoring tool. 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.

### 25 **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.

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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 [km <sup>2</sup> ]	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

## Figure Captions

- 5 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.,  
10 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,  $\Delta s$ : horizontal velocity (projected velocity),  $\Delta d$ : absolute surface elevation change,  $\Delta a$ : point  
mass balance (relative surface elevation change from accumulation or ablation).
- 15 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. Fig. 1.
- Figure 4: Annual horizontal flow velocities ( $\Delta s/a$ ) at the accumulation and ablation stakes on Kesselwandferner (e.g. the year  
20 2015 refers to the hydrological year 2014/2015) and the specific surface mass balance (b direct) (Strasser et al., 2018;  
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1.
- 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  
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- 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; location s. Fig. 1: 71: orogr. left, 73: centre, 75: orogr. right.

5 Figure 7: Mean daily horizontal velocities ( $\Delta s/\text{day}$ ) 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)).

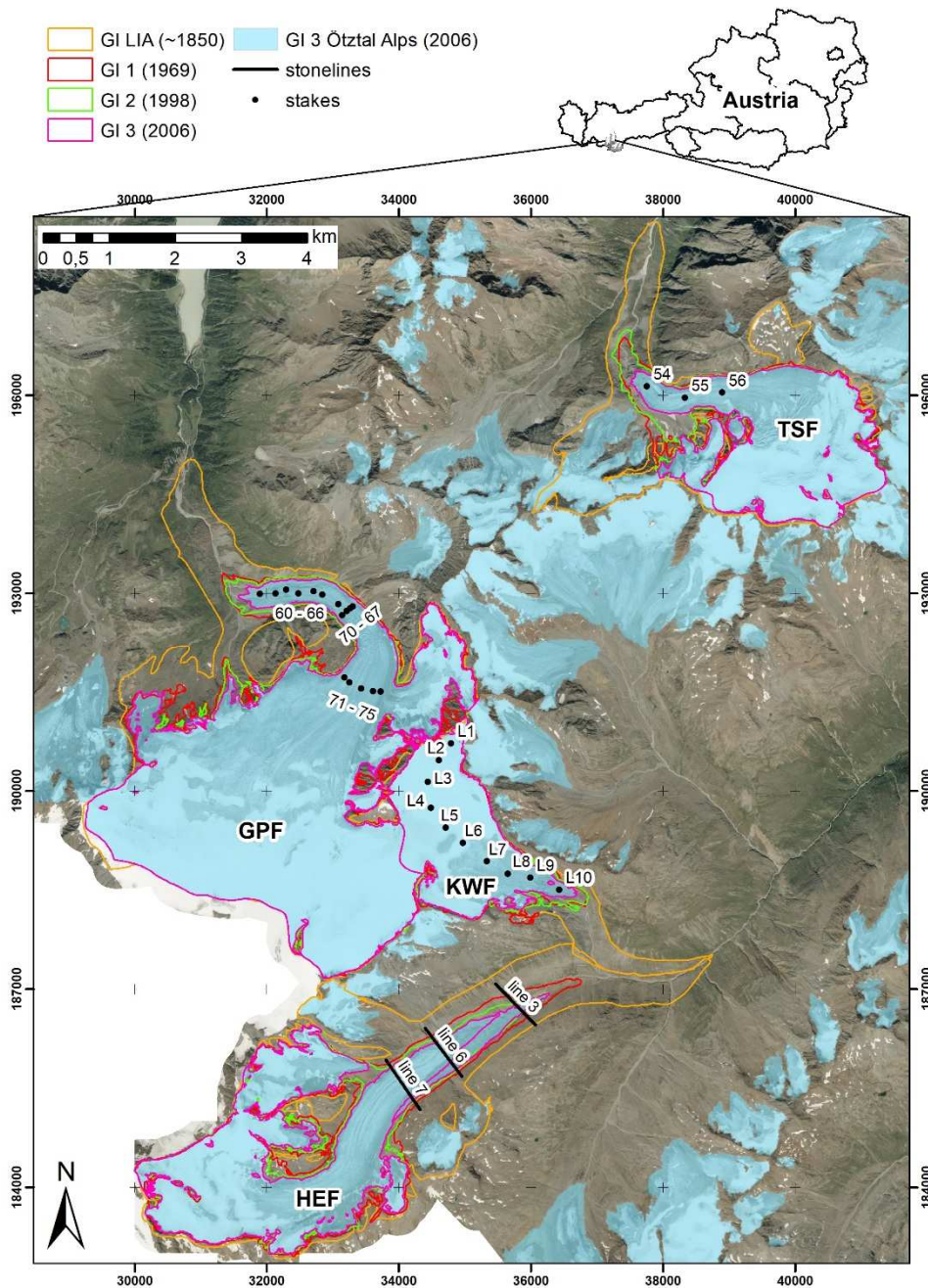


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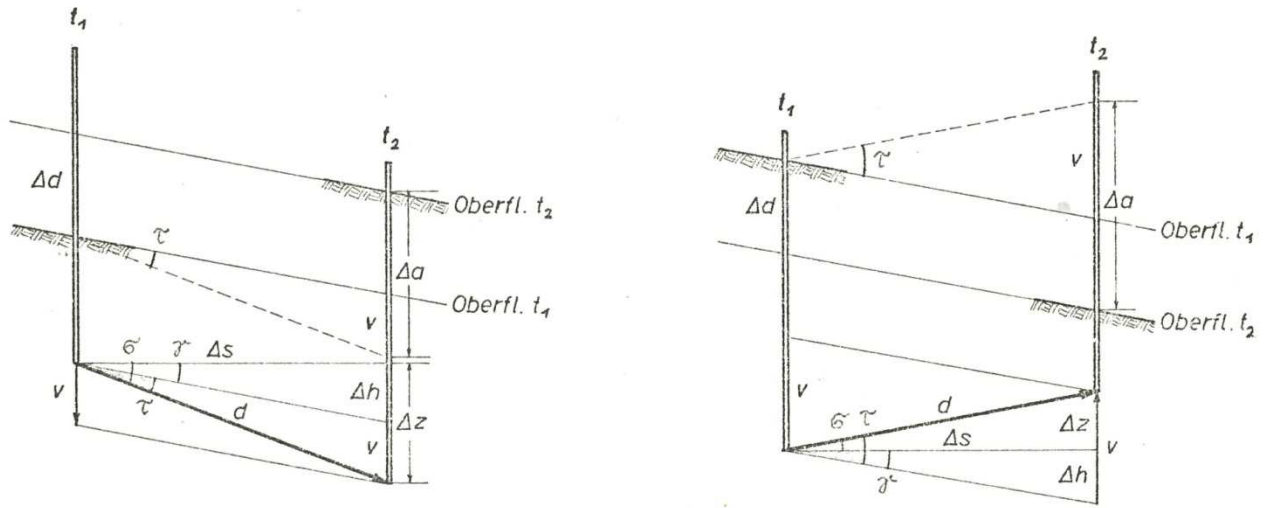


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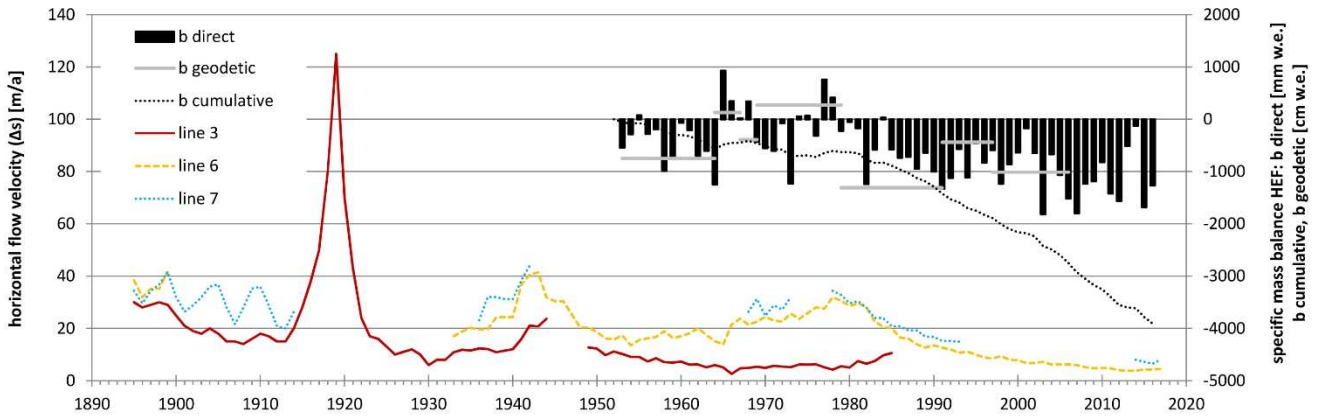


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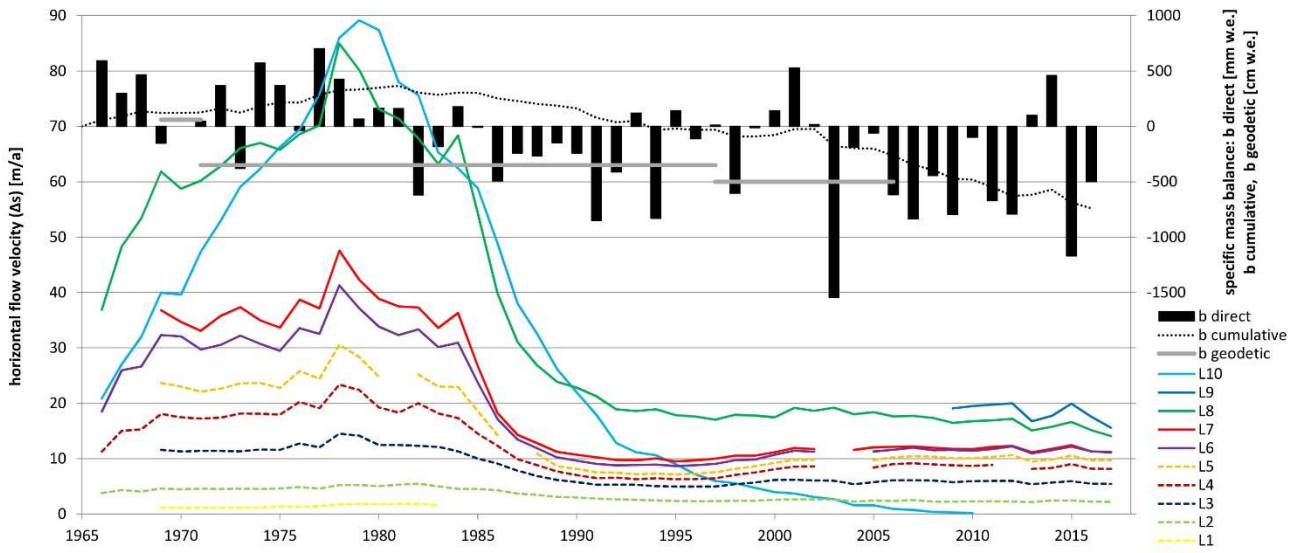
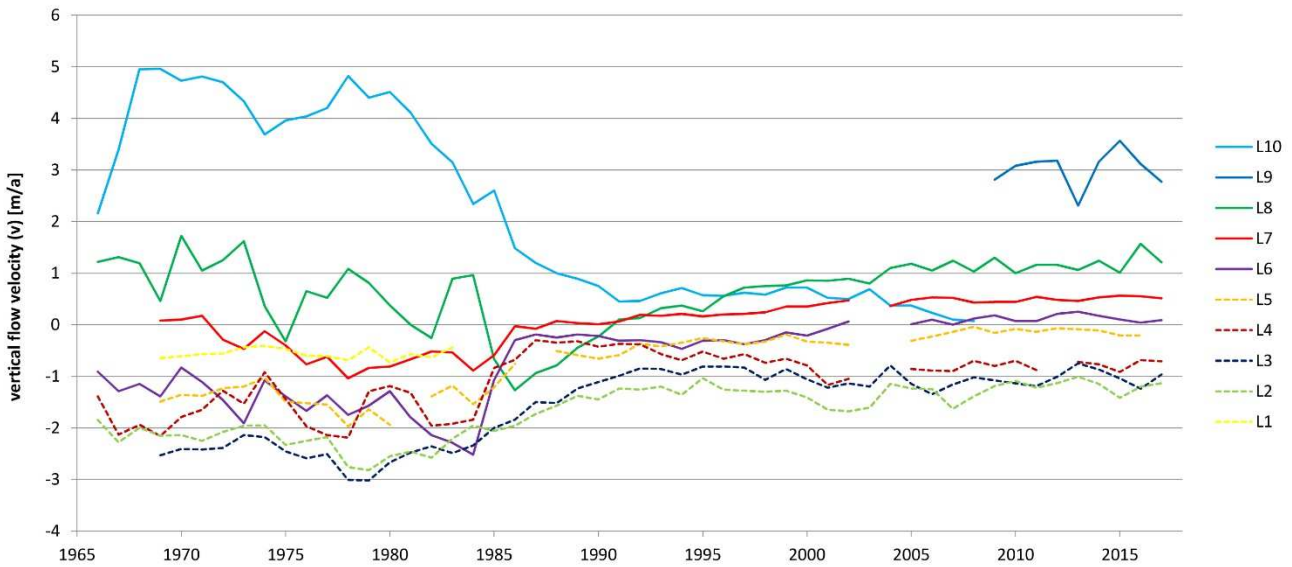


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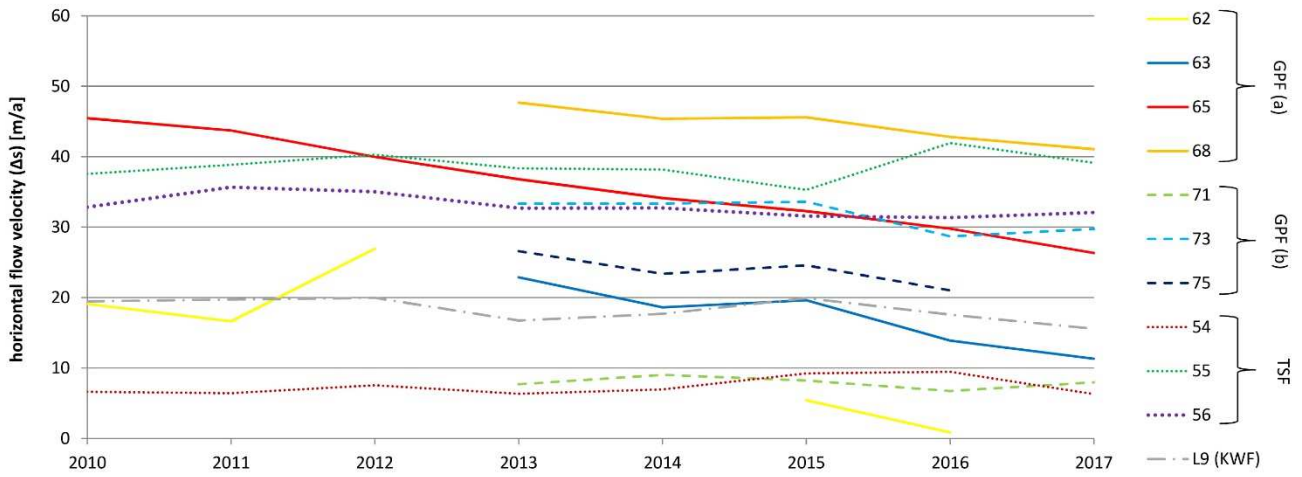
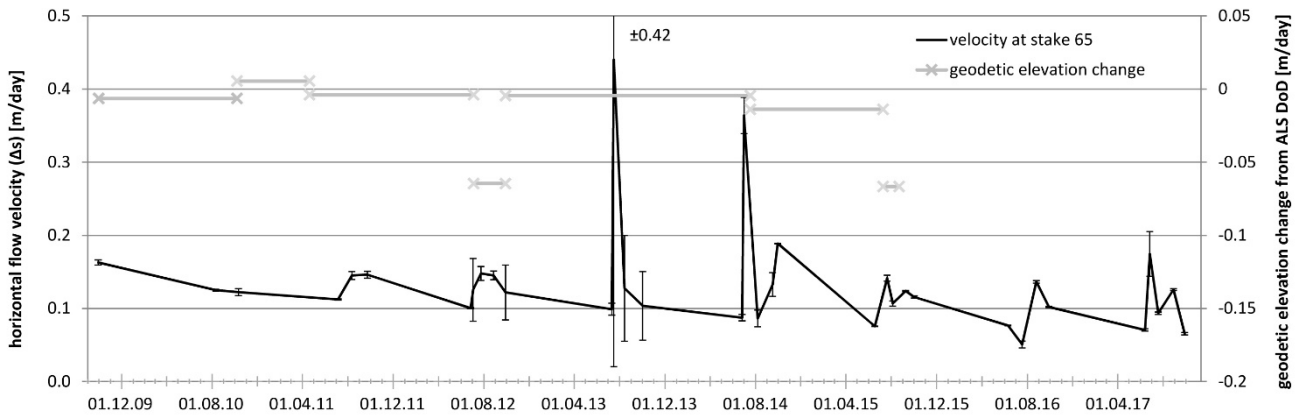


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