Response prepared for reviewer #1

We would like to thank the reviewer for their detailed comments and suggestions for the manuscript. We believe that the comments have identified important areas which required improvement. After completion of the suggested edits, the revised manuscript has benefitted from an improvement in the overall presentation and clarity. Below, you will find a point by point description of how each comment was addressed in the manuscript. Original reviewer comments in boldface, responses in regular typeface.

The paper addresses and important subject, which is that the datum surfaces to which digital terrain models are referred should be identified. It goes on to discuss four cases in which the horizontal datum either is or is not correctly identified and independently whether the vertical datum is or is not correctly identified. It considers data from three glaciers – Andrei, Bridge, and Peyto – in western Canada although detailed results are given for only Peyto.

The writing is very hard to follow. Each datum surface and each surface topography is a single-valued function of two horizontal coordinates. The subject, therefore, is eminently amenable to precise mathematical description and should be discussed in those terms. Introduction of a modest amount of mathematical notation would make the paper much more readable. Instead, it makes heavy use of vague terms such as inconsistency.

We agree that more precise mathematical formulations clarify the description. To this end, a precise mathematical description of vertical error due to horizontal translation now appears as equation 1. We have also included several equations (eq.3 through eq.7) which describe the various methods for quantifying and describing errors throughout the manuscript. We believe this change improves the readability of the manuscript and thank the reviewer for the valuable suggestion.

Table 6, which contains much of the quantitative information in the paper, defied over an hour of intense scrutiny because so much in it and in the text introducing it is ill defined. The paper takes up a highly technical subject and should not do so in such nontechnical language. To become comprehensible to glaciologists, it needs to be thoroughly rewritten. Terms such as residual error need to be defined explicitly. The slang "scenario" should be replaced by the standard word "case" throughout the paper.

We agree Table 6 was ambiguous, several of the ill-defined terms noted in the following review have been changed. Table headings now reflect the mathematical notation added to the manuscript. Scenario was changed to 'case' throughout the document.

58,8 Errors are intrinsic to all predictions, so it is just inadequate statement of uncertainties that will undermine planning.

Thank you for identifying this area of potential ambiguity. We agree that inadequate statements of uncertainty will also undermine planning initiatives. In this manuscript, the term error is used as the departure of the predicted value from its true value,where uncertainty

represents a lack of knowledge about errors. We have added this definition of error to the introduction. The errors in this paper do not represent error that would be included in typical statements about uncertainty since they are normally 'assumed' to have been corrected (implying there is not a lack of knowledge). The introduction of these errors, in addition to inadequate statements of uncertainty, will undermine attempts at long term planning as they provide false information to the dynamics of the glacial system.

To clarify this point, a paragraph has been added which reads:

'Errors, defined as the departure of an observed value from its true value,will introduce bias and undermine attempts at long term water resources planning. One source of error in the geodetic method (Østrem and Brugman, 1991; Cogley et al., 2011) of glacial change detections is the spatial co-registration of multi-temporal datasets. Often, national datum definitions will have changed during the course of the historical glaciological records, requiring spatial transformations between datums for accurate co-registration. Although the reconciliation of datums is a known pre-processing step prior to the geodetic method of glacial mass balance, there have been no studies which have quantified the error due to the incorrect reconciliation of datums relative to glacial surface changes that have occurred over recent decades. Additionally, important methodological details pertaining to datum reconciliation are often absent within existing literature, leaving the reader unaware of the potential for errors. If predictions of final mass balance results do not correctly account for datum reconciliation, systematic errors will reduce the quality of mass balance estimates and uncertainty predictions will not adequately reflect the magnitude of these errors.'

58,16 Syntax of the sentence is disrupted

This has been modified to:

This method allows the consideration of larger glaciers and glacier systems whose measurement would be impractical using the *direct* or "traditional" *glaciological method.* In addition, the glaciological method only represents an estimate of the surface climatic mass balance,where the *indirect* method provides an estimate of the total mass balance needed in the context of water resource and sea-level change analyses.

58,25 'at discrete elevation bands' should be omitted

This has been omitted

60,1 What horizontal intervals are is unclear

This sentence has been modified to 'The contemporary elevation profiles of glacial surfaces are often observed at a consistent horizontal spacing'

60,5 Syntax of the sentence is disrupted

Sentence has been modified to 'To obtain a historical observation, elevations are extracted from the intersection of a profile path and contour lines on a topographic map.'

60,23 Two sentences are joined by a comma and need to be separated

This sentence has been modified to, 'In addition, the common historical vertical datum for referencing elevations has been mean sea level while contemporary GPS elevations are reported relative to the surface of an ellipsoid model.'

61,21 Between "-107 and 86 m' would be better.

This has been changed

62,1 Explain why the apparent difference between the two epochs cannot be corrected by the amount of the undulation

The apparent difference between the two epochs **can (and should)** be corrected by the amount of the undulation. This is the typical procedure for implementing the correction. We are illustrating here that observed historical changes in total glacial surface downwasting have a similar magnitude to geoidal undulation. Therefore, changes observed due to negligence in implementing the required correction could be confused with true changes in surface elevation.

63,1 More concise and precise than 'bi-axial ellipsoid of revolution' is 'oblate spheroid'

This has been changed. We would like to identify that original terminology of bi-axial ellipsoid of revolution was used to maintain consistency with terminology in Chapter 6 of Vaníček and

Krakiwsky (1986) (pg. 78). Torge (2001) also describes the use of a 'rotational ellipsoid' (pg. 91).

64,20 It would be helpful to indicate what similar endeavours are underway elsewhere.

We agree that details on the development of other national vertical datum programs would be helpful to an international audience, however, the section is dedicated to the datum scenario in Canada. This is a necessary limit of scope that specifically relates to the glaciers tested in the analysis. In the conclusion, we identify that in other geographic regions researchers should be aware of their local datum history and perform the appropriate due diligence in reconciling datums. To provide a thorough discussion of historical datum updates and evolutions around the world would be a large undertaking and outside the scope of this paper.

64,24 Spirit levelling should be described, particularly its connection to other altimetry methods.

A detailed description of spirit levelling is outside of the scope of this manuscript. However, a reference has been provided to Anderson and Mikhail (1998), in which Chapter 5 provides an excellent summary of spirit levelling.

65,12 Locations of Bridge and Andrei are mixed up in Fig.2

Thank you, this has been corrected

66,15 Fig. 3 would be better were UTM coordinates used instead of Lat, Long

Since the three sites are located within 3 separate UTM zones (Zone 9, Zone 10, Zone 11) we believe it is preferable to maintain latitude and longitude to maintain relative positional information. We understand advantages exist in using UTM coordinates, such as direct measure of map features in metres. However, each site does contain a scale bar which can be used to understand glacial scale in terms of a Cartesian mapping system based on metres.

66,22 What is meant by 'even' should be explained

This sentence has been modified to "The surface profiles of contemporary datums were sampled on 100 m horizontal intervals to simulate a reasonable distance for field sampling with GPS."

68,12 Writing Eqn (1) as U=E-G would be more readily understood, where U is the undulation, E height of the ellipsoid and G height of the geoid

While we agree that the letters U, G, and E would be more descriptive we are following standard convention for these parameters. Please note, in Chapter 6 (Pg.89) of Vaníček and Krakiwsky (1989) it is stated that "Separation between the geocentric reference ellipsoid and the geoid is called the *geoidal height,* or *geoidal undulation,* and is generally denoted by *N."* In chapter 6 (pg. 216) of Torge (1998) it states "If *P* is located on the geoid, we obtain the *geoid height N* (also

called geoid undulation) as the vertical distance between the ellipsoid and the geoid. *A geometric definition follows by differencing the ellipsoidal height h and the orthometric height (3.106):*

N = h-H,

where the effect of the plumb line curvature has been neglected."

If we adopt the notation suggested (U=E-G), it could be argued we are using non-standard notation for widely accepted and understood terms.

68,16 "profile extents along the centre of the glacier margin" needs to be stated differently, for according to Fig. 3 the profile appears to be in the middle between the lateral margins.

This sentence was modified to "The geoidal undulation for profile extents along the lateral centreline of the glacial margin and a cross-section of the glacial margin were obtained from GPS-H, a software package available from Natural Resources Canada which provides an interface for accessing the CGG2000 and CGG2005 geoid models."

68,21 The caption of Table 4 says geoid heights, not undulations, and should define the undulation as difference between ellipsoid and geoid, as Eqn. (1) should say.

Please see response to 68,12. Geoid height and geoidal undulation are synonymous terms, which represent the vertical separation between the ellipsoid and the geoid. Please note that the geoid height and 'height above the geoid' are not the same, where the former represents the vertical separation between the ellipsoid and the geoid and the latter represents the vertical distance

above the geoid. To avoid confusion, each mention of 'geoid height' has been changed to geoidal undulation.

68,23 Presumably geoid undulation is meant instead of geoid height.

Please see response to 68,12 and 68,21

68,25 According to Table 4, range for Andrei is 0.51

This has been changed 0.52 in the text

69,8The exact date, not just the year, should be shown for each survey in Table 2. If surveys are made at about the same time each year, effects of seasonal variation are reduced. If not, an adjustment must be made taking into account the variation of the density of the upper layer of the glacier between spring and autumn.

Aerial photos for the 1966 Peyto DEM were flown in late August, which is seasonally consistent with the LiDAR acquisition. Metadata for the air photo campaign used to generate DEMs for Bridge and Andrei did not indicate the month of survey, although air photo campaigns in mountainous regions are typically performed in late summer prior to first snowfalls (normally August or early September). Therefore, we also assume there is little seasonal variation between these DEMs and the 2006 LiDAR acquisition. These assumptions have been included in the manuscript in the methods section describing the data as follow

"Historical photogrammetric DEMs were obtained for Andrei and Bridge glacier from British Columbia's Terrain Resource Information Management (BC TRIM). Details on this dataset can be found at http://archive.ilmb.gov.bc.ca/crgb/products/mapdata/trim_positional_maps.htm). The Andrei and Bridge DEMs were originally observed with horizontal reference to NAD27, and vertical reference to CGVD28. Although the metadata for the aerial photographs used to create the DEMs for Bridge and Andrei did not indicate the month of observation, the aerial survey campaigns are typically flown in the late summer. In house historical DEM information obtained in August of 1966, derived from photogrammetric analysis, was available for Peyto Glacier (Hopkinson et al. 2012). The Peyto DEM was also originally referenced to NAD27 horizontally and CGVD28 vertically. Contemporary observations for Andrei, Bridge and Peyto glacier are obtained from LiDAR DEM acquisitions conducted in August of 2006 (Demuth, 2006). Contemporary LiDAR datasets were observed with horizontal and vertical reference to NAD83. Since data acquisition for historical and contemporary DEMs occurred in the late summer, negligible seasonal variability is assumed for the surface change estimates."

69,10 This sentence is an example of where use of mathematical notation would achieve much greater readability.

As per above comment, the notation has been included. Also changed scenario to case

69,13 Why analysis of difference of effects of using the two sampling schemes is not included should be explained

Analysis of the two different sampling schemes is provided, see Figure 6. An **error ratio** was not included for the two different sampling schemes because the ratio requires a 'true' or 'correct' surface. In the case of the two different sampling schemes, there is no 'correct' surface.A sentence has been added at the end of Section 3.2 which reads No error ratio was provided for the *SE* analysis because there is no correct surface, such as Δz_5 for the *DEI*, as a basis for relative comparison.

69,26 Does the DEM give mean elevation over a 2.5-meter grid cell or does it give elevations at discrete points, albeit at 2.5 meter spacing in each of two horizontal directions.

To clarify the DEM creation process the following sentence was added 'Each DEM contained elevations with cells which were 2.5 x 2.5 m in size and were determined through a TIN interpolation routine. Therefore, elevations result from a linear interpolation of the triangular plane containing the DEM grid node.'

69,28 Under the assumption of Sorge's Law (Cogley et al., 2011), change of mass in a vertical column is caused by change in the ice component of the column. In most geodetic determinations of mass balance over multi-year periods, change in the snow and firn components is usually neglected unless the time of year of each survey is known and change of those components is separately estimated for each. Otherwise, change is assumed to be solely in the ice component.

We appreciate this is not a simple problem; i.e. as stated in Cogley (2009) "a volume change is not the same as a mass change" especially in a situation where the glacier ELA is known to have risen through time and where much of the observed volumetric loss is through lateral recession as well as downwasting. However, we agree our approach of attempting to account for the difference in above and below ELA effective average density is too simple and will lead to under-estimation of the total loss of mass between the dates studied. To avoid unnecessary complexity and ensure our analysis is consistent with similar studies, we have recalculated the mass loss based on the suggestion to adopt Sorge's Law. In practice, we believe this will lead to a small over-estimate of the mass lost but the error associated with this method is likely less than the error we would propagate by choosing an above ELA density value based on field-based snow and firn observations. This does not alter the nature of results but the absolute mass balance values and relative proportions do change slightly. Table 6 and the associated text has been adjusted. We thank the reviewer for this useful suggestion.

70,17 What is meant by 'totalised' should be explained

This sentence changed to "Although Reinhardt and Rentsch (1986) recommend reporting hypsometric volume changes at 100 m vertical intervals the interest here was the net mass balance and therefore the above and below ELA volumes were separated"

71,1The error curve in Fig. 6 needs to be defined, whether it is some function of the two subsets of points on the elevation curve, and this should be done by introducing clear notation for the three. Close inspection of Fig. 7 suggests this is true. Its error curve seems

to have a point wherever there is a point on either of the elevation curves, each of which is taken to be a piecewise linear function passing through its points. At any point on either curve, the error is the difference between its elevation and the linear functionrepresenting the other curve.The foregoing interpretation seems likely for Fig. 7 but it is not clear whether it isvalid for Fig. 6.

To avoid confusion, we have reworded the process for determining the error curves was described in Section 3.2, Page 66 to the following:

"To create profiles which contain coincident discrete sampling locations, both the historical and contemporary profiles are densified with a linear interpolation routine between sample points. Each profile was densified to a 10 m horizontal interval with a common starting point at the historical glacial terminus."

71,13 Table 5 has a maximum error 5.0 m for Peyto

The intent was to report the maximum absolute error. Therefore, this sentence has been changed to"The *SE*shows means of 0.01, -0.21 and -0.39 and reach absolute maximums of approximately 10.5 m, 6.0m and 16.3m on Bridge, Andrei and Peyto Glaciers, respectively (Table 3)."

71,12Eqn (2) would be better as $\Delta v = \Delta h \tan\alpha$, and the symbols v and h should be defined precisely as vertical and horizontal components respectively.

On the suggestion of Reviewer #2, this equation was modified to also include terrain aspect. We have chosen to maintain the notation to be consistent with notation used in the original source, Nuth and Kääb (2011).

72,23 Why the change profile of Fig. 8A has a minimum at ≈800 m is worthy of comment, particularly if it is because the terminus receded between 1966 and 2006. See comment 98 below.

The following sentence has been added "The maximum surface downwasting occurs at approximately 800 m, where the 2006 terminus of the glacier is located."

72,25 What is mean by "consistently transition" should be explained.

This sentence was modified to read "In the presence of a horizontal datum shift the amount of change is variable along the profile line and does not show a gradual reduction in surface elevation change as the profile ascends the glacier surface."

73,10 Why the relative error would have the most significant impact on accumulation estimates should be explained. The paper needs to make the case for why relative error is more important than absolute error.

The sentence has been shortened to remove the unintended ambiguity that relative error impacts accumulation estimates.

73,25 The validity of assuming a spatially constant vertical datum error should be discussed as a function of glacier area. Presumably the effect vanishes as area goes to zero, but how it might scale with area should be described.

This point was identified in Section 3.2 which indicated the change in geoidal undulation across each site is within the noise level of the data. Geoidal undulations are spatially variable, therefore an exact functional relationship of changes in geoidal undulation with area is unavailable. However, the general effect in sufficiently large areas will be a gradual change, as the geoidal undulation surface is continuous and differentiable. To mitigate any confusion on this point, we have added qualitative information describing the upper limit on elevation variations over a 10km distance in a very steep mountainous landscape, such as the Himalaya as follows:

"The assumption of a constant vertical datum shift was made due to the small spatial extent of the glaciers tested here. In larger systems, the change in geoidal undulation may reach levels which prevent this simplifying assumption. For example, the Himilayas are characterized by some of the most extreme changes of geoidal undulation in the world. An investigation of global EGM08 geoidal undulation data (NGA, 2009) in the Himilayas reveals a variability in geoidal undulations of approximately 1.2 m over 10 000 m extents. Depending on the level of associated glacial change in the region, a non-constant surface of geoidal undulation may have to be applied in order to transfer between vertical datums."

74,14 What is meant by errors being inconsistent should be defined. Explain why Table 5 has both H and V errors (Case 4) for Bridge and Peyto but not for Andrei.

The sentence was modified to "For example, the mean error reported in Table 5 increased on Bridge and Andrei glacier when both horizontal and vertical **datums** were inconsistent, while it decreased on Peyto."

The exclusion of V error for Andrei is explained in Section 3.2 which states "Andrei glacier represents an atypical scenario in which the ellipsoid and geoid are nearly coincident allowing the conversion to be effectively ignored"

74,16Direction of the geoid height should be defined, for it seems that the height is a scalar function. Maybe the author means direction of its gradient, but the reader should not have to guess.

See response to comment 68,12 and 68,21. This has been changed to geoidal undulation to avoid confusion.

74,26 Instead of "play a critical role," the effect would be better described in terms of the inner product of the gradient of the glacier surface and the direction of the shift. Here it is that gradient that is pertinent, not the direction of glacier flow, although the two are generally very similar.

Sentences have been modified to "Following equation 1, the prominent aspect direction of the glacial terrain and direction of the horizontal datum shift play a critical role in the magnitude of observed DE_2 and DE_4. If the glacier surface gradient is in the same direction as the horizontal

datum shift the datum inconsistency will reduce the amount of apparent downwasting or potentially introduce apparent surface growth. If the glacier surface gradient opposes the direction of the horizontal datum shift, then apparent surface downwasting will increase."

75,1 The datum inconsistency cannot introduce surface growth

Sentence has been modified to "If the glacier surface gradient is in the same direction as the horizontal datum shift the datum inconsistency will reduce the amount of apparent downwasting or potentially introduce **apparent** surface growth.

75,18 "<50% of the change error" is unclear because change error is undefined and because < 50 is imprecise.

Sentence was modified to "For example, on glaciers where annual surface downwasting can be high, this effect may be less significant."

75,27 Why detailed results are given only for Peyto (Table 6) should be explained

This was explained in Section 3.3 "Peyto was chosen because data were available for a longer time interval between epochs and because it is a well studied site with yearly mass balance information."

84,8 **Meier (1984) appeared in Science not nature**

Thank you for catching this. This has been changed

87 The second column in Table 1 is not the melt rate but rather is the negative of the average annual balance over the period. Were there no elevation change at all, there can still be melting, albeit counteracted by an equal amount of accumulation. In view of the paper's emphasis on uncertainties, they should also be shown for the values in the last column of Table 1.

The heading in the second column has been changed to 'Average surface downwasting (m / a).'

We agree a more comprehensive reporting of the studies in Table 5 would include the uncertainty in glacial mass balance estimates. However, after review of these papers, only two of the five provided uncertainty estimates for the mass balance estimates. Given that the uncertainty was not universally reported, and that it is not required for the concept we are attempting to illustrate with the Table (general comparison of downwasting estimates relative to the level of geoidal undulations), these have not been included.

88 The reader should not have to look closely at Table 2 only to see that it is extremely repetitive. It should be replaced by two simple sentences: "Photogrammetry for all three glaciers (1982 at Andrei, 1988 at Bridge, 1966 at Peyto) used NAD 27 for the horizontal reference system and CGVD 28 for the vertical. LiDAR was obtained in 2006 for all three glaciers using the NAD 83 for both the horizontal and vertical reference systems."

The following sentence has been included "The historical photogrammetric datasets were originally observed with horizontal reference to NAD 27 and vertical reference to CGVD 28. Contemporary LiDAR datasets were observed with horizontal and vertical reference to NAD 83."

Table 2 was removed.

89 Table 3 and 4 should be combined.

Table 3 and Table 4 have been combined.

90 In Table 4, −0.19 to 0.32 and −12.80 to −12.66 would parallel −10.54 to−10.50 in giving each range in increasing algebraic order."Ends of analyzed profiles" would be better than "extents of analyzed profile lines."

Thank you for this clarification, Table 4 (now Table 2) has been changed to reflect this suggestion.

91 It seems the first three numerical columns are the mean, maximum, and minimum of the elevation change from the first survey until 2006 over the entire surface. Why it is called residual error is not clear. Meanings of +m and−m in the column headings are undefined.

Table 5 has been modified to say Min (m) in column 4, and the heading has changed to "Table 3 – Summary surface change error for cases 1 to 4, and true change for case 5 at each study site"

92 The Table 6 caption should state the years over which the change occurred, 1966 and 2006. Does "subtraction statistics" mean volume change? Of the eight columns in the table, the relation between those in columns 6 and 7 is not obvious: how can the volume change Δ be greater than the volume? How can the water volume (column 7) be negative? Notation in the column headings should be clarified. Does $-\Delta$, for instance, mean that all values in the column, which are shown as positive, are to be understood to be negative? Does "Water volume ($\times 10^6 m^3$) mean that all change in ice volume are converted to water equivalent? If so, why not use the standard m3w.e.?

Table caption has been changed to "Table 4 – Estimated DEM surface change and water resource analysis under different Datum scenarios for Peyto Glacier between 1966 and 2006."

Table headings were modified to reflect the mathematical notation introduced in this version of the paper.

Footnotes were added to clarify meanings of $+\Delta$ and $-\Delta$ for ΔDEM_z

"Consistent Horizontal and Vertical Datums" would be better as "Correct Horizontal and Vertical Datums," and "Inconsistent Horizontal Datum" would be better as "Incorrect

Horizontal Datum and Correct Vertical Datum," and similarly for cases 3 and 4. (See note above concerning "scenario")

While we understand the intent of the suggested clarification, we believe it is inaccurate to describe any single horizontal or vertical datum as 'correct' or 'incorrect.' The 'correct' datum, in this case, is the one which is consistent between the two epochs. Technically, either datum can be considered 'correct' and we believe describing the datums as correct or incorrect would introduce more ambiguity and not improve clarity.

96 Fig. 4 should be identified as showing Bridge Glacier.

This has been changed

97 What the caption says would be the negative of the change from 1966 until 2006.

The caption appears to be correct.

98 The origin from which distance along the profile is measured needs to be defined, and if it is from the terminus, including which terminus, 1988 or 2006. This obscurity needs to be remedied in many places in the paper.

This was identified in Section 3.2 with the sentence "The profiles begin at the toe of each glacier and approximately follow the centreline of the glacial surface to the highest elevation point the dataset would allow."

To provide additional clarification the sentence was modified to "The profiles begin at the terminus of the historical glacier and approximately follow the lateral centreline of the glacial surface to the highest elevation point the datasets would allow."

98 A more manageable coordinate measures glacier length from the head of the glacier, because its position changes negligibly compared with change in terminus position.

While we agree that starting the profile from the head of the glacier provides a more stable location for the start of the profile we believe selecting the terminus also has advantages. Notably, GPS observations would typically be started at the terminus so organizing results in this manner is directly relatable to the field observations. Additionally, in other studies such as Hagen et al. (2005), GPS profiles were begun at the terminus, not the head of the glacier. Further, field based transects often don't make it all the way to the head of the glacier but they typically do represent the terminus position. We believe either approach is valid but have chosen to stick with defining the zero point of the profile as the terminus of the glacier at the time of the first measurement.

100 What the curves are in Fig. 8B is unclear. The one labeled Residual Error appears to be the negative of the absolute error, incorrect minus true. The title mentions only ratio

error, which apparently is that of the absolute error to the true change. The title mentions only ratio error.

The method of obtaining errors was clarified in Section 3.2 to read:

To determine the datum induced error, the correct change profile (scenario 5) was determined and the incorrect surface change profiles described in scenario two, three and four were subtracted. An error ratio, the difference between the correctly observed surface changes (scenario 5) divided by the difference between the correct and incorrect profiles (scenarios 2-4), was determined as an additional quantitative estimate.

Figure 8 and 9 have been changed to include better descriptions of the data.

101 So that the solid curve in Fig. 9B is noticed, it would be useful to say it has constant value (≈13 m), which is the difference between the two vertical datums (CGVD 28 and NAD 83, presumably) in the vicinity of Bridge Glacier. See also comment 73,25. It should be clearly defined that way, ideally with a more readily understood name than residual error

The sentence describing this error was modified to include the numerical value as follows "Although the magnitude of the error remained constant **(~12.7 m)** the ratio of this error to true surface change varied along the profile, as seen for Bridge Glacier in Figure 9b."

References

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