The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-239-AC2, 2020
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The Cryosphere
Discussions

Interactive comment on "Geodetic point surface mass balances: A new approach to determine point surface mass balances from remote sensing measurements" *by* Christian Vincent et al.

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Received and published: 9 December 2020

Response to Reviewers:

We thank the Reviewers for their comments and suggestions to improve this manuscript. We address their comments below. Reviewers comments are in italics, and our responses are in normal font below. Changes to the text have been highlighted in the revised manuscript.

Response to Reviewer 2

General comments

Vincent et al. present a method to derive glacier point surface mass balances from vertical ice velocities and surface elevation changes. Their method avoids the large uncertainties associated with determining representative surface slope with which to calculate emergence velocities. Typically, surface roughness and irregular larger-scale glacier surface topography account for considerable uncertainty in slope estimates. By eliminating this large error source, this method reduces uncertainty on estimates of geodetic point surface mass balance. Determining vertical velocity at the glacier surface remains a challenge, which here, the authors measure at ablation stakes. Their method demonstrates the potential for expanding the limited number of point observations available globally of surface mass balance, which are labor-intensive. The authors demonstrate that their method can also be used with remote sensing informationâĂŤnecessary for wider applicability of this approach. The challenge of well-representing the vertical velocity, particularly with respect to time, requires further attention. If attended to, this method represents a valuable contribution to the glaciological community. There are numerous uses for this method beyond the primary aim, including the establishment of new records of mass balance, or the filling of data gaps in glaciological records. When new glaciological records are established, this method could be applied to extend the point mass balance record to the years preceding the in situ record by collecting geodetic data until in situ measurements can begin. Further, glaciological observations for some glaciers, or some portions of some glaciers, are incomplete in some years, due to logistical or other challenges. This year (Covid-19) offers one such example for some glacier records. This method would allow for point mass balance to be determined from only remote sensing information for given points or a given glacier, avoiding the issue of gaps in valuable long-term records. Like Reviewer 1, I agree that some form of a sensitivity analysis regarding the spatial and temporal representation of vertical ice velocities would be beneficial, and not onerous to conduct. I elaborate this point in comments below. I also find it interesting that the trend of vertical ice velocity decrease seems relatively constant e.g. Figure 11, and that the potential bias introduced by assuming constant vertical ice velocity may

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in part be accounted for by applying a empirically-based decrease-rate factor (perhaps via horizontal velocities using the ratio of horizontal ice velocity to vertical ice velocity for a given area (either modeled or observed)) to represent the decline in vertical ice velocities expected to accompany horizontal ice velocity over decadal-scales.

The reply to this comment is similar to the reply we have done to Reviewer 1. It is a crucial point indeed.

The uncertainties relative to the spatial and temporal changes of vertical velocities are discussed in different sections in the manuscript and we acknowledge that it may lead to confusion. In addition, we acknowledge that the temporal trend is not analysed accurately from our observations and not discussed rigorously enough. We suggest to complete this analysis according to the following analysis :

Regarding the spatial variations : Our detailed observations from the network used between 2016 and 2018 at Argentière glacier (2350 m) showed that the vertical velocity change can exceed 0.3 m a-1 if the stakes are located at distances of more than 25 or 30 meters (section 5.1). This conclusion come from the errors relative to the locations of the stakes (some stakes are located at distances of more than 25 meters from the initial positions). In section 5.3, we showed that the surface mass balance can be reconstructed with an accuracy of about 0.2 m w.e. a-1 using the vertical velocities observed within a radius of less than 15 m. The whole network suggest that the vertical velocity spatial gradient can exceed 1.5 m a-1/100 m in this region. As a consequence, a horizontal deviation of 10 m could lead to a vertical velocity change exceeding the measurement uncertainty (0.15 m a-1). It seems not reasonable to interpolate the vertical velocity from measurements performed 100 m away from each other. For the new version of the manuscript, additional observations have been analyzed (new Figure S1) in order to better assess the vertical velocity spatial gradient over length scales of 20 to100 m. For this purpose, the vertical velocities have been calculated from 10 stakes set up in 2018/2019 on a longitudinal profile located between the stakes 3 and 13 (see Figure 2 for the locations of these stakes). Note that the distances between

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these stakes are short and enable to assess the vertical velocity variations at small scale. According to these measurements shown in the following Figure, the spatial gradient can reach 0.02 a-1. It is a little more important than that we found previously (0.015 a-1). However, it does no change the main conclusion: in order to reconstruct the surface mass balance from remote sensing, it requires measurement of the horizontal ice flow velocity and the altitudes of the ends of the velocity vector exactly at the same location, within a radius of less than 15 m compared to that of vertical velocity determination. However, further detailed and numerous observations would be needed to better assess the spatial gradient of the vertical velocities at the scale of 10 – 20 m. Although the general spatial changes of the vertical velocity shown in Figure S1 seem homogeneous, a detailed examination shows that the vertical velocity cannot be interpolated with an accuracy better than 0.3 or 0.4 m a-1 from measurements performed 100 m away from each other.

Caption of Figure S1 (included in the Supplementary of the new version of this paper): Vertical velocities measured from 10 stakes set up in 2018/2019 on a longitudinal profile located between the stakes 3 and 13 (see Figure 2 for the locations of the stakes 3 and 13).

Regarding the temporal changes :

It is not easy to accurately analyse the temporal changes of the vertical velocities from our observations given that (i) our detailed observations performed at Argentière glacier (2350 m) between 2016 and 2018 is not long enough to study the temporal changes. Note however that the temporal changes over the 3 years observations does not reveal temporal changes exceeding the measurements uncertainties as shown in Figure 5b and explained in Section 5.1, (ii) the longer series of observations available to study the temporal changes were not designed to measure the vertical velocities. For this reason, the following conclusions should be regarded with some caution until better data becomes availabe. From the longer series of observations performed at Argentière glacier at 2550 m and 2700 m a.s.l. (Fig. 11b), we assessed a general temporal

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trend of about 0.07 m a-2. We can conclude that the past period on which we have determined the vertical velocities should no exceed 4 years in order to not exceed an uncertainty of 0.3 m w.e. a-1 on the reconstructed surface mass balance. This conclusion could be different with stronger temporal change in vertical velocities. Another idea could be to assess the temporal change in vertical velocities from the temporal change in horizontal velocities and to apply the same ratio. Unfortunately, the changes in vertical and horizontal velocity observed at Argentière glacier at 2550 m and 2700 m a.s.l. (Fig. 11b) are very different, 2-3% a-1 and 1.5 % a-1 respectively. Further observations and analysis are needed to clarify this point.

To reply to this comment, we completed this analysis and summarized the impact of spatial and temporal changes in vertical velocities on the reconstructed surface mass balance uncertainties in Section 6.2. In addition, we added some sentences in the Conclusion to summarize the main conclusions of this analysis.

Specific comments

1 Add “glacier” to the title.

It has been done.

L 54-60 Are valid statements, though it should be highlighted that a series of point surface mass balance observations, e.g. across an entire glacier or elevation band, can be considered a direct climate signal. Individual point balances may indeed respond to climate, but may represent local processes (wind scour, avalanching, etc.). Perhaps this should be briefly discussed.

Agree. Some explanations have been added in the new version of the manuscript

L107-109 Were there any observations taken to constrain this error? It is often useful to test a few control points with the same method (occupation length etc.) to assess uncertainty.

We performed tests from several measurements on the same fixed point during the

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day. If the antenna is fixed on a base which is attached on a rock outside the glacier, the accuracy is better than 0.01 m provided that the number of visible satellites is greater than 7 and the distance between fixed and mobile receivers is less than 1 km. This is the intrinsic accuracy (the manufacturers usually guarantee better accuracy). It does not take into account the possible tilt of the antenna and others factors which could affect the accuracy of the measurements. Concerning our observations, the main source of uncertainty is not the intrinsic accuracy of the GNSSS instruments but is related to the size of the boreholes and the possible tilt of the stakes

L112 Emergence measurements seems confusing to me. This refers to stake height, or stake protrusion, correct? I would re-word for clarity, as emergence velocity is used throughout this manuscript, it is confusing to use emergence to describe measuring a different quantity, even though the word is correctly used here.

The emergence measurement refers to the stake protrusion. The emergence observations enable (i) to calculate the surface mass balance from two field campaigns and, (ii) to obtain the altitude of the bottom tip of the stake using the altitude of the surface. We tried to clarify this point in the new version.

L133-135 Resampled from 1.0 m to 0.1 m? But I thought the ortho was 0.1 m-resolution and then used to produce a 1.0 m-resolution DEM. Perhaps clarify.

Agree. It was an error. The initial resolution of ortho-mosaic was 0.1m and we resampled it to 1.0 m. It has been changed.

L149 The contours are nearly invisible. Either make them stand out more or reduce their number (larger interval). The blue and green dots are difficult to make out as well.

Figure 2 has been improved.

L174 Perhaps down-glacier direction instead of downslope direction, local slopes will often be upslope but down-glacier.

Agree. We provide more explanation to clarify this point. Here, before the Equation 2,

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we wrote Âń If the horizontal x-axis is taken in the flow direction. . ..”. and four lines later, we wrote “In this way we assume that the downslope direction is the flow direction. Âż.

L217-219 Yes, and perhaps most importantly, will not be affected by the advection of surface topography, that is, if we measured a given point through the year, crevasses, surface roughness, supraglacial streams, etc, may be advected over a given point, but your formulation, measuring a stake embedded in the ice, avoids these complications.

Ok

L264 Nice graphic, it seems to me that the vertical ice velocity is in fact changing over the three-year period, with a decrease across the three years, as can be seen in the horizontal velocities in the figure as noted in L242-244. The vertical velocities are decreasing with the horizontal velocity decrease.

Yes, but note that the vertical velocity can be positive or negative as seen in Figure 4b or Figure 5b. Consequently, a decrease in horizontal velocity leads to an increase in vertical velocity (if the vertical velocity is negative) or a decrease in vertical velocity (if the vertical velocity is positive). The absolute value of vertical velocity should decrease but the consequence on the reconstructed mass balance (Equation 4) is not always in the same way. Some further explanations are provided in Section 6.2.

L281 It may be valuable to describe how slope was determined, between the two GPS survey locations? From the DEM? From slope measurements around the two survey points? It may be worthwhile to test using different methods to determine slope, if remote methods can be used, does this represent the slope better, or not? Either way the conclusion will be of value.

Between the two GNSS positioning surveys, the slope was determined from the Digital Elevation Model using UAV measurements, between the two GPS survey locations. It has been clarified in the new version. It is crucial to calculate the slope for a given year, from elevations measurements at the two GNSS survey locations, whatever the

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method used (remote sensing or in-situ observations) in order to resoect Equation 3. If we use the slope of the year t, i.e tanαt , we have to use Δh2, which is the annual thickness change observed at the end of the annual ice flow vector. Conversely, If we use the slope of the year t+1, i.e tanαt+1 , we have to use Δh1, which is the annual thickness change observed at the beginning of the annual ice flow vector.

L298 Figure 7. Certainly greater dispersion, but the comparison does not look unfavorable. The decrease in emergence velocity through time can be seen with the red dots below the black. Why not add in the regression lines?

Agree. Unfortunately, the regression lines do not allow pointing out a significant change between the first year and the following years. We did not add the regression lines in ordre not to overload the Figure.

L337 Figure axes labels are difficult to read at this size. Perhaps use only a single y-axis label and slightly increase font size for all text.

It has been done

L377 remove extra period

Agree

L517-530 This section describes the competing factors which influence vertical velocities well. Overall, the authors make a compelling argument for minor changes in vertical ice velocity. However, two primary issues arise from their formulation: 1) that this method is only suitable for relatively low-angle glacier terrain, which implies that this method can primarily only be applied for valley glacier tongues; and 2) that while the change in vertical ice velocity is indeed minor, that it may not be negligible. As the authors point out, the horizontal ice velocity decreased by around 4% per year—regardless of whether this trend were to continue—such a rate of decrease over a decade is substantial, and thus is cannot be assumed that vertical ice velocity is stable over decadal scales. Decreasing ice velocity has been observed for many glaciers around the globe (Dehecq et al., 2019; Heid and Kääb, 2012), and given the current rate of ice wastage, that is, disequilibrium of glaciers (Christian et al., 2018; Zemp et al., 2015), assuming stable vertical ice velocities is questionable. Figure 11 highlights this, with vertical velocity falling by 0.5 m a-1 to 1.0 m a-1 over a decade which likely would present a non-negligible bias in assessing surface mass balance from remote data with this method over decadal periods. As the authors state, part of the decrease in vertical ice velocity will be compensated by reduced ice flux convergence/divergence produced by bedrock topography.

To reply to this comment and to the general comments, we completed this analysis and summarized the impact of spatial and temporal changes in vertical velocities on the reconstructed surface mass balance uncertainties in Section 6.2. See our detailed reply to the general comments.

L469 An uncertainty of 0.2 m w.e. a-1 seems optimistic for decadal periods, but accurate for short periods, like the three-year window of this study. Perhaps it would be best to state this directly, that surface mass balance can be obtained from this method with an accuracy of about 0.2 m w.e. a-1 over periods of 1-5? years, but over periods of 5-10+ years with an accuracy of XX m w.e. With the XX value determined by calculating the uncertainty or bias in using one year's vertical ice velocity to calculate mass balance for years in the 5-10 year range for stakes where that length of record is available in this study.

Agree. It has been clarified. Moreover, the final uncertainties are mentioned in Conclusions

L591 It is not clear what the range represents: 0.2 m w.e. if the elevation accuracy is determined to be 0.1 m and 0.6 m w.e. if it is determined to be 0.3 m? This is a critical point that should be expanded upon. If this method is to be applied elsewhereâĂŤe.g. with other remote datasets, what accuracy/resolution is needed, or how will uncertainty scale with reduced accuracy/resolution?

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Agree. It has been clarified. In addition, the requirements and the final uncertainties are mentioned in Conclusions.

L616 Change “dataset” to “datasets”.

It has been done

Citations: I suggest adding DOIs to all references for which one exists. Currently only some entries have a listed DOI, and some DOIs are “https:. . .” and others just the DOI itself. Ensure consistency with the TC formatting guidelines.

It has been done

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Please also note the supplement to this comment:

Interactive comment

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https://tc.copernicus.org/preprints/tc-2020-239/tc-2020-239-AC2-supplement.pdf

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