Response to reviewer #2

Overview

The objective of this study is to exemplify the sensitivity of the glaciological "geodetic balance", or simply elevation differences over glaciers, to differences in horizontal and vertical datums. Three study sites chosen are located in western Canada in which acquisition datums have varied through time. The study outlines 4 datum inconsistencyscenarios from which the effects on elevation changes and glacier geodetic balancesare assessed. The conclusions of the study are that consistent horizontal and vertical datums should be used when comparing elevation data through time over glaciers.

The study is rather long to describe an elementary concept that is a "standard" pre-processing step for any comparison between elevation data, whether on glaciers ornot. Everyone knows that datums must be consistent before comparing elevation data.The findings and conclusions are not surprising but just as expected. For example, ofcourse the relative error of a constant bias is larger over glacier sections where theelevation changes are smallest (i.e. above the ELA). Overall, it is difficult to extractthe relevance of this study in relation to what is already known by the community. Thestudy would be more useful had it focused upon the actual geodetic balance of theglaciers with a minor focus on some of the mistakes and methodological considerations ("lessons learned") that were encountered during the derivation of the geodeticbalance, or if it found that previous studies did not contain consistent datums. To summarize, this manuscript in its present form does not satisfy the scientific relevance andquality for publication in the Cryosphere.

>>While we agree with the reviewer that datum reconciliation is an essential processing step, and that co-registration of multi-temporal elevation information is well-studied within the glaciological community, we do believe issues surrounding datum reconciliation are not given due treatment in the literature. However, we do not wish to specifically identify literature which has potentially incurred this error. A review of literature investigating mass balance with the geodetic method reveals that datums are given detailed treatment in some papers , while partially covered or completely ignored in others. The detailed treatment carried out in some manuscripts provides evidence that these issues are not always standard pre-processing steps, as individual areas or competing elevation acquisition technologies will have unique circumstances surrounding spatial reference. For manuscripts which do not adequately describe the methodology for reconciling datums while providing detail on other, more standard, aspects of the comparison methodology, it can be reasonably assumed that datum reconciliation has not been fully addressed. We cannot accept that the reconciliation of datums is so trivial it does not warrant mention in the steps of co-registration of multi-temporal datasets.

We have discussed this topic with several colleagues in the climate change community, and there appears to be growing consensus that lack of consideration for datum evolution through time and space is a problem and it must be acknowledged and addressed. It is our intention with this paper to simply communicate that the process of datum reconciliation. While standard to an expert in survey or geodesy, these issues can be easily missed by a researcher that is not expert with geodetic techniques. Further, by providing case studies from one relatively confined part of the world where datum history is

well documented, we believe the variations in horizontal and vertical datum shifts and the implications for long term change detection can be clearly communicated.

We would also like to clarify that this study does not represent 'lessons learned' of mistakes made during the derivation of geodetic balance in the case study glaciers. The datum study was the primary focus of the analysis, and data sets and sites were specifically selected to demonstrate issues related to the datum problem. We were well aware prior to initiation of this analysis that the reconciliation of datums was a critical step in geodetic balance, and believe it required specific analysis to provide information on the historical reasons for datum changes, potential complications to their reconciliation, and the typical error which can be expected.

Major Remarks

- It is obvious that datums must be consistent before comparing elevation data. For vertical datums, there is a difference when considering global variations (Fig. 1) vs.local variations. Since the glaciers studied here are rather small, the global variations described between the vertical datums (Pg 61, Ln 14-end) has little relevancebesides describing the potential constant bias that may persist if consistent datums are not used. It is even further described on pg 62-64 that single constant offsets area rather good assumption for glacier sizes of this study. Therefore, maybe a single 3-Dco-registration is sufficient to account for horizontal and vertical datum variations, especially if the datums are not sufficiently known. So, the reader than asks, what doesthis study contribute?

>>We agree with the assessment that datums must be consistent before comparing elevation data. We do not believe the details of this problem are as well understood as the reviewer suggests. We assume the reviewer is expert in this field and thus is well aware of the steps required to facilitate accurate long term surface change assessments. However, given the lack of methodological description of this step that is common in the literature on glaciological change it appears that not all authors are as familiar with this requirement. Indeed, the authors of this submission have first-hand experience where such mistakes have propagated into submissions by expert authors into prestigious journals and where such mistakes have led to elaborate hypotheses about time lags and glacier flow dynamics. This alone convinces us that the topic requires wider discussion and communication given the broader implication for climate change research as a whole.

Although a single 3D co-registration (without consideration of datums)might correct most datum-related offsets, we believe a more informed and scientific approach models the systematic offsets with appropriate theoretical justification. Once all known co-registration effects have been considered then a single 3D co-registration can proceed. The pre-emptive correction of datum differences allows the subsequent 3D transformation to be more accurately described with minimal parameters. Additionally, it is important to identify, separate and document systematic influences (such as the horizontal and vertical datum offsets) to prepare for future mass balance calculations in coming decades which will be compared against current information. This information has been added to the conclusion.

Additionally, this study considered GPS or lidar profile measurements which do not have aspatial extent sufficient to enable block 3D adjustments. Datum issues associated with a single profile will be much

more difficult to identify than with entire DEMs. When profile measurements are provided (as they frequently are in the literature), the datum of a GPS base station used to differentially correct roving observations is rarely identified, indicating these types of measurements are of great concern.

- The conversions between the various datums is easily performed within standard softwares, like ArcGIS or as stated from a free software provided by the Canadiangeospatial service. So, the main result of this study is basically describing the magnitude (amplitude) of these transformations over the glaciers studied. These results canbe easily extracted, for example, from your Fig. 1 for any glacier in the world. Why then spend an entire paper describing this for 3 small glaciers in western Canada?

>>The information provided by the Canadian geospatial service and contained within some GIS software packages are not similarly available in all areas of the world (this was identified in the manuscript). Therefore, this problem is relevant to a large number of glaciers located in developing regions where historical information may not be as well documented.

We believe the case studies of the three glaciers represent different scenarios of potential datum errors (different predominant aspect of glacial surface, different geoidal undulations, different horizontal translations) which manifest systematic error combinations differently. The choice of three different glaciers demonstrates that these errors will not be consistent in all cases and requires careful consideration of several contributing factors.

Section 4.2: Which direction is the horizontal datum inconsistency in Fig. 7 and 8?

>>The distance and direction of the horizontal datum inconsistency for Fig.7 and Fig. 8 is shown in Table 2.

Is ita simple translation over the glaciers in this study or is it a higher order transformation?

>>Strictly speaking, it is a conversion between two datums with a 7 parameter (3 translations, 3 rotations, 1 scale) affine transformation, but at this scale it can be assumed to be a direct horizontal translation (scale and rotation differences are negligible).

In both these figures a bias results from the horizontal inconsistency. Was the verticaldatum corrected for first and or was the vertical bias as obtained by comparing ice-freeterrain removed first?

>>The vertical bias (if any existed) was corrected first. This can be identified in Figure 6 and Table 5, which shows the sampling errors when the datums are correctly reconciled. The error that is introduced by sampling has a mean value near zero for each glacier (0.01, -0.21, -0.39) indicating negligible vertical uncertainty is present when the datums are correctly reconciled.

-If not, it should be. If it was already removed, it means thatthe horizontal misalignment is somehow in a direction (aspect) parallel to the generalglacier aspect. It is possible to solve this, and not sure why it is not solved for (i.e. specifically what is the x and y transformation parameters)?

>>The x and y transformation parameters can be determined from the information provided in Table 3.

After the correct horizontal and vertical datums are reconciled, is there still a mis-alignment between the DEMS? Often subpixel misalignments are visible, and as stated above, these will bias yourresults depending upon the direction of the misalignment in relation to the direction ofthe glacier surface.

>>Some residual, albeit minor, sub-pixel alignment issues were noted and described on Page 76, Line 20

[Pg 69, Ln 3-13] – why not use the entire DEMS? Moreover, why not use the terrainsurrounding the glacier to describe the variations, or even better to use for deriving astatistical correction had the datums not been known... Also, co-registration betweenDEMs should be checked even when correct datums have been used.

>>Entire DEMs were not used because the types of errors introduced by profiling methods require attention. It is much more difficult to isolate datum errors from a single profile as opposed to the difference between two DEMs, therefore this type of observation technique was also analyzed. We did not use terrain surrounding the glaciers to describe the variation because we were interested in the relative contribution of actual surface change on the glaciers as well. This showed that the datum errors are not negligible when compared to actual surface change.

>>We agree co-registration should be checked even when correct datums have been used, removing the datums first allows a better understanding of the sources of residual bias and an enhanced understanding of how to properly model remaining systematic bias with minimal parameters.

- [Pg 70, Ln 1-8] – This density scenario assumes no glacier dynamics between the two epochs. Therefore, it only represents a lower bound for volume to mass conversion.

At the suggestion of Reviewer 1, we have adapted the density scenario to be consistent with Sorge's Law (Cogley et al., 2011). We appreciate the identification of the limitations of our previous methodology by both reviewers.

-[Pg 71-72] The slope dependency on elevation errors (eq 2) due to mis-alignments of horizontal datum errors is only half of the picture. The error is also dependent uponthe terrain aspect in relation to the direction of the translation, mis-registration etc. Ifthe translation is perpendicular to the aspect direction of the steep slopes, then verylittle bias over those steep slopes will be incurred. Equation 2 is thus not fully valid andthe full equation should be used. Having slope, aspect, and direction of the horizontaldatum misalignment, one can easily model the error imposed. . . What does the readerlearn here?

>>We have added the full formula (now eq. 1), and changed its location within the manuscript to the Introduction. From this, the reader learns the potential magnitude of these error sources and the resulting errors to surface change or mass balance. It is a demonstration of the principles of the equation with respect to the datum problem. Despite the fact the reader could determine the results of eq2 from the information given, we believe it is a valid exercise to illustratethe expected error magnitudes and patterns on the case study glaciers.

We would like to thank the reviewer for the useful and insightful comments. We believe the changes which have been implemented as a result of the suggestions have improved the overall clarity of the presentation of the material.