Response to Mauri Pelto, Referee #2

The review is cited underlined, answers of authors are formatted indented.

> We thank Mauri Pelto for his helpful suggestions and valuable discussion of the draft! His review, together with the suggestion of the first reviewer, points out that we should clarify the research question, the framework and setting and intensify the discussion of the results. We look forward to do so, following the suggestions of both reviewers.

The authors provide an interesting long term data set on velocity in concert with mass balance on two glaciers Kesselwandferner (KWF) and Hintereisferner (HEF). They provide a short term data set on two others. The data is limited to the ablation zone on HEF.

> Thank you for the interest in the long term data set. For further discussion: it is not entirely clear to us which of the presented data you refer to long term: Is it the Hintereisferner series only (ablation zone), or also the Kesselwandferner series (ablation and accumulation zone)? As these do not include seasonal, but only annual data, we thought it would be useful to add the shorter data sets with higher temporal resolution.

The paper examines the concept that the velocity changes observed might have a comparable use to the annual mass balance or ELA observations. This concept cannot be demonstrated with the spatially poor and temporally infrequent velocity record. The results indicate several long periods of glacier acceleration during periods of positive mass balance, and glacier deceleration during periods of negative mass balance, which has been documented and is expected.

> It is correct that all available velocity data measured in field or by remote sensing, are discontinuous in space and time, and, for remote sensing and stone line measurements, are limited to two dimensions only introducing uncertainties. The authors compared measured mass balance data only, so that they did not draw the conclusion that during the period of rising velocities in the 1920s with rare documentation of glacier advances also positive mass balances did occur. There is only one period of measured positive mass balances (at Kesselwandferner only), where also velocity increases have been measured. As for the first review of this draft, the authors find these comments helpful to work out a better focus of the draft on more explicit research questions. There is enough (maybe too much material) available, so that we will do our best to focus and structure the paper in a new way.

The annual mass balance record and terminus change record provide a more detailed record for both glaciers. The terminus record reflects the cumulative mass balance over a span of years commensurate with a glaciers response time. Velocity is a lagging record to cumulative mass balance over a span of years. This lag varies by glacier and location on the glacier, hence does not provide a good climate record. If the velocity record had a broader spatial distribution on the glacier and had been completed with greater frequency over the period of record, the results would be useful. The level of detail and analysis of HEF and KWF provided by one of the authors Fischer (2011) sets a high bar for mass balance and geodetic analysis of these glaciers that this paper does not add to.

We will restructure the paper using the comments of Mauri Pelto as guidelines. The phrasing in the first draft seems to very misleading: Our intention was not primarily to present velocity records as an alternative to mass balance observations, but rather contributing complementary information to direct or geodetic mass balance records or other parameters as snow line, etc. This could be useful when ELA rises above summit level and, in a historical perspective, when direct mass balance measurements are incomplete (e.g. before 1953 on HEF).

It seems that the title of the manuscript is misleading so the expectations of the reader are not fulfilled. We will change the title.

We will restructure the whole manuscript in two main parts or even two paper drafts. In the first part we will present the valuable data useful for e.g. glacier modelling. In the second part we will extend the discussion and add time series of temperature and precipitation from the HISTALP data set (e.g. Auer et al. 2007): http://www.zamg.ac.at/histalp/

Specific Comments:

1-16: Catastrophic in what sense?

Because of the glacier advances, the river Rofenache was dammed several times during the little ice age. The failure of the dam caused catastrophic lake outburst floods, i.e causing large damages and devastating the inhabited valley. We will add this information and citations.

1-23: Remove sentence. No need to discuss ice sheet dynamic changes particularly since these often have retreat associated with acceleration. Ice sheets also have long response times. Marine margins of ice sheets also impacted by ocean temperatures in contact with the ice.

We will remove this sentence.

2-3: Not sure the point of this sentence. Feature tracking is quite valuable in velocity determination, particularly to build a rich spatial data set across a glacier and through the seasons. It is true we do not have long term velocity records from feature tracking.

Yes, we actually consider feature tracking or DINSAR as very important methods for monitoring glaciers (and ice caps, ice sheets…). Having worked with these methods at small mountain glaciers, we just wondered about the relationship between the results of the various methods including in situ data. So far, few comparisons of remote sensing and in situ data exist. The interpretation of the direction of motion from remote sensing usually lacks one dimension. We will discuss this in more detail, although this topic could be enough material for a draft itself, adding remote sensing data of the area.

2-12: Not sure how the term mass balance theory is used. The suggestion of velocity replacing mass balance is poorly outlined. Mass balance is a good annual measure of volume change for a glacier. Velocity is a longer term response, not an annual measure it is a lagging indicator (Johannesson et al 1989; Zemp et al. 2015). A mass balance perturbation is distributed over a glacier at a finite rate, which results in a lagged response of both glacier velocity and glacier length to changes in mass balance forcing (Johannesson et al 1989; Bahr et al 1998). Velocity changes can identify changes in state, but these are typically associated with other easily observed changes such as terminus change or snow line rise.

We will add an introduction and some citation what we refer to as mass balance theory. In short, it is the theoretical framework allowing the interpretation of a measured value based on general theory of science. Apart from teaching books, the cited papers together with the books of Oerlemans should give a good basis. We will try to quantify the mass balance/velocity response time lag!

We do not want to replace direct mass balance measurements, but we want to show if or how velocity records can complement these datasets. We agree that the response time/time lag is a major issue. We will clarify this and discuss this in more detail.

2-14: There have been some years where the ELA has risen above a number of glaciers. A glacier cannot be sustained in such a situation as it has no accumulation zone (Pelto, 2010). The AAR of zero is a good measure in such a year as well and can be identified using satellite imagery as well. Six and Vincent (2014) have illustrated the quantitative relationship between ELA and temperature at a number of glacier indicating the value for understanding climate response. Such a quantitative relationship between climate and velocity has not been established.

From the results of the last decade of direct mass balance measurements, we agree that a repeat AAR of zero is indicating a potentially vanishing glacier. Nevertheless, melt rates can differ significantly, depending not only on the time when the AAR occurred for the first time in the season, so that we consider additional information as helpful. As the time and the rate for a glacier to vanish might be interesting at least for local stake holders, we think that it might be helpful to extend monitoring for these years even in absence of many stakes (which are often hard to maintain on disintegrating glaciers with much debris cover.

As some of the data describing glacier retreat in the Autrian Alps point out the possibility of nonlinear behaviour (e.g. Stocker-Waldhuber et al., 2016), we cannot confirm that the relationships between temperature and mass balance also presented e.g. by Kuhn for the Austrian Alps will also be valid in near future. Nevertheless, we are grateful for pointing out that it will be beneficial to add some time series of temperatures and precipitation from the

HISTALP dataset (Auer et al. 2007) and discuss the relationship to various glaciological parameters in the paper. The disintegration of large glaciers into small ones in higher elevation causes a higher frequency of missing ELAs: Glaciers are either totally snow covered, or no accumulation takes place.

5-20: The acceleration is not necessarily the cause of the advance. The increase in mass balance which leads to higher volume flux down glacier would be the formative cause. Schwitter and Raymond (1993) observed some of the complexity noting a difference in longitudinal thickness changes (profile shape factor) for short time-scale changes compared to long time-scale changes illustrating on a short time-scale response where transient responses may cause complex localized thickness-change patterns, as observed here on GPF, and a long time-scale response displaying changes in near steady-state profiles.

Thank you, we will add this information to the text. For the first draft, we ignored thickness and density changes as well as basal sliding completely, a strategy which we recognized is not useful for a further discussion ….

5-23: This sentence and figure 3 underscore the insufficiency of the velocity data series as a replacement for annual mass balance. There is a consistent decline in velocity, while this fits the mass balance trend line it does not identify the annual mass balance variability. Berthier and Vincent (2012) in looking at the contribution of mass balance versus surface flux to ice thickness changes on the tongue of Mer de Glace note that "Between 1979–94 and 2000–08, two-thirds of the increase in the thinning rates was caused by reduced ice fluxes and one third by rising surface ablation." To interpret the velocity record for KWF or HEF in the context of climate requires this level of flux analysis is required.

We carried out flux analyses as part of a very different paper. Unless velocities are very low, the unknown basal sliding makes a large difference. But that can be shown straight forward in an introduction.

We will clarify in the text that we do not want to replace mass balance observations.

6-9: The pattern of this glacier of acceleration during a period of mass gain followed by reduction during a period of retreat, does not offer any new insights to the glaciers behavior.

We see that we significantly will have to improve the description of the data, pointing out the remarkable events.

6-12: The decline of velocity to nil on KWF raises the same issue as an ELA rising above a glacier it does not offer a specific annual value of use for climate measure.

In contrast to ELA, the measurements did not decline to nil at every stake at KWF, sorry for the misleading phrasing here. We will point out that the 'inactive' fraction of a glacier itself can provide some information.

6-17: The velocities reported for TSF are of insufficient temporal and spatial range to be a useful measure for understanding glacier mass change or climate response.

We will show the differences between the individual glaciers and discuss this in more detail. The added value of the velocity measurements on GPF and TSF is the relatively high velocity for recent glacier states. On GPF and TSF we like to show also the seasonal variability.

6-21: The GPF velocity record is of both short duration and generally limited to the terminus reach of the glacier and is not capable of addressing glacier wide velocity changes in response to climate change. Nor can it be demonstrated that velocity change is consistently responsive to mass balance or climate change.

We will discuss this in more detail as we want to show the seasonal variability, we will also add some values of the surface ablation at the stake positions. The measurements are limited to the glacier tongue but the velocity records in this region can provide information on the glacier state.

7-5: And what was the response time?

Great question. We see that we need to define, discuss and quantify response time, lag, relaxation, delay …

7-10: It is not demonstrated that the simultaneous velocity change is indicative of mass change in a single year. This can be a response due to a similar multi-year mass balance pattern. The multi-year response affect is indicated by the sequence of small positive balances in the early 1980's that led to glacier velocity reduction despite this positive balance, simply because the balance was not as positive as it had been.

We thank for the valuable suggestion and see that we have to present a more elaborated and distinct analysis of the data.

8-1: The long term velocity data set presented here is from two glacier HEF and KWF, with data in the accumulation zone only from KWF. This data set does not demonstrate that velocity consistently responds rapidly to climate change. The data indicates decadal velocity responses, not annual velocity changes that are correlated with climate data or mass balance.

We will carry out a statistical analysis to confirm or decline this hypothesis – thank you for suggesting this hypothesis

The velocity observations here do not provide the seasonal details that mass balance records do.

Unfortunately, seasonal mass balances are not available for the measured glaciers (no winter mass balance is available).

This allowed Zemp et al (2015) to observe from the WGMS records a seasonal difference in mass balance "The increased mass loss over the past few decades is driven mainly by summer balances which are dominated in most regions by ablation processes. Winter balances seem to be of secondary importance and show no common trend. As a consequence of both the extended period of mass loss and the delayed dynamic reaction, glaciers in many regions are in strong imbalance

Another important point of discussion is the definition and quantification of imbalance…

with current climatic conditions and, hence, destined to further substantial ice loss." The delayed dynamic response to climate change makes identification of seasonally driven trends difficult. The velocity change smooths out response and will lead to continued velocity change despite short term mass balance changes that could or will influence the glacier.

We will check that in the data.

8-2: The ELA is traditional and may not be the right measure, but the transient snow line elevation on specific dates, including the date when it rises above the glacier if it does, can provide a useful comparable measure (Mernild et al 2013).

This is a great possibility which provides important information in such years, but there is a lack of information on these changes in the sense of long term investigations. We will add observations of the transient snow line and the citation here.

Berthier, E., and Vincent, C.: Relative contribution of surface mass-balance and ice-flux changes to the accelerated thinning of Mer de Glace, French Alps, over 1979-2008.

Journal of Glaciology, 58(209), 501-512. doi:10.3189/2012JoG11J083, 2012.

Fischer, A.: Comparison of direct and geodetic mass balances on a multi-annual time scale, The Cryosphere, 5, 107-124, https://doi.org/10.5194/tc-5-107-2011, 2011.

Johannesson, T., Raymond, C., and Waddington E.: Time-scale for adjustment of glacier to changes in mass balance, J. Glaciol.,35(121), 355–369, 1989.

Mernild, S., Pelto, M., Malmros, J., ; Yde, J., Knudsen, N., ; Hanna, E.:: Identification of snow ablation rate, ELA, AAR and net mass balance using transient snowline variations on two Arctic glaciers. Journal of Glaciology, 59, 649-659, 2013.

Pelto, M.: Forecasting temperate alpine glacier survival from accumulation zone observations. The Cryosphere, 4, 67–75, 2010.

Schwitter, M. P. and Raymond, C.: Changes in the longitudinal profile of glaciers during advance and retreat, J. Glaciol., 39(133), 582–590, 1993.

Six, D., & Vincent, C.: Sensitivity of mass balance and equilibrium-line altitude to climate change in the French Alps. Journal of Glaciology, 60(223), 867-878.

doi:10.3189/2014JoG14J014, 2014.

Zemp, M., and 16 others. Historically unprecedented global glacier decline in the early 21st century. J. Glaciol. 2015, 61 (228), 745-762. doi: 10.3189/2015JoG15J017, 2015.