Dear Dr. Radić,

to enhance the quality of our paper we have, in the end, resolved some of the reviewers criticisms differently than previously indicated in the initial response to the reviews. Please find our updated responses to the comments of the two referees, as well as the indication of the respective changes applied to the revised manuscript below.

While Section 1 of the present document provides detailed answers to the most important concerns raised by the two referees, Sections 2 and 3 offer a point by point response to their specific remarks. The referee's comments are given in *grey italics* while our responses are in blue regular font.

In reaction to the referee comments the revised version of our manuscript includes a number of changes. The most substantial ones are the following:

- We have significantly shortened the introduction and pointed out the aim of the paper more explicitly as suggested by referee II.
- As demanded by referee II we re-structured the manuscript. This was achieved by moving parts of the former introduction to Section 3 and by revising and shortening Sections 4 and 5 of the original manuscript. Furthermore we split the original Section 5 into two sections (5 Results, 6 Discussion). However we did not follow the suggestions of the referee to present Section 4 prior to Equations 1 and 2 (Sect.3) since in our opinion methods have to be introduced in general (Sect. 3) before they are discussed in detail (Sect.4).
- We omitted the misleading density conversion factor and changed Equation 5 which now explains how we calculated our conversion density $\overline{\rho}$ for individual years.
- We recalculated uncertainties related to DEMs as suggested by the referees and changed all concerned numbers and figures in the revised manuscript.
- We changed the symbology of mass balance and uncertainty terms to be in line with Cogley et al. (2011) and Zemp et al. (2013).
- We reduced the number of figures and tables and revised the remaining ones including their labels and captions.

The last part of this document contains a marked-up version of the revised manuscript indicating all the changes applied.

Thank you for your consideration of our revised manuscript for publication in *The Cryosphere*.

Best regards,
Christoph Klug & Stephan P. Galos on behalf of the Co-authors

1 Author's response to most important referee concerns

1.1 Major comments by referee I (M. Zemp)

1.1.1 DTM-related uncertainties of geodetic mass balance

DTM-related random uncertainty of geodetic balances: The authors use the standard deviation of the DTM-differencing over selected stable terrain as random uncertainty for the geodetic balance (cf. equation 3, lines 196-207). I do not agree with this approach because it assigns a local DTM error to a zonal glacier change value. The standard deviation of the elevation differences on stable terrain indicates the uncertainty of the DTM differences for individual pixels. Instead, I propose to use the standard error, defined as the standard deviation divided by the square root of the number of independent items of information in the sample (cf. Zemp et al., 2013, The Cryosphere, Section 2.3). In the present case of ALS (> 1 point per m2) it can probably be assumed that the number of independent items is about the number of glacier pixels (cf. Joerg et al., 2012, RSE). Note that there is also the implicit assumption that the DTM uncertainty over stable terrain is representative for the DTM uncertainty over the glacier (cf. Rolstad et al., 2009, J. Glaciol.). Maybe that needs just to be mentioned somewhere in the paper.
In the revised manuscript we followed the referee‘s suggestion and recalculated the uncertainties related to DTMs according to Zemp et al. (2013). We therefore calculated the standard deviation and divided it by the square root of the number of grid cells. This of course leads to a significantly lower uncertainty. All numbers of concern were adjusted.
Indeed we assume comparable DTM-uncertainties over the whole DTM, which should consequently not differ (significantly) between stable areas and glaciated terrain. We also stated this more clearly in section 3.2 of the revised manuscript.

1.1.2 Geodetic method as substitution for the glaciological method

Geodetic method as substitution for the glaciological method: The authors conclude that the geodetic method (i) "can represent a valuable possibility to overcome shortcoming in the glaciological measurements even on an annual scale" (Lines 469-470) or (ii) "even as a substitute for the glaciological method". I can only partly support these conclusions for three reasons: (1) the geodetic and the glaciological methods are rather complementary in nature (than to substitute each other): the strength of the glaciological method is to capture the spatial and temporal variability of the glacier surface balance even with only a small sample of observation points but it is sensitive to systematic errors which accumulate linearly with the number of seasonal or annual measurements. The geodetic balance is able to cover the entire glacier but requires a density conversion, which becomes more challenging over short time periods because of meteorological influences on the elevation change. (2) the nature of uncertainties: typically, ten years of data are required for the detectable difference to become lower than the annual random "noise" of the glaciological balance (cf. Zemp et al., 2013, The Cryosphere). A validation at annual time intervals might actually miss a bias. (3) cost-benefit considerations: the costs of the geodetic method are one to two orders of magnitudes higher than the costs of the glaciological method. I suggest adding a short section that discusses these issues and rewording the corresponding conclusions.
We agree with the reviewer and changed the manuscript accordingly, especially regarding the

wording and the complementary nature of the two methods. We removed statements about a possible replacement of the glaciological by the geodetic method. We tried to elaborate more comprehensively why a reanalysis based on geodetic data is needed for HEFs glaciological mass balance record and what the benefit of such a reanalysis is.
We also agree that the strength of the glaciological method is the ability to capture spatial and temporal (year to year) variability of surface mass balance and to extract the part of mass change which is a consequence of meteorological forcing. However, this is only given if the analyses follow a certain quality standard. In terms of unexplainable differences between the methods, a thorough uncertainty assessment has to be conducted in order to indicate that available glaciological balances are questionable and geodetic data can help in identifying shortcomings in the glaciological measurements.
We agree on the limited expressiveness of annual comparisons between the two methods but we show that if analyses are carried out thoroughly significant differences between the mass balance methods are detectable even on the annual scale. We have highlighted and discussed this issue in the revised manuscript.

1.2 Major comments by referee II (Anonymous Referee)

1.2.1 Streamline introduction

Streamline introduction - I found the introduction of the paper to be too long and lack appropriate focus for what comes next. While many of the points brought up in the paper are important, they have already been stated in many previous papers. The point (I think) is to see how well geodetic and traditional mass balance methods compare over a suitably long period of time (decade). Perhaps focus on the point that analysis over shorter intervals may miss important processes that reveal themselves for longer periods. At the top of page three we first learn where the paper is going. Please state your objectives earlier and reduce introduction by about 50%. A reader should know at about page 1.5 where we are heading.
We mainly agree with the argumentation of the referee. The revised introduction is significantly shorter than the original one. We changed the introduction section with the aim of clearly showing the background, motivation and starting point of the paper. This was reached by omitting passages containing information which is common knowledge within the community or which is not relevant for the reader in this part of the paper. Thereby the main objectives of the study are presented earlier in the paper. We also tried to sharpen the motivation of the paper by pointing out the research focus more clearly.

1.2.2 Reorganization required

Reorganization required – I appreciate the detailed attention that the authors pay to processes that could make traditional and geodetic methods differ, but the current organization of these sections comes after key equations used to convert volume change into mass (w.e.) change. You really should present sections (4.1, 4.2 ...) before you present equations (1) and (2). This is especially evident when one reads section 4.2 and then needs to consider whether equation (5) really differs from equation (2) – it doesn't really. This change would make your paper easier to read (certainly more logical).

Indeed the structure of the paper was a point of long discussions between the authors. However, we re-structured the paper by shortening the introduction and shifting some of the former content to the beginning of Sect. 3. Furthermore we fully revised Sections 4 and 5 which makes it much easier for the reader to follow the paper.
Apart from that, our (revised) paper is presented following a commonly used structure (Introduction, Study Site, Data and Methods, Results, Discussion, Conclusion...). However, we do not see a logical way to present method inherent differences (sections 4.1, 4.2...) before explaining the methods themselves. Equations 1 and 2 are both fundamental for the geodetic method presented in section 3.2. Only after this method is presented/discussed (Sect.3) there can be a discussion about it (Sect. 4).
Note that we revised Equation 5 and we omitted the conversion factor K. However, Equation 5 now specifies how the conversion density $\overline{\rho}$ (which is part of Equation 2) is calculated in our paper (Sect. 4.2). The equation clearly differs from Equation 2.

1.2.3 Spatial noise

Spatial noise – On page 7 the authors discuss using SDz from stable control area to define spatial variability, but I don´t understand how this would yield that information. These control patches serve as so-called "check points" used in traditional photogrammetry. What would they tell us about spatial variability and how it might affect their results? Not much I'm afraid. What would yield that information, however, is the decorrelation length inherent in their data. The authors have gridded data where they can correct their sample sizes for spatial autocorrelation. You should assess the degree of spatial correlation of your data and reduce number of independent samples accordingly. There are several key papers on this topic, one of them (Rolstad et al., 2009) is cited below.
We did not intend to show the spatial variability of the DTM errors, but to give a measure on the overall DTM accuracy affecting the geodetic mass balances. Since the errors are quite low and do not show large spatial variation within the DTM, this was deemed a comprehensible approach. In our case of ALS (> 1 point per m^2) it can be assumed that the number of independent items is about the number of glacier pixels (cf. Joerg et al. 2012). However, since both reviewers criticized this, we changed the way in which we calculate the random error of the used DTM. This also leads to a much lower random error in the DTM. Although we are aware that there is also the implicit assumption that the DTM uncertainty over stable terrain is representative for the DTM uncertainty over the glacier (cf. Rolstad et al., 2009), we did not correct our sample sizes for spatial autocorrelation, but added a clearer discussion of this issue to the revised manuscript.

1.2.4 Dimensionless conversion factor K

Dimensionless conversion factor K - I have a few problems with the introduction of this variable (K) into the literature. First, this is something that is routinely applied in sequential DEM differencing in many previous studies even though it isn´t always stated as such. Second, unless I´ve missed something K should range between 0-1 yet it is state as ranging between 820-930 (line 267). Third, on lines 386-387 the authors state that their new dimensionless conversion factor K now has units of kg m-3. Many have used this conversion factor in past studies; it´s not new, so please let´s not

re-invent the wheel and muddle the literature with new dimensionless numbers.
We omitted this misleading factor from our paper. Equation 5 was revised now explaining the calculation of the mean glacier density $\overline{\rho}$ used for density conversion.

1.2.5 Clearer explanation and discussion of uncertainties

Clearer discussion needed for explaining discrepancies - One of the major conclusions of this paper is that based on the geodetic balance calculations the authors feel that the years 2002/3, 2005/6, and 2006/7 are biased in the traditional mass balance data. I think they are trying to state that the glacier lost most of its accumulation area and the bias was caused by having no stakes high up on the glaciers (in this case probing and pits would yield nothing). This point isn´t as clear as it need to be in lines 410-444; they need to shorten this section, explicitly implicate the methodological factors that could account for the error and then implicate meteorological factors. As it stands they start with the latter without a clear discussion of the former.
We agree with the referee. In the revised manuscript we attribute the differences between the mass balance methods more clearly to an insufficient measurement set-up and missing observations in the former accumulation area. Furthermore we shortened and restructured Section 5 which results in a more logical stream flow of discussion which is easier to follow for the reader.

1.2.6 Overly bold statements

Avoid overly bold statements - A minor point, but it is best to avoid absolute statements in papers. The authors suggest that their study is the first to compare annually-resolved geodetic and traditional mass balance records, yet a quick literature search indicates that this isn´t correct. For example, Beedle et al. (2014) did this for a shorter period of record and Krimmel (1999) did this for a longer period of time. You should either modify your statements to reflect that your comparison exceeds those of other studies or simply drop statements like this. My preference would be to do the latter.
We omitted such statements from our paper. Wherever needed we specified the innovative aspects of our study more precisely and we added appropriate references.

2 Author's response to specific comments by referee I (M. Zemp)

Page 3, Line 67, "first use of annual geodetic records": At South Cascade Glacier, annual results from both geodetic and glaciological methods have been analysed by Krimmel (1999): Robert M. Krimmel (1999) Analysis of difference between direct and geodetic mass balance measurements at south cascade glacier, washington, Geografiska Annaler: Series A, Physical Geography, 81:4, 653-658.

In the revised manuscript we avoid/correctly specify such statements (as also suggested by referee II) and we added references on previous studies.

P4, L119, "Results are submitted to the WGMS ...": you could add a reference to WGMS (2017, and earlier reports): WGMS 2017. Global Glacier Change Bulletin No. 2 (2014–2015). Zemp, M., Nussbaumer, S. U., Gärtner- Roer, I., Huber, J., Machguth, H., Paul, F., and Hoelzle, M. (eds.), ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland.

In the revised manuscript we refer to WGMS (2015, 2012, and earlier volumes).

P6, L178-184, Equation 2: the geodetic balance is usually calculated using the average glacier area of the two surveys (Zemp et al., 2013, The Cryosphere, Eq. (5) and (6)). At annual time steps, this might not make a big difference, but for the decadal period with a surface area reduction of 15% it does become relevant.

We agree. The calculation of geodetic mass balances was adapted now using the time averaged area mean $(S_{t0} + S_{t1})/2$.

P6, L188 & Fig 1, stable areas: I fully support the decision to complement the down-valley soccer field with stable areas near the glacier. Please add a short comment about the selection criteria for the stable areas A-E.

The selection is based on visual inspection and expert knowledge about the terrain (Sailer et al., 2012; Bollmann et al., 2011). A respective comment was added to the revised manuscript.

P8/9, L240-267, density conversion: the density conversion factor depends on changes in the three-dimensional firn body and is a function of (i) the additional snow layer incl. related densification and metamorphosis, (ii) firn compaction and metamorphosis, and (iii) sub/emergence velocity. From the text, I cannot fully comprehend how these factors are covered (or not) by the author's approach combining differential DTMs, surface classifications, and density assumptions. Please clarify and discuss the opportunities and limitations of the used approached.

The conducted density conversion consists of three steps within our approach. First, the dDTM was calculated. In a next step, the glacier surface was classified into two classes (firn and ice) by using the intensity images of the ALS campaign, resulting in surface grids for each year. By subtracting the classified intensity rasters and reclassifying the resulting new surface raster, we incorporated the changing extent of the perennial firn zones in a third step. This should answer point (ii) raised by the reviewer. However, we are aware that firn compaction and metamorphosis are not covered by this approach. Point (iii) could not really be considered using the available data, which is why we already mentioned in the introduction that we will not incorporate glacier flow dynamics in the presented analysis. Regarding point (i), the snow layer was incorporated by combining a maximum snow height at the time of measurement with in-situ measured snow-densities, to redistribute the mass according to the snow layer to the glacier surface. Nevertheless, we are aware that this type of spatial distributed density conversion is rather a best guess than a three-dimensional modelling of the firn body. The revised manuscript contains a fully revised Section 4 where we tried to clarify and better discuss our way of density conversion. In the revised text we refer to Figure S1 which was added to the Supplement of the paper (see Fig. 1). This helps the reader to better follow our analysis.

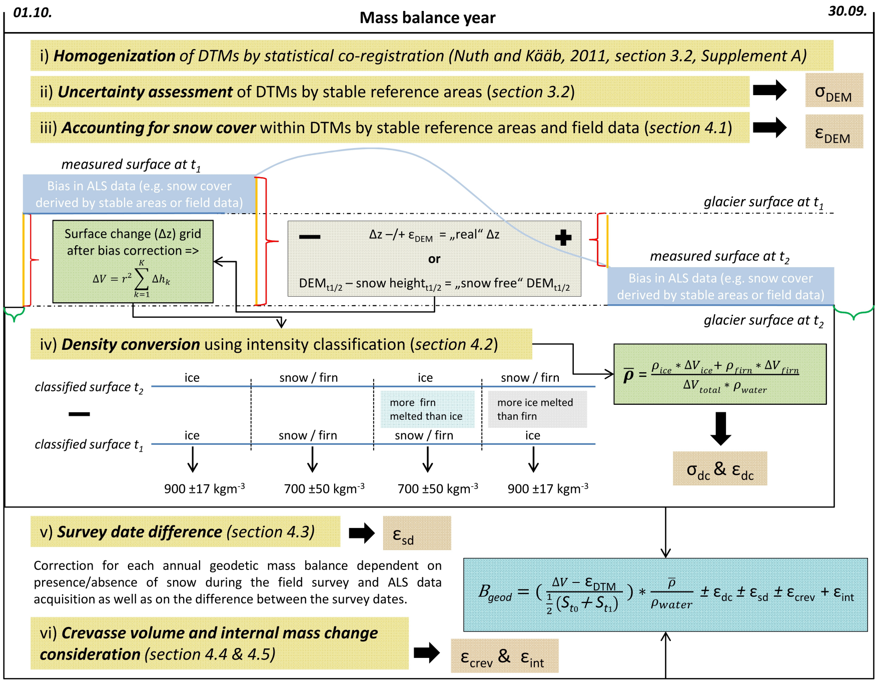

Figure 1: Flow chart illustrating the scheme of density calculation.

P9, L266-267 & Table 5, density conversion factor and related uncertainties: for a non-expert it is hard to follow how the density conversion factor and corresponding random uncertainties (together with the annual balance) relate to K.sigma and K.epsilon in Table 5. Adding a corresponding equation in Section 4.2 might help.

The misleading density conversion factor K was omitted from the revised manuscript. Equation 5 was changed accordingly. The revised symbology of uncertainties, as well as their calculation, now is in line with Zemp et al. (2013). We added a respective statement at the end of the revised introduction.

P9, L271, "stratigraphic year": I think this should be "end of the hydrological year" or "fixed date system" (cf. P9, L275, "30th September").
Changed accordingly to "end of hydrological" year

P10, L285-287, "elevation dependent mean ablation gradient": do you use the same gradient for the ablation and the accumulation zone? Please clarify.
Yes we do. This is explicitly mentioned (and justified) in the revised manuscript.

P11, L323-324: for comparability, convert the values by (Thibert et al., 2008) to annual change rates.
Done.

P15, L448-251, "were the first and so far only": consider rewording in view of earlier studies at South Cascade by Krimmel (1999, Geogr. Ann.).
The sentence was changed and the reference was added to the paper.

Text, Figs & Tabs, "altitude" versus "elevation": in most cases, you could replace "altitude" by "elevation" (cf. McVicar, T. R., & Körner, C. (2013). On the use of elevation, altitude, and height in the ecological and climatological literature. Oecologia, 171(2), 335-337.)
Done as far as possible.

P24, Fig. 1: For clarification, you could write in the figure caption: "Note that in 2003, no accumulation measurements COULD have been carried out DUE TO THE STRONGLY REDUCED ACCUMULATION ZONE. HENCE, only ablation stakes were available."
Done.

P25& 30, Fig. 2 & 7: the two figures are redundant to a certain degree. On the other side, it is not fully clear, which differences and uncertainties are included. Please at least clarify in captions. In addition, you could consider merging Fig 2 & 7, showing bias corrections for both glaciological and geodetic results. Instead, you could remove the cumulative curves (=¿ shown in Fig. 8).
Figures and their captions were revised and their number was reduced. We omitted the bias correction from the revised manuscript since the analysis of reduced discrepancies between the two mass balance methods does not justify such.

P26. Fig. 3: I would add a bar showing the intensity range (values) to the legend of the left image. In the legend of the right one, I would replace "perennial firn" by "snow and firn".
Done

P27, Fig. 4: In the caption, please clarify what you mean with "Corrected". It might be sufficient

adding a reference to the corresponding section in the paper. I would add the terms glaciolocial and geodetic to the label of the x-axis in the left and right figure, respectively. In addition, please add a note on the effect of the sub/emergence velocity.
Done

P28, Fig. 5: you could add the data point(s) for the full period (glaciol.cum versus geod.cum, glaciol.cum versus geod.01/11).
Figure 5 was omitted from the revised manuscript since it was redundant to Figure 2.

P29, Fig. 6: please add a note on the effect of the sub/emergence velocity.
The following note on the influence of glacier dynamics was added: Note that vertical profiles of the two methods cannot be directly compared due to the effect of glacier dynamics which leads to more negative geodetic results (than the glaciological ones) in the higher elevated areas and vice versa in the lower glacier regions.

P31, Fig. 8: typically, one would calibrate the glaciological with the geodetic over the decadal period (i.e. 2001-11). Hence, it might be good to show that result here too.
Since the results of the two methods agree well on the decadal time scale, a calibration is of the glaciological series is not justified and was hence omitted from the revised manuscript.

P34, Tab. 2: you could add a column for the two dDTM of the full period, i.e. 01/11.
Done. However, this table was shifted to the Supplement in the revised paper version.

P35, Tab 3: please explain why the density given in the cation (900 kg m^{-3}) differs with the one mentioned in the text (850 kg m^{-3}, cf. P8, L249)
The set of tables was reduced and fully revised. Table captions are also revised and the mentioned typo and was clarified.

P36, Tab 4: in the caption, there are some problems with the symbol for average SC. What is the "mean acc. area"? Do you refer to the end-of-summer accumulation area?
Symbol problems have been revised. Mean accumulation area is the classified firn area (AF). To avoid ambiguity it was changed.

P37, Tab 5: I would expect the annual uncertainties for the density conversion (sigma K) to be larger than for the (zonal) ones for the ALS-DTM (sigma DTM)... see also my comments above (substantial point (a) and comment related to density conversion, P9, L266-267)
Since we changed the calculation of the errors for the ALS-DTM (sigma DTM), those are now lower than in the originally submitted manuscript.

P38, Tab 6, caption: consider rewording “improved balance” into “bias-corrected balances”; consider rewording “statistical significance“ by “reduced discrepancy”. Use the same symbol for the common variance in caption (now wrongly epsilon.comvar) and table (=> sigma.comvar).
Done

3 Author's response to specific comments by referee II (Anonymous Referee)

A clunky title. I'd suggest. 'Geodetically corrected (or Homogenized) mass balance series of Hintereisferner Glacier, Austria for the period 2001-2011'
The revised manuscript is entitled: *"Geodetic reanalysis of annual glaciological mass balances (2001-2011) of Hintereisferner, Austria"*. The revised title is more specific and less clunky.

First sentence needs to be reworded. It sounds like you obtained 2001-11 mass bal- ance(s) records ...
The sentence was changed.

Line 18: Sentence needs revision (grammatically incorrect)
The sentence was revised by a native speaker.

Line 23: Replace 'as a substitute for' with 'superior to'
The sentence was revised.

Line 39: Delete 'and within the snow' since the top of this layer defined glacier surface by definition.
Done.

Line 40: Replace 'subtracts' with 'differences'
Done.

Line 45: Full stop missing after 'glacier'
Full stop added.

Line 50: Beedle et al. (2014) is missing from this list
The reference was added.

Line 63-66: Confusing and poorly worded sentences. Please revise.
The section was revised.

Line 67: See major comment (F)
We avoided such statements in the revised manuscript. Please also see our detailed reply to the respective major comment.

Line 86: Add 'an average' after 'with' and strike 'in average'
Done.

Line 86: What is a 'totalizing rain gauge' - bulk collector?
We use the term totalizer rain gauge as defined in the meteorology glossary by the American Meteorological Society. See *http://glossary.ametsoc.org/wiki/Totalizer_rain_gauge*.

Lines 90-94: Tangential to paper's focus (delete).
Done.

Lines 100-101: Add 'Annual' at start of sentence, strike 'annual mass balance' and 'have been started' and replace with 'commenced' and strike 'are carried out regularly since then'
Done.

Line 129: Strike 'among others' - meaningless in its usage here.
Done.

Line 132: 'Further explanation...' - Unclear why this statement is here. Reads like an orphaned one.
The sentence was deleted.

Line 143: replace 'wrong' with 'incorrect'
Done.

Line 148: 'For extrapolating ... ' - This sentence is linked to nothing (a single thread). Not sure why it is here.
The sentence was deleted. The whole section has been revised.

Line 154: Replace 'according to the law of error propagation' with 'by error propagation' - There are few physical laws.
Done.

Line 180: I had commented in the paper margin 'are density differences treated per elevation band' and hence my suggestion for you to move sections 4.1 and 4.2 before equation (1). See major point (B).
We refer to our detailed response in Sect.1.2.2 of this document.

Lines 198-200: See major point (C).
We refer to our detailed response in Sect.1.2.3 of this document.

Lines 212 (and throughout paper): Try not to state things like 'Figure 2 shows... '. State trend, ob-

servation and refer to figure at end of the sentence. For example, 'Density increases with elevation (Figure 2)'. This allows reader to digest your point and then refer to figure (it also reduces verbiage).
We avoid such throughout the revised manuscript.

Line 220: Move 'significantly' before 'influence'
Done.

Line 228: Add 'absolute' before 'vertical' and strike vertical lines as they are impossible to see in running text.
Done.

Line 231: Strike 'very' and avoid this vague qualifier at all costs.
Done.

Line 265: See point (D).
We refer to our response in Section 1.2.4 of this document.

Line 271: Replace 'a multi methodical approach was applied incorporating' with 'we incorporated'
Done.

Line 276: remove (s) from extrapolations
Done.

Line 280-281: How does this standard lapse rate compare to one assessed with station data. Does this help to explain differences in the extreme melt years?
In the case of significant snow fall we assume the atmosphere to be saturated which justifies the use of the moist adiabatic lapse rate. This is supported by analysis of station data which shows that the use of this gradient in such cases is quite a reasonable assumption. However, the large differences between the two mass balance methods are not sensitive to the choice of temperature lapse rates which, hence, do not significantly contribute to explaining those differences.

Line 291: Replace '5' with five. Write out all numbers less than 10 unless number has a unit. For example, seven stakes but 3 cm.
Done.

Lines 305-212: So how does this approach potentially affect your results? So if you simply ignored effects of crevasses what would results show?

The negligibly small effect of crevasses is discussed in detail in the revised manuscript (Sections 4 and 5).

Line 326: Stylistic point, but 'frictional dissipation' I believe is the more precise term.
Changed.

Line 348: Write out 'E.g. - Never start a sentence with this.
Changed.

Line 353: If it's a small term at the annual scale, it's small and within error at decadal scale. It can't be significant for one but not the other. Suggest dropping last clause in sentence.
Changed.

Line 357: 'The 2001 to 2011 one step...' - Not sure what sentence is trying to state.
Mass change over the whole 10-year period can be calculated either by summing up the results for individual years or by calculating $\Delta V_{2001-2011}$ by differencing the two DEMs of those years and converting this volume change to a change in mass (the latter is the *one-step* analysis). The results for both ways are slightly different due to density issues and different reference areas. However, in the revised manuscript we only show the 'one-step analysis' since the cumulative geodetic balance does not add any value but causes confusion.

Line 358-359: See earlier comment about 'Table and Figure shows...'
Changed.

Line 363: What does 'respectively' refer to? The penultimate sentence? Revise.
Revised.

Line 370: Sometimes last word before equation has a colon sometimes not, be consistent with journal standards.
Revised according to author-guidelines of TC.

Line 371: How does δ change if you incorporate effective degrees of freedom in the geodetic estimate of uncertainty (i.e. correct for spatial autocorrelation)?
We kindly refer to our detailed response in the general comments (Section 1.2.3 of the present document).

Line 376: Replace 'coherent' with 'similar'
Done.

Line 378: How is bias defined in this paper? Should be formally defined.
The introduction of the revised manuscript contains a statement pointing out that our analyses and interpretations follow the guide lines of Zemp et al. (2013). This is also valid for the term *bias* which is used as a synonym for systematic errors.

Line 383: Did you really explore the parameter space? This phrase is typically used with Monte Carlo sampling or Latin Hypercube sampling. Did you do that?
No. We rephrased this section in the revised manuscript.

Line 388: Why does K now have units? You told us earlier that it was dimensionless...
K was omitted from the paper. See above statements.

Line 400: If you used results that weren't smoothed (removal of crevasses) how does this affect your results?
This (small) impact is discussed in the original and the revised paper version.

Lines 410-440: I found this portion extremely difficult to follow for reasons outlined in major point (E).
We refer to our response in Sect. 1.2.5 of this document. The paper section of concern was revised.

Line 448: See point (F). Several papers out there that do this. Your paper, however, does this for the longest series, and will be well received. But please don't oversell its novelty.
We avoid such statements and added references in the revised manuscript. We refer to our response in Sect. 1.2.6 of this document.

Line 452: Change sentence to, 'It neither include(s) a through...nor '
Sentence was revised.

Line 453: Remove 'ed' from showed.
Done.

LIne 456: Change 'a snow cover' to 'snow'
This sentence was rephrased.

References: I did not check these for typos, but suggest you add the ones in this review to the list.

Done.

Figures:

Fig. 2 - A legend added to this figure would help reader. It would be nice in the figure caption to state level of uncertainty (68, 95%).
Done.

Fig. 3 - What are units of Intensity (DN?). kg m^{-3}.
Intensity has no units. The used intensity rasters only show the backscattered energy stored in 8 bit or 256 grey values.

Fig. 4. - You don't deal with dynamics (flux divergence) so it is not appropriate to plot these data as 'Mass balance [m w.e.]' as a function of elevation. $\frac{dh}{dt}$ and b are not equal due to dynamics. This plot must be redrafted showing 'Elevation change [m w.e.] and not 'Mass balance'.
It is true that we do not explicitly resolve ice dynamics. Nevertheless, the change in surface elevation can be used to calculate a mass balance which is the result of accumulation/ablation processes (surface, internal, basal) and ice flux divergence. In principle it does not matter if this is done for a point/column, an elevation band or the whole glacier (e.g. Cogley et al., 2011, page 5). However, we think that comparisons of geodetic and direct balances are only problematic if not done on the glacier wide scale. Hence, we did not redraft the plot but added a statement (as suggested by referee I) discussing the effect of ice dynamics on the local mass balance and the implications on method-comparisons on scales others than "glacier-wide".

Fig. 6. Remove titles from figures and simply use 'a)' and 'b)' . Avoid excessive qualifiers. Change 'The extraordinary mass' to 'Mass'
Done.

Fig. 9. Is this really the best way to show these data? Why not simply remove the figure and tell reader in text if homogenized hintereisferner series correlates more strongly (or use of other statistic than Pearson) with nearby series.
This figure was moved to the supplementary material. The text section relating the mass balance of Hintereisferner to those of nearby mass balance glaciers was shifted to the supplementary as a caption of figure S3.

Tables:

There are a lot of them and not sure if they are all needed. Any individual wanting your data would request them, no? Alternatively you could deposit them with the WGMS or other agency (or include

as electronic supplementary data). They take up a lot of journal space and some repeat what figures show.
We reduced the amount of figures and tables and shifted some of them to the supplementary material.

Table 5. Replace 'cum' with 'Sum'.
Done.

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A Geodetic reanalysis of one decade of the annual glaciological mass balance series on balances (2001-2011) of Hintereisferner, Ötztal Alps, Austria: a detailed view into annual geodetic and glaciological observations

Christoph Klug[1], Erik Bollmann[1], Stephan Peter Galos[2], Lindsey Nicholson[2], Rainer Prinz[3], Lorenzo Rieg[1], Rudolf Sailer[1], Johann Stötter[1], and Georg Kaser[2]

[1]Institute of Geography, University of Innsbruck, Austria
[2]Institute of Atmospheric and Cryospheric Sciences, University of Innsbruck, Austria
[3]Department of Geography and Regional Science, University of Graz, Austria

Correspondence to: Christoph Klug (christoph.klug@uibk.ac.at)

Abstract. This study presents a reanalysis of the glaciologically obtained 2001-11 annual glacier mass balances record at Hintereisferner, Ötztal Alps, Austria for the period 2001-11. The reanalysis is accomplished through a comparison with geodetically derived mass changes, using annual high-resolution airborne laser scanning (ALS). The grid based adjustments for the method-inherent differences are discussed along with associated uncertainties and discrepancies of the two forms methods of mass balance measurements. A statistical comparison of the two datasets shows no significant difference for seven annual, as well as the cumulative, mass changes over the ten years record. Yet, the statistical view hides significant differences in the mass balance years 2002/03 (glaciological minus geodetic records = +0.92 m w.e.), 2005/06 (+0.60 m w.e.) and 2006/07 (-0.45 m w.e.). The validity of the results is critically assessed and concludes that exceptional atmospheric circumstances meteorological conditions can render the usual glaciological observational network inadequate. Furthermore, we consider that ALS data reliably reproduce the annual mass balance and can be seen as calibration tools of or, under certain circumstances, even as a substitute validation or calibration tools for the glaciological method.

1 Introduction

The mass balance of a glacier defines its hydrological reservoir function (e.g., Kaser et al., 2010) and is a high-confidence reliable indicator of climate change (e.g., Vaughan et al., 2013; Bojinski et al., 2014). There are two primary methods for determining the mass balance of a glacier. The glaciological method is the most widely used for assessing annual and - more rarely - seasonal mass changes of individual glaciers (e.g., Anonymous, 1969; Hoinkes, 1970; Kaser et al., 2003; Cogley et al., 2011). It spatially extrapolates in situ point measurements of ablation and accumulation to the glacier-wide surface mass balance, encompassing changes at the glacier surface (Cogley et al., 2011). Earliest glacier mass balance measurements started around 1950, but only about 30 reference glaciers have uninterrupted annual time series going back to 1976 (e.g., Zemp et al., 2009). This small number of annually measured directly measured annual glacier mass balance series provides the basis for reconstructing past contributions to sea level rise (e.g., Kaser et al., 2006; Marzeion et al., 2012; Gardner et al., 2013; Vaughan et al., 2013), extrapolating glacier contribution to regional water supply (e.g., Kaser et al., 2010; Weber et al., 2010; Huss, 2011; Bliss et al., 2014), and glacier change detection, attribution (e.g., Marzeion et al., 2014; Slangen et al., 2017) and projection studies (e.g., Radić and Hock, 2006; Marzeion et al., 2012; Radić et al., 2014; Huss and Hock, 2015; Mengel et al., 2016).

The surface mass balance is defined as the mass change at the glacier surface and within the snow cover which evolves during the balance year (cf. Cogley et al., 2011). In contrast to the surface mass balance obtained with the glaciological method, the geodetic method subtracts two consecutive digital terrain models (DTMs) of a glacier and provides its volume change. This method integrates over all processes that lead to surface height changes at any single point of a glacier, i.e. the surface, internal, and basal mass changes as well as those from ice flux divergence, and densification (Cuffey and Paterson, 2010). Consequently, the mass balance values at a certain point of the glacier may differ significantly between the glaciological and the geodetic mass balance method. However, according to the principals of mass conservation, the ice flux divergence becomes zero if integrated over an entire glacier Moreover, by assuming internal and basal mass changes on mid latitude mountain glaciers to be of minor importance (e.g., Cuffey and Paterson, 2010), andby applying either measured or estimated snow or ice density to convert volume into mass changes, the two methods should obtain fairly similar numbers for the total mass balance. In this way, geodetically Since errors and uncertainties in long term records of directly measured mass balance exert influence on such studies they must be quantified and, wherever possible, corrected (e.g., Zemp et al., 2015). Geodetically obtained results have been used as controls for annual glaciological mass balances at decadal scales and are commonly applied to identify random, and to correct systematic, uncertainties in glaciological mass balance time series (Hoinkes, 1970; Haeberli et al., 1998; Fountain and Vecchia, 1999; Krimmel, 1999; Østrem and Haakensen, 1999; Hagg et al., 2004; Cox and March, 2004; Huss et al., 2009; Thibert and Vincent, 2009; Koblet et al., 2010; Zemp et al., 2010; Prinz et al., 2011; Zemp et al., 2013; Galos et al., 2017)(Hoinkes, 1970; Haeberli et al., 1998; Fountain and Vecchia, 1999; Krimmel, 1999; Østrem and Haakensen, 1999; Hagg et al., 2004; Cox and March, 2004; Huss et al., 2009; Thibert and Vincent, 2009; Koblet et al., 2010; Zemp et al., 2010; Prinz et al., 2011; Zemp et al., 2013; Beedle et al., 2014; Galos et al., 2017). Geodetic measurements have also been merged with glaciological mass balance series to increase coverage and representativeness of large regions and global glacier mass balance information (e.g., Cogley, 2009; Gardner et al., 2013). Indeed, the interconnection of different methods is increasingly suggested in order to ensure progress in advance glacier mass change estimates for large regions or even on the global scale (Gardner et al., 2013; Marzeion et al., 2017).

At Hintereisferner in the Austrian Ötztal Alps, glaciological and photogrammetry based photogrammetry-based geodetic mass balances are available since the early 1950s (e.g., Kuhn et al., 1999). Early analyses showed good agreement between the two data series on a decadal time scale for the periods 1952/53 to 1963/64 (Lang and Patzelt, 1971) and 1952/53 to 1990/91 (Kuhn et al., 1999). Yet, a more detailed examination by Zemp et al. (2013) revealed discrepancies at Hintereisferner for the periods 1963/64 to 1968/69 and 1978/79 to 1990/91. Geodetic mass balances for Hintereisferner were obtained at annual time steps between Between 2001 and 2011, when high resolution air borne laser scanning (ALS) became available, geodetic mass balances for Hintereisferner were obtained annually. Gross results from the first data pairs indicated considerable differences to the glaciological mass balances (Geist et al., 2007). These differences and the meanwhile available 11 annual high-quality ALS-data sets motivate and enable a so far unique validation and, finally, a reanalysis of annual surface mass balances of a glacierThis motivates a deeper investigation of the apparent discrepancies between the two methods at an annual scale.

This study presents the first use of annual geodetic records for a detailed reanalysis of an annual Hence, the goal of the present study is to reanalize the glaciological mass balance record of Hintereisferner for the period 2001 to 2011 and to thereby detect possible shortcomings for individual years or the whole period. This is achieved by a stepwise assessment of method-inherent uncertainties in each dataset based on a detailed uncertainty assessment using annual geodetic records from high resolution ALS-data. The reanalysis scheme and the assessment of random (σ; section 3) and the accounting for method-inherent differences) and systematic (ϵ) between the surface (glaciological) and the total (geodetic) mass balance (section 4). In section 5 we thoroughly perform and discuss the final reanalysis of the glaciological record, ending with concluding remarks in section 7.

uncertainties presented in this paper follows the guidelines of Zemp et al. (2013). Hence we refer to this paper for detailed explanations regarding the principal work flow.

2 Hintereisferner

Hintereisferner (46.79° N, 10.74° E) is a valley glacier in the Austrian part of the Ötztal Alps (Figure ??Fig. 1). The glacier consists of three main tributary basins. Langtaufererjochferner (1.11 km^2) and Stationsferner (0.28 km^2) disconnected from Hintereisferner in 1969 and 2000, respectively, but are still treated as part of the glacier in mass balance assessments in order to maintain consistency in mass balance assessments over the whole time series of observations. Hence, "Hintereisferner" in this paper refers to all three glacier bodies.

The area of Hintereisferner in 2011 was 6.78 km^2, about 15% smaller than in 2001, when the first ALS campaign was conducted. The glacier front terminus retreated by 390 m during the same period. The glacier elevation ranges from 2456 to 3720 to 2456 m a.s.l. and the median altitude is 3039 m a.s.l. The accumulation area covers aspects from northeast to southeast while the long and narrow tongue faces northeast. Meltwaters feed the Hintereisbach, which joins the runoff from Kesselwandferner, Hochjochferner and a few smaller glaciers and subsequently drains into Rofenache and finally into the Ötztaler Ache, one of the major tributaries of the Inn River.

Hintereisferner is located in the "inner dry Alpine zone" (Frei1998)(Frei and Schär, 1998), which is amongst the driest regions of the entire European Alps. Precipitation in Vent (~1900 m a.s.l.), about 8 km west of the glacier terminus, reaches 677 $\mathrm{mm\,a^{-1}}$, with air temperatures of 1.5 °C in average (1906-2011). Precipitation amounts double at the totalizing rain gauge near the Hintereis Research Station (3026 m a.s.l.; Figure 1Fig. 1), reflecting the altitudinal difference of approximately 1100 m but also the enhanced precipitation activity further up the valley. Over the study period 2001 to 2011, the values for annual temperature and precipitation in Vent are 2.3°C and 676 mm, respectively. The mean annual 0°C-isotherm is located at 2450 m a.s.l.

Like many glaciers in the Eastern European Alps, Hintereisferner has experienced strong shrinkage compared to its Little Ice Age maximum extent, which was reached sometime between 1847 and 1855 (Richter, 1888). Since that time, the glacier area in the Ötztal-Alps has shrunk by more than 50% (Fischer et al. 2015). After a period of rather stationary glacier lengths in the late 1970s and early 1980s (e.g., Patzelt, 1985), glacier mass loss and area shrinkage dominate with particularly high rates during and after the extraordinarily hot summer of 2003 (e.g., Abermann et al., 2009).

3 Mass balance methods and data

In this section we introduce the glaciological There are two primary methods for determining the mass balance of a glacier: The glaciological (or direct) and the geodetic measurement methods used to obtain the annual mass balances of method. The glaciological method (e.g., Anonymous, 1969; Hoinkes, 1970; Østrem and Brugman, 1991; Kaser et al., 2003; Cogley et al., 2011) is the most widely used for assessing annual and - more rarely - seasonal mass changes of individual glaciers. It spatially extrapolates in situ point measurements of ablation and accumulation to the glacier-wide surface mass balance, encompassing all mass changes at (near) the glacier surface during the hydrological year (cf. Cogley et al., 2011).

In contrast to the surface mass balance obtained with the glaciological method, the geodetic method differences two consecutive digital elevation models (DEMs) of a glacier and provides its volume change. This method integrates over all processes that lead to surface height changes at any single point of a glacier, i.e. the surface, internal, and basal mass changes as well as those from ice flux divergence, and densification (Cuffey and Paterson, 2010). Consequently, the mass balance values at a certain point of the glacier may differ significantly between the glaciological and the geodetic mass balance method. However, according to the principals of mass conservation, the ice flux divergence becomes zero if integrated over the entire glacier. Moreover, by assuming internal and basal mass changes on mid latitude mountain glaciers to be of minor importance (e.g., Cuffey and Paterson, 2010), and by applying either measured or estimated snow or ice density to convert volume into mass changes, the two methods should obtain fairly similar numbers for the glacier wide mass balance. In this way, geodetically obtained results can be used to cross-check glaciological mass balances on various time-scales (Zemp et al., 2013, and references therein).

In the subsequent sections we introduce the glaciological and the geodetic measurement methods as applied at Hintereisferner. We first determine a common base for the two datasets, by the homogenization of glacier outlines and DTMsDEMs, followed by quantifying method-inherent uncertainties.

3.1 The glaciological method

Glaciological measurements of annual mass balance at Hintereisferner have been started Annual glaciological measurements at Hintereisferner commenced in 1952 (Hoinkes, 1970)and are carried out regularly since then, resulting in one of the longest continuous glacier mass balance time series worldwide. The distribution of 40 to 50 (maximum 100) ablation stakes over the main tongue of Hintereisferner is a compromise between representative coverage and logistic feasibility (Kuhn et al., 1999; Fischer, 2011). During the study period no ablation stakes are placed were maintained in the upper part of the glacier, where the accumulation is was usually determined by means of snow pits and probings at the end of the mass balance year. The location of individual snow pits has been kept more or less constant over the whole study period. Their number changed according to the varying extent of the accumulation area from none in e.g. 2002/03 up to 14 pits in 2003/04 (see Figure 1Fig. 1). The series follows the fixed date system as defined by the hydrological year, spanning from October 1^{st} to September 30^{th} of the following year, with additional measurements in spring and during about fortnightly visits between June and October.

The annual mass balance at each measurement point is derived by converting the individual change of surface height as obtained from stakes and pits. Ice ablation obtained from repeat stake readings is converted into point specific mass balance by applying an assumed constant density of 900 $\mathrm{kg\,m^{-3}}$. Accumulation is determined by measuring the snow depth in conjunction with depth-averaged snow density in snow pits. The point values and additional observational information such as the position of the snowline from an automatic camera and from terrestrial and air photographs, topographic conditions, and the expert knowledge about typical spatial patterns are the basis for drawing contour lines of equal mass balancevalues. The resulting areas of equal mean mass balance are then intersected with 50 m altitude bands in order to derive the vertical mass balance profile. By integrating over the altitude bands, both the total the total glaciological mass balance of the glacier B_{glac} and ΔM_{glac} is obtained. Dividing ΔM_{glac} by the glacier area S results in the glacier wide mean specific mass balance b_{glac} are obtained (e.g., Kaser et al., 2003; Cogley et al., 2011)B_{glac} (Cogley et al., 2011). Results are submitted to the World Glacier Monitoring Service (WGMS) annually . (e.g. WGMS, 2015, 2012, and earlier volumes).

In order to provide a common base for both the glaciological and geodetic analyses we re-generate the annual glacier outlines from the ALS data rigorously strictly following the guidelines presented in (Abermann et al., 2010). This led to minor changes (ϵ_{area}) in annual glaciological balances in the order of -0.015 to +0.039 The remaining annual random uncertainties due to possible errors in glacier outlines $\sigma_{glac.ref}$ are estimated as ±0.015 $\mathrm{m\,w.e.\,a^{-1}}$, accumulating to +0.12 over the 2001 to 2011 period(cf. Galos et al., 2017).

Before approaching the reanalysis of the annual surface mass balances of Hintereisferner for the time period 2001 to 2011 further uncertainties in the glaciological mass balances series must be addressed. The glaciological method suffers mainly from uncertainties related to (i) point measurements and (ii) their spatial extrapolation over the entire glacier (e.g., Zemp et al., 2013; Galos et al., 2017). For both uncertainty sources and due Due to the lack of respective data on Hintereisferner we synthesize appropriate information from the literature as follows. (Zemp et al., 2013) analysed , among others, to estimate both sources of uncertainty. Zemp et al. (2013) analysed the mass balance series of Hintereisferner for six periods between 1953 and 2006 and attributed an uncertainty of ±0.10 $\mathrm{m\,w.e.\,a^{-1}}$ to field measurements for the years after 1964 and doubled the value for the years before. For the spatial interpolation of point data they assigned values between ±0.14 and ±0.54 $\mathrm{m\,w.e.\,a^{-1}}$ with an average of ±0.33 $\mathrm{m\,w.e.\,a^{-1}}$ for the entire period. Further explanations are not provided by Zemp et al. (2013).Fountain and Vecchia (1999) found combined uncertainties for (i) and (ii) of up to ±0.33 $\mathrm{m\,w.e.\,a^{-1}}$ by analysing the modelled variability of the mass balance of South Cascade glacier. Thibert et al. (2008) and Thibert and Vincent (2009) analysed 51 years of mass balance for Glacier de Sarennes and reported a combined annual uncertainty of ±0.20 $\mathrm{m\,w.e.\,a^{-1}}$ for (i) and (ii). For Gries- and Silvrettagletscher, Huss et al. (2009) assumed overall uncertainties related to (i) and (ii) of ±0.16 to ±0.28 $\mathrm{m\,w.e.\,a^{-1}}$. By investigating the glaciological and geodetic mass balances of Storglaciären, Zemp et al. (2010) determined the random uncertainty for (i) and (ii) with ±0.10 $\mathrm{m\,w.e.\,a^{-1}}$ each, which resembles the results of Jansson (1999). For Findelengletscher, Sold et al. (2016) roughly estimated a random uncertainty of ±0.04 m $\mathrm{m\,w.e.\,a^{-1}}$ for (i), referring to Huss et al. (2009), and of ±0.17 $\mathrm{m\,w.e.\,a^{-1}}$ for (ii) by evaluating contour lines drawn independently by 18 analysers. On Nigardsbreen, Andreassen et al. (2016) obtained a total point measurement uncertainty of ±0.25 $\mathrm{m\,w.e.\,a^{-1}}$ as the root sum square (RSS) of a false determination of the previous year‘s summer surface (±0.15 $\mathrm{m\,w.e.\,a^{-1}}$), upwelling up-welling of stakes (±0.20$\mathrm{m\,w.e.\,a^{-1}}$), and wrong incorrect density assumptions of snow and firn (±0.05 $\mathrm{m\,w.e.\,a^{-1}}$). Uncertainty of spatial integration was taken as ±0.21 $\mathrm{m\,w.e.\,a^{-1}}$, made up by point measurements insufficiently covering both the vertical range and the total area of the glacier.

Based on the findings of Zemp et al. (2013) combined with expert knowledge about the study site, we assess the uncertainty related to point measurements at Hintereisferner, being to be in the order of σ_{point} $\sigma_{glac.point}$ = ± 0.10 m w.e. a^{-1}, resulting in a decadal value of about ± 0.32 m w.e. For extrapolating point data into reasonable patterns of mass balance, the contour line method uses expert knowledge. Based on Sold et al. (2016) , we estimate a respective uncertainty Hintereisferner we estimated the uncertainty related to extrapolation of point data based on Sold et al. (2016) leading to an annual value of ± 0.15 m w.e. $a^{-1}$for Hintereisferner. In addition and according . Additionally we accounted for the presence of large areas not covered by point measurements. According to Andreassen et al. (2016), we assume that the extrapolation over areas not covered by point measurements inherits those areas inherits further uncertainties of ± 0.10 m w.e. a^{-1}. Hence, the uncertainty due to spatial integration of the respective measurements over the entire glacier is defined to be $\sigma_{spatial}$ $\sigma_{glac.spatial}$ = ± 0.18 m w.e. a^{-1} and result in decadal uncertainty of the related decadal uncertainty is ± 0.57 m w.e.. Overall uncertainties for the glaciological mass balances are calculated, according to the law of error propagationfollowing Zemp et al. (2013, Eq. 14), leading to σ_{glac} an annual value of $\sigma_{glac.total}$ = ± 0.21 m w.e. for annual and which corresponds to a cumulative uncertainty of the glaciological method (2001 to 2011) of ± 0.65 for the cumulated valuesm w.e.

3.2 The geodetic method

Between 2001 and 2011, eleven 11 ALS flight campaigns had been carried out near the end of each mass balance year (see Table 1Tab. 1). During each ALS data acquisition campaign, the glacier was covered with a number of overlapping flight strips in order to increase the point density and to ensure high quality and complete coverage of the glacier (Wever and Lindenberger, 1999; Geist et al., 2007). As there is essentially no high vegetation in the study area, ALS points are classified into ground points and flying objects (outliers) only. The ground points of all datasets are imported into a laser database system (Rieg et al., 2014) which facilitates storage and further processing. DEMs of 1 m resolution DTMs are were calculated for all datasets, whereby the mean value of all ALS points located in each cell represents the elevation of the cell. The elevation values for the few raster cells that do not contain a single point are interpolated from the neighbouring cells using a least squares method. In order to provide high-quality DTMs DEMs used for mass balance calculations, horizontal misalignment of the DTMs DEMs being differenced has to be excluded. Therefore a statistical co-registration correction procedure as suggested by Nuth and Kääb (2011) was performed for this study. Following Joerg et al. (2012) we applied the first two steps of the procedure to the ice-free areas for identifying potential horizontal shifts and vertical offsets between two ALS-DTMsALS-DEMs. The statistical co-registration reveals horizontal shifts smaller than the DTM DEM pixel resolution with no elevation-dependent bias, and the DTMs hence, the DEMs can be subtracted from each other without performing DTM DEM corrections. The total volume change ΔV between two dates is then derived from the respective elevation difference Δh_k of the two grids at pixel k with cell size r of the DTMsDEMs, summed over the number of pixels K covering the glacier at the maximum extent and is expressed as (cf. Zemp et al., 2013)follows (cf. Zemp et al., 2013):

$$\Delta V = r^2 \sum_{k=1}^{K} \Delta h_k,. \tag{1}$$

For a comparison with the glaciological balance, ΔV is then converted into a specific mass balance in the unit meter water equivalent (m w.e.):

$$B_{geod} = \frac{\Delta V}{1/2 \cdot (S_{t1} + S_{t2})} \times \frac{\Delta \mathrm{V}}{1/2 \cdot (\mathrm{S}_{\mathrm{t0}} + \mathrm{S}_{\mathrm{t1}})} \cdot \frac{\overline{\rho}}{\rho_{water}}, \qquad (2)$$

where S_{t0} and S_{t1} are the glacier areas at the first (t_0) and second (t_1) acquisition date respectively and $\overline{\rho}/\rho_{water}$ is the ratio between the average bulk density (see Eq. 5 in Sect. 4.2) of ΔV and the density of water, at the first acquisition date t_1.. Despite a thorough co-registration, surface elevation differencing of two DTMs DEMs is still subject to various uncertainties. The vertical accuracy of the raw ALS point data was first assessed by comparing the point clouds with differential global navigation satellite system (dGNSS) measured points on a homogeneous horizontal surface outside the study area (e.g. in our case a football field in Zwieselstein 20 km down-valley of Hintereisferner). Table 1 shows the The standard deviations (SD) of vertical accuracies of the individual datasets are shown in Table 1 t1. As the reference surface does not reflect the surface conditions in terms of slope, aspect and roughness, and therefore is not representative for vertical accuracies, Bollmann et al. (2011) Bollmann et al. (2011) compared dGNSS ground control points with laser returns (deviation to laser points 0.07 m, standard deviation 0.08 m) and calculated an absolute slope-dependent vertical accuracy for Hintereisferner ALS point data (<0.10 m on slopes <40°). Sailer et al. (2014) analysed the uncertainties resulting from rasterizing laser point clouds, revealing that a cell size of 1x1 m as used for our study causes only negligible errors of less than 0.10 m. For the raw geodetic balance ($b_{geod.raw} B_{geod}$), the results of DTM DEM differencing over stable terrain are taken to define uncertainties associated with the DTM DEM comparison. Therefore, we selected five 5 stable control areas ($3 \times 10^4\ m^2 3 \times 10^4$ m^2) surrounding the glacier (Figure 1Fig. 1), in order to quantify grid-based uncertainties of spatially averaged elevation differences. As The selection of these sites is based on visual inspection and expert knowledge about the terrain around Hintereisferner (Bollmann et al., 2011; Sailer et al., 2012). According to (Rolstad et al., 2009), we assumed that the DEM uncertainty over stable terrain is representative for the entire glacier. However, we did not correct our sample size for spatial autocorrelation, but, following (Joerg et al., 2012), we assumed that the number of independent pixels is about the number of glacier pixels and used the standard error as uncertainty measure. Thereby the standard deviation of the elevation differences ($SD\Delta_z$, Table 2) provides information on the spatial variability of the selected stable areas, we used the related RSS for an approximation to our DTM uncertainty : Tab. S1 in the Supplement) provides the basis for assessing the influence of random pixel-elevation uncertainty on the glacier wide geodetic balance σ_{DEM}:

$$\sigma_{DTM\,\mathrm{DEM}} = \sqrt{\sum_{1}^{i} (SD_i^2)}\, \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{SD}_{\mathrm{i}})}{\sqrt{\mathrm{n}}}, \qquad (3)$$

where SD is the standard deviation within the reference surfaces i. The result was converted into mass using the density of ice. Comparison of the differential DTMs (dDTMs) show uncertainties of $\pm 0.06 < \sigma_{DTM} < \pm 0.17$ i and n is the number of pixels in stable areas. This procedure yields uncertainties of $\pm 0.012 < \sigma_{DEM} < \pm 0.024$ m w.e., resulting in and $\sigma_{DEM} = \pm$0.36 0.087 m w.e. cumulated over the observation period (01-11$_{cum}$; Table 3). In contrast, for the 2001 to 2011 one step application of the geodetic method (01/11; Table 3) yields a value of $\sigma_{DTM} = \pm 0.14$. Table 3 summarizes the results of sections 3.1 and 3.2 and shows the differences between the adjusted glaciological and the raw geodetic mass balances ($b_{glac.hom}$ - $b_{geod.raw}$analysis (Tab. 3).

4 Accounting for method Method inherent differences

Figure 2 shows The differences between the glaciological and the geodetic mass balance series as revised in sections 3.1 and 3.2. The expected differences vary from year to year, being particularly high in some years (Table 3certain years (Fig. 2, Tab. 2). The potential causes of these discrepancies in the mass balance series are related to a number of factors: snow cover at the time of ALS acquisition(4.1), different glacier-wide density assumptions in mass balance calculation(4.2), survey date differences between the glaciological and geodetic observations(4.3), the way the methods consider the existence of crevasses (4.4), and the differences between the surface (glaciological) and the total (geodetic) mass balance (4.5)and the different processes captured by the two mass balance methods. All those issues are thoroughly assessed below.

4.1 Differences induced by snow cover present in DTMsDEMs

Whereas the vertical accuracy tends to be very of ALS-DEMs is high, biases as a result of snowfall events preceding the ALS surveys significantly influence the calculated volume changesignificantly. From the analysis of elevation differences in the non-glaciated terrain, the mean difference between two DTMs ($\overline{\Delta Z}$) stable areas ; Table 2) with DEMs in stable areas ($\overline{\Delta z}_{stable}$) can be used to correct for DEM-biases (ϵ_{DEM}) caused by the presence of snow as follows:

$$\epsilon_{dtm}\mathrm{DEM} = \frac{\sum_1^n \overline{\Delta Z_l}}{n} \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \overline{\Delta \mathrm{z}_\mathrm{i}}}{\mathrm{n}}, \quad (4)$$

where n is the number of DTM DEM grid cells covering stable and non-glacierized terrain, can be used for inevitable volume corrections, caused by preceding snow fall events. For the periods 2001/02, 2005/06, 2006/07 and 2007/08 the investigation of stable areas within the dDTMs dDEMs revealed snow induced absolute vertical offsets between (0.18) and (and 0.58) m ($\overline{\Delta Z}$); bold numbers in Table 3m (see bold numbers for $\overline{\Delta z}_{stable}$ in table S1 of the Supplement). In all other dDTMsdDEMs, the vertical bias was below 0.10 m. In 2004 and 2010 a snow fall event occurred some days before the ALS measurements. However, this is not reflected in the stable areas of the respective dDTMdDEM, because the snow in non glacierized areas had melted from off-glacier surface by the time of the ALS survey. This leads to a very low small offset in the non-glacierized terrain in the related mass balance periods. Yet, as snow cover increases, the ALS elevations measured on reference surfaces have to be cross-checked with snow depth data from the closest field survey data for snow depth estimation and subsequently and subsequently they have to be corrected. Based on the altitude distribution of stable areas and in-situ measurements a linear regression in 50 m elevation bands yielded yields mean snow depths of 0.52 m in 2001, 0.23 m in 2004, 0.46 m in 2005, 0.13 m in 2006, 0.12 m in 2007 and 0.26 m in 2010. This leads to adjusted DTMs DEMs and, finally, to a respective mass balance correction value ϵ_{DTM} ϵ_{DEM} (Table 5). Furthermore this approach was integrated to the estimation of differences related to unequal survey dates (see section Sect. 4.3).

4.2 Density conversion

One of the method-inherent differences between glaciological and geodetic method can be found in the density conversion. Glaciological While glaciological mass balances are derived from mass change measurements calculating mass change based on well constrained in situ density measurements , whereas the geodetic ones in-situ measurements of density, geodetic balances are based on volume change measurements, which require conversion to mass by an estimated densityfor the material lost or gained (e.g. Thompson et al., 2016). volume-to-mass conversion using estimates of bulk density. Several studies assume that density in the accumulation area is constant over time and, hence, use glacier ice density for the conversion (e.g. Andreassen, 1999; Haug et al., 2009). As (e.g., Andreassen, 1999; Haug et al., 2009). But as long as snow or firn is present, the density of ice (ρ_{ice}=900 $kg\ m^{-3}$) doing so causes an overestimation of the mass change. Hence, only below the equilibrium line altitude (ELA), where altitudinal changes are either due to ice ablation or emergence, the use of the density of ice is appropriate. However, if only appropriate in glacier areas without firn. If year-to-year firn line changes are known, the volume to mass volume-to-mass conversion can be approximated by improved by using an average density of firn (e.g. Sapiano et al., 1998; Prinz et al., 2011).To make a first calculation of mass change (Figure 2) for changes in the accumulation area (e.g. Sapiano et al., 1998; Prinz et al., 2011), we follow the recommended approximation for density conversion of 850 .

In the present study, ice density (ρ_{ice} = 900 $\mathrm{kg\,m^{-3}}$) was only applied to the ablation areas, where altitudinal changes are either due to ice ablation or glacier dynamics while the geodetic mass change in (perennial) firn areas was calculated using a density of ρ_{firn} = 700 $\pm$60 $kg\ m^{-3}$ suggested by Huss (2013). However, this approach revealed differences in some periods of the data series, as the assumption of Huss (2013) is suitable for geodetic analyses over periods which span over five years or more and which show relatively stable mass balance gradients, non-negligible changes in volume and a relatively stable extent of the firn region.Therefore 50 $\mathrm{kg\,m^{-3}}$ (Ambach and Eisner, 1966; Huss, 2013). Consequently, we calculate the annual conversion density $\overline{\rho}$ as used in Eq. 2 as follows:

$$\overline{\rho} = \frac{\rho_{\mathrm{ice}} \cdot \Delta \mathrm{V}_{\mathrm{ice}} + \rho_{\mathrm{firn}} \cdot \Delta \mathrm{V}_{\mathrm{firn}}}{\Delta \mathrm{V}}, \tag{5}$$

where ΔV_{ice} and ΔV_{firn} are the mass changes in ice and firn areas respectively which both add up to the glacier wide volume change ΔV.

In order to classify the glacier surface into ice and firn zones we designed a pixel-based surface classification workflow, in order to account for changing firn areas. The present classification is work-flow based on ALS-intensity data as described by Höfle and Pfeifer (2007) . Following Fritzmann et al. (2011), a classification of ice and firn zones on the glacier surface for each survey year could be achieved (Figure 3). If no suitable intensity following Höfle and Pfeifer (2007) and Fritzmann et al. (2011) (Fig. 3). This approach was applied to all years with suitable intensity-data while for years when no such data are availablefrom the ALS, the most contemporary ortho-images (e.g. for the year 2010) and/or LandsatTM images (e.g. for the years 2001 and 2004) are were used for surface classification . To incorporate the changing extent of the perennial firn zones we subtracted the surface grids of the respective mass balance periods from each other and reclassified the resulting new surface raster. The glacier surface is classified in two categories: glacier ice with a density of 900$\pm$17 kg m$^-$3 and perennial firn with 700 $\pm$50 kg m-3 (Ambach and Eisner, 1966; Huss, 2013), whereas the difference to maximum/minimum estimates ($\pm$17 and $\pm$50 kg m-3) serve as an uncertainty measure within our approach (σ_K; Table 5(see Fig. S1 in the Supplement). The resulting grids are used to convert volumetric changes into a massfor every pixel (see equation 2). For a better interpretation we introduce a dimensionless conversion factor as

$$K = \frac{\rho_{ice} \cdot \Delta V_{ice} + \rho_{firn} \cdot \Delta V_{firn}}{\rho_{water} \cdot \Delta V_{total}}.$$

Corresponding volume-to-mass conversion factors (K) resultant grids for each survey year were then used for a pixel-based conversion of volumetric changes to changes in mass. Respective values for the conversion density $\overline{\rho}$ lie in the range of 820 to 930 $\mathrm{kg\,m^{-3}}$ and are shown in table 3. Although neither firn processes like compaction or melt water refreezing, nor the impact of glacier dynamics are explicitly resolved our approach is considered to notably improve the quality of our annual results

compared to calculations based on a fixed glacier wide conversion density.
Uncertainties related to density conversion were estimated as follows: σ_{dc} was assessed based on the estimated uncertainty ranges of ρ_{ice} and 930. The change in mass balance values compared to the raw geodetic results (Table 2) is ascribed to the density conversion deviation (ϵ_K; Table 5).ρ_{firn} ($\pm$17 and $\pm$50 $\mathrm{kg\,m^{-3}}$) while ϵ_{dc} was calculated as the difference between our geodetic mass balance values and those based on a $\overline{\rho}$ of 850 $\mathrm{kg\,m^{-3}}$ as suggested by Huss (2013).

4.3 Survey date differences

Temporal differences between the geodetic and glaciological observations need to be addressed. To align the geodetic dates with the end of the hydrological year used for the glaciological mass balance measurements, a multi-methodical approach was applied, incorporating field measurement minutes, DTM analysis results from section 4.1 and data from in situ measurements. Apart from 2011 with in situ measurements conducted on the same day as the ALS flight (Table 4Tab. S2 in the Supplement), the changes in snow depth and ice ablation between the two measuring dates mass changes during the period between the survey dates of the two mass balance methods have to be considered. If the date of the ALS acquisition deviates from the 30th of September (To align the geodetic dates with the end of the hydrological year), the geodetic mass balance is adjusted to the fixed dates by linear extrapolations as follows. In case of ablation between the survey and the fixed date the extrapolation is based on the ablation trend over the immediately preceding time for each stake. This is calculated from used for the glaciological balances and for a corresponding adjustment of the geodetic results we incorporated data from in situ measurements and field work minutes as well as dDEM-based snow cover analysis (Sect. 4.1). Thereby ablation was assessed based on available stake readings during the summer justified by extrapolated air temperature late summer. Observed ablation trends between the observation dates were used to calculate mass change. If necessary, ablation was reconstructed by linearly extrapolating observed trends beyond the stake reading dates. Such cases were cross checked and adjusted based on meteorological data from Ventallowing ablationconditions. In the case of accumulation between the survey . The linear regression of point ablation versus altitude was finally used to calculate spatially extrapolated ablation. Note that the same altitudinal ablation gradient was used for the whole glacier since considerable ablation is restricted to the lower glacier part in this time of the year.
Accumulation between the ALS-survey and the fixed date , the precipitation gradient was assessed based on recorded precipitation at Vent which was extrapolated to the glacier applying observed long-term precipitation gradients between Vent and five 5 rain gauges in the Hintereisferner basin (Figure 1)is used for adjustment to the fixed dateFig. 1). The snow-rain threshold of 0°C is obtained from the Vent temperatures along a lapse rate of 0.0065 $^{\circ}\mathrm{K\,m^{-1}}$.
The survey date adjustment is performed individually for each annual geodetic mass balance, dependent on the presence/absence of snow during the field survey and the ALS data acquisition as well as on the difference between the survey dates and the end of the hydrological mass balance year. Accordingly, we proceeded as follows:

i) If there was no snow cover during both surveys, and the ALS campaign took place before the field survey, an elevation dependent mean ablation gradient as described above is applied. This is the case in 2003 and 2008.

ii) If there was no snow cover present during the field survey, but before a later ALS campaign, the mass balance has been adjusted to the survey date by subtracting the amount of snow from the corresponding DTMDEM, as described in section Sect. 4.1. This is the case for the years 2006 and 2007. The amount of snow determined agrees well for these years agrees well with extrapolated precipitation data using the altitudinal gradients between 5 rain gauges in the areafrom Vent.

iii) If snow was present during the field survey, but the ALS campaign had been conducted before the snowfall event, the mass of the snow cover measured during the field survey is added to the geodetic mass balance using the measured densities and the linear regression of snow probings for the elevation distribution. This is the case in 2002 and 2008.

iv) If snow was present during the field survey and the ALS data acquisition, the ALS-DTM ALS-DEM was adjusted regarding the snow cover conditions. When the ALS campaign was conducted after the field survey, the geodetic geodetically determined snow height is subtracted (section Sect. 4.1), and the mass of snow determined by field survey is added to the geodetic mass balance. This is the case for the years 2001, 2004, 2005, 2010.

There were no cases with snowfall between both surveys when the ALS data have been acquired before the field data. It is noted Note that two corrections have been applied for the year 2008 when the ALS data acquisition took place 21 days before the field survey and ablation as well as accumulation occurred . No survey date correction was necessary for in this period. For 2009 and 2011. 2011 no survey date corrections were necessary due to ALS-measurements very close to September 30^{th}.

4.4 Representation of crevasses

While crevasses are neglected in the glaciological method, they are partially resolved in the geodetic method. Although some crevasses might have been covered by snow during data acquisition, in all DTMs a number of big crevasses are visible , which open during the ablation season. However, depending in all DEMs. Depending on snow / melt conditions , crevasses are differently represented in the respective dDTMs, due to the ice movement between two ALS acquisitions andtherefore have different impacts and their impact on ice movement, the recognition of crevasses in the single dDEMs and, hence, their impact on mass balance calculations . We varies widely. However, in this study we detected crevasses by assuming that they are deviations from a regular homogenous surface. By using the variance of elevation as a measure of terrain smoothness and by applying a closing filter, we derived a surface without crevasses (for detail we refer to Kodde et al. (2007) and Geist and Stötter (2010). Hence(Kodde et al., 2007; Geist and Stötter, 2010). Consequently, we calculated the volume change of a "crevasse free" glacier, to quantify differences possible uncertainties due to open crevasses ϵ_{crev} in the geodetic mass balance (ϵ_{crev}; Table 5Tab. 3).

4.5 Internal and basal mass changes

Internal and basal mass balances are not captured by the glaciological method, but are implicitly included in the geodetic mass balances. Thus, when comparing glaciological with geodetic balances, internal and basal mass changes need to be assessed separately. Particularly for mountain glaciers studies on this topic are rare and published values represent estimates rather than verified measurements. On Storglaciären, for example, Östling and Hooke (1986) estimated the contribution of basal melt due to geothermal heat as about 0.001 -0.001 $\mathrm{m\,w.e.\,a^{-1}}$ and Holmlund (1987) suggested 0.01 -0.01 $\mathrm{m\,w.e.\,a^{-1}}$ of internal melting by released melt caused by the release of potential energy from descending waterrun-off. Albrecht et al. (2000) considered internal ablation due to ice motion being small on Storglaciären and, thus, negligible. For South Cascade Glacier, Mayo (1992) estimated the combined effect of either frictionalor frictional/geothermal basal melt, melt by the loss release of potential energy of water flowing through the glacier and melt by the loss of potential energy of the ice mass as 0.09 through ice-flow as -0.09 $\mathrm{m\,w.e.\,a^{-1}}$. Thibert et al. (2008) estimated 0.009 -0.009 $\mathrm{m\,w.e.\,a^{-1}}$ of basal ablation due to geothermal heat and 0.008 -0.008 $\mathrm{m\,w.e.\,a^{-1}}$ of internal melt due to water flow on Glacier de Sarennes over a period of 51 years. Huss et al. (2009) estimated the contribution to ablation from of geothermal heat, internal deformation, and basal friction as -0.01 $\mathrm{m\,w.e.\,a^{-1}}$ for glaciers in the Alps. Andreassen et al. (2016) calculated internal and basal ablation due to heat of dissipation based on Oerlemans (2013) for 10 glaciers in Norway, yielding a range of 0.01 to 0.08 m w.e. a-1. Sold et al. (2016) -0.01 to -0.08 $\mathrm{m\,w.e.\,a^{-1}}$. Sold et al. (2016) assessed a value of 0.014 -0.014 $\mathrm{m\,w.e.\,a^{-1}}$ for internal and basal processes at Findelengletscher following different previous studies (e.g. Herron and Langway, 1980; Pfeffer et al., 1991; Medici and Rybach, 1995; Huss, 2013).

In this study, we assess internal and basal ablation due heat of dissipation related to the dissipation of potential energy following Oerlemans (2013) and Andreassen et al. (2016), because it is the most appropriate method for the available data for Hintereisferner. The methodical disregard of internal and basal processes in the glaciological mass balance (ϵ_{int}; Table 5) is assumed to yield values of internal ablation around . The resultant values are in the order of -0.04 $\mathrm{m\,w.e.\,a^{-1}}$, which corresponds well to published data in Oerlemans (2013) for glaciers of the data for glaciers similar to Hintereisferner in terms of size and climate setting like Hintereisferner. According to Huss et al. (2009) melt published by Oerlemans (2013). Melt from basal friction and geothermal heat flux was estimated according to Huss et al. (2009) as about -0.01 $\mathrm{m\,w.e.\,a^{-1}}$(hence, . Hence, we estimate the total contribution of basal and internal processes to the mass balance to be -0.05 $\mathrm{m\,w.e.\,a^{-1}}$cumulated). As the uncertainty of internal and basal processes was not subject to any detailed analyses due to lack of independent data, we assume a value of our estimation of .

5 Results

5.1 Glaciological mass balance

Within this study existing glaciological mass balance records were homogenized in terms of reference area (see Sect. 3.1) in order to make them comparable to the geodetic analyses. This showed only minor impact since glacier outlines have been frequently updated in the original record. However, the use of methodologically homogenized glacier outlines based on Abermann et al. (2010) changed the annual glaciological balances between -0.015 to +0.039 $\mathrm{m\,w.e.\,a^{-1}}$ (see ϵ_{ref} in table 2), while the over-all impact over the 2001 to 2011 period is +0.12 $\mathrm{m\,w.e.}$. Numbers for annual glacier-wide specific mass balances range from -0.624$\pm$30% or 0.21 $\mathrm{m\,w.e.}$ in 2001/02 to -1.813$\pm$0.015 m w. e. a-1 (ϵ_{int}; Table 5). 0.21 $\mathrm{m\,w.e.}$ in 2006/07. Results for individual years are shown in Fig. 2 and in table 2 while the altitudinal profiles of glaciological mass balance are depicted in Fig. 4. Note that the uncertainty range $\sigma_{glac} = \pm 0.21$ $\mathrm{m\,w.e.}$ represents the random uncertainty as assessed in Sect. 3.1 and does not reflect any possible deficiencies in the glaciological series which shall be detected in the subsequent reanalysis.

6 Reanalysing the glaciological records

The geodetic balance

5.1 Geodetic mass balance

The corrected geodetic mass balance of Hintereisferner over the ten years period 2001 to 2011 is -13.38±0.34 m w.e. which is 1.31 m w.e. more negative than the cumulative glaciological series (Tab. 2). Annual results range from -0.685±0.06 m w.e. in 2001/02 to -2.713±0.18 m w.e. in the year 2002/03 (Tab. 2).

The geodetic mass balance of Hintereisferner over the entire study period was mainly affected by snow being present in the year 2001 resulting in ϵ_{DTM} ϵ_{DEM} = +0.29 m w.e. Taking snow heights and densities in DTMs into account the effect of fresh snow on the DEMs of individual years into account (Sect. 4.1) leads to -0.41 $< \epsilon_{DTM} <$ $< \epsilon_{DEM} <$ +0.32 m w.e. (section 4.1). The value of -0.41 m w.e. occurs in 2004/05 when snow was present at both ALS flight campaigns (Table 5Tab. 3) making up for 37% of the initial mass balance value.Applying the workflow uncorrected mass change in this year.

Applying the work-flow for the spatially distributed density conversion (section Sect. 4.2) leads to $-0.04 < \epsilon_K < +0.31$ $-0.04 < \epsilon_{dc} < +0.31$ m w.e., with maxima in 2002/03 and 2005/06 (Table 5Tab. 3). These maxima are due to the total lack of snow and firn at the end of these mass balance years. The uncertainty related to our density assumption (section 4.2) is between $\pm 0.01 < \sigma_K < \pm 0.18$ Sect. 4.2) lies between $\pm 0.01 < \sigma_{dc} < \pm 0.18$ m w.e. with ±0.22 m w.e. over the entire period of record.As dates of the ALS campaigns diverge from the end of the hydrological year a survey date correction is required. Values for related adjustments

Values for adjustments related to survey date correction are in the order of $-0.08 < \epsilon_{survey} < +0.06$$-0.08 < \epsilon_{sd} < +0.06$ m w.e. (section 4.3 and Table 5Sect. 4.3 and Tab. 3). Significant melt amounts between ALS flight and field survey dates occur on small parts of the glacier tongue only. E.g. a nearly Ice ablation of almost 1 m ice ablation at the lowest stakes of Hintereisferner measured between 30th September (field survey) and 8th October (ALS campaign) 2006 corresponds to a glacier wide specific mass loss of only 0.03 m w.e. during the same time. The differences Uncertainties related to the consideration of crevasses (ϵ_{crev}) in the geodetic method are insignificantly small and vary between -0.04 and +0.06 m w.e. with +0.05 m w.e. for the 2001 to 2011 period (section Sect. 4.4 and Table 5). While the glacier wide effect of internal mass changes is small on an annual basis is(ϵ_{int} = +0.05 m w.e. a^{-1}), it is significant on the decadal timescale (+0.50 m w.e.) (section 4.5 and Table 5on the decadal timescale (Sect. 4.5 and Tab. 3).

Annual totals for method-inherent differences (ϵ_{geod}) are in the range of -0.40 to +0.57 m w.e. and accumulate to +0.28 m w.e. for the 2001 to 2011 period while the respective uncertainties are $\pm 0.07 < \sigma_geod < \pm 0.20$ and ± 0.51 random uncertainties for individual years are $\pm 0.042 < \sigma_{geod} < \pm 0.183$ m w.e. for the cumulated values. The (Tab. 3. The geodetic balance calculated from the 2001 to and 2011 one step application of the geodetic method shows DEMs yields ϵ_{geod} = +0.77 m w.e. and σ_{geod} = ±0.20 0.34 m w.e. All applied corrections accounting for method inherent differences numbers for the applied corrections and the single uncertainty sources (ϵ) as well as numbers for related uncertainties (and σ) are summarized in Table 5. Figure 4 shows the vertical 3 while the altitudinal profiles of the now corrected glaciological and geodetic mass balances for each year from (2001/02 to 2010/11.The geodetic mass balance of Hintereisferner corrected for ϵ_{geod} for the ten years period 2001 to 2011 is -12.99 ±0.51 and -2.45 ±0.20 for the 2001 to 2011 one step analysis (Table 6) . In turn, the homogenized glaciological mass balance series (-12.04 ±0.65) is 0.95 and 0.31 less negative respectively. Figure 5 depicts the annual glaciological versus geodetic mass balances and their uncertainty ranges. All 11) are shown in Fig. 4.

5.2 Methodological intercomparison

The comparison of annual glaciological to geodetic balances shows that all but three annual data pairs match satisfyingly within the assessed uncertainty ranges (Fig. 2). The largest positive differences ($b_{glac} - b_{geod} = \Delta_b$differences ($\Delta B$ = $B_{glac.hom} - B_{geod.corr}$) between the two methods occur in the balance years 2002/03 with Δ_b ΔB = +0.92 m w.e. and 2005/06 with Δ_b ΔB = +0.60 m w.e. respectively. In 2006/07 the difference between glaciological and geodetic method is -0.45 m w.e., which means the geodetic result is less negative than the glaciological one. Note that the three years displaying the largest differences are at the same time the years with the most negative annual balances.Following Zemp et al. (2013) we perform a statistical significance test with The difference for the whole study period is 1.31 m w.e.. In order to detect significant biases between the two methods we calculated the reduced discrepancies (δ) as described by Zemp et al. (2013) as

$$\delta = \frac{\Delta b}{\sqrt{\sigma^2_{glac} + \sigma^2_{geod}}} \frac{\Delta \mathrm{B}}{\sigma_{\mathrm{common}}}, \tag{6}$$

where the term $\sqrt{\sigma^2_{glac} + \sigma^2_{geod}}$ represents the common variance (σ_{comvar}) common variance σ_{common} (Tab. 2) is defined as the RSS of the method-inherent uncertainties (Table 6$\sqrt{\sigma^2_{glac} + \sigma^2_{geod}}$). The more consistent the two methods, the closer δ is to zero and the null-hypothesis (H_0) on the 95% confidence level to ($H_{0_{95}}$) can be accepted. As δ falls within the 95% confidence interval ($\delta < 1.96$) for seven annual (all but 2002/03, 2005/06 and 2006/07) and the cumulative mass balance values, the two applied methods can be considered as statistically coherent. Hence, for these years, the glaciological method accurately captures the annual mass changes at Hintereisferner. similar (Tab. 2). Note that this approach is mainly designed for comparisons on longer (typical 10 years) time scales since biases on the annual scale might be missed. Nevertheless, in our case it allows the identification of significant deviations in three years.

From the common variance it is also possible to calculate the smallest bias that could theoretically be detected in the glaciological record (Zemp et al., 2013). The bias calculated at the 5% risk limit lies between 0.79 and 1.03 and far above the uncertainty of 0.76 and 0.96 m w.e. and is by far larger than the calculated uncertainty of annual glaciological balances of 0.21 in the glaciological balance measurementsm w.e.. In contrast, the detectable bias decreases with the length of the analysed period, which can be explained by error propagation. However, it is not possible to statistically identify any biases that might explain the observed discrepancies in the mass balance years 2002/03, 2005/06 and 2006/07 (see Figure 5).

6 Discussion

In search for possible causes of these discrepancies large discrepancies between the methods in three of the sampled years, we explore the parameter space in which potential contribution of individual components of ϵ_{geod} vary. in the years of concern: The influence of temporary snow cover ($\epsilon_{DTM}\epsilon_{DEM}$) on the geodetic mass balances is high and but a thorough consideration in our study ensures that the results are within the 95% confidence interval. In contrast, the survey date differences show little effect.

Concerning the conversion of glacier volume to mass changes, we used a new classification approach and a dimensionless conversion factor ($K$to derive a more accurate value of annual conversion density ($\overline{\rho}$). Calculated values for K correspond to densities $\overline{\rho}$ are in the range of 820-930 $\mathrm{kg\,m^{-3}}$. This is in line with a generally recommended the glacier-wide value of $850{\pm}60\ \mathrm{kg\,m^{-3}}$ recommended by (Huss, 2013). Nevertheless, in 2010 K $\overline{\rho}$ reaches 930 $\mathrm{kg\,m^{-3}}$, a value which at a first glance appears unrealistic. In this year opposite signs of elevation changes in the accumulation and ablation area compensate for each other, which results in a conversion factor which is higher than the density of ice. Such is possible in cases of (i) short observation periods (1-3 years), (ii) small volume changes, (iii) strong year to year changes in the vertical mass balance gradientsprofiles, or combinations of these factors. Our approach accounts for year to year changes in the spatial extent and distribution of the snow/firn zones. Highest uncertainties arise in the years 2002/03 and 2005/06 when all snow from the previous winter melted entirely. As the uncertainty associated with density is of particular importance (Moholdt et al., 2010; Huss, 2013) we conducted a sensitivity test for the periods of good agreement by holding all other parameters fixed. Densities calculated within our $K\overline{\rho}$-range (Table 5Tab. 3) still lead to results within the 95% confidence interval.

As crevasses may influence geodetically calculated volume changes we assessed their impact on the geodetic method. The largest impact (0.06 m w.e., or 3% of glaciological mass balance) was detected for 2002/03 when numerous crevasses opened due to the extremely hot summer causing extraordinary high glacier velocities (Geist et al., 2007). Hence, crevasses contribute negligibly to the differences between geodetic and glaciological mass balances.

Internal and basal fluxes processes are also of rather minor importance (-0.05 $\mathrm{m\,w.e.\,a^{-1}}$; section Sect. 4.5) and do not change the differences between the two data series substantially. Yet, we note that in years with extreme melt rates as in 2003 and 2006 meltwater penetrates the glacier body additional melt water from outside the glacier may enter the glacier bed in the tongue-area during the ablation season and leads to the internal which leads to basal melt rates possibly exceeding the above estimate. . HoweverHowever, even a doubling of our estimate to -0.10 $\mathrm{m\,w.e.\,a^{-1}}$ does not explain the large discrepancies between the glaciological and geodetic method in the years 2002/03, 2005/06 and 2006/07.

Other uncertainties possibly contributing to the high mass balance discrepancies in 2002/03, 2005/06 and 2006/07 may be method-inherent uncertainties related to the field measurements, such as the false determination of the last year‘s summer surface. This might be an issue for the high discrepancies in the individual survey years, but cannot be quantified due to the lack of corresponding information. However, none of the discussed method-inherent uncertainties issues can explain the considerable high differences high deviations between glaciological and geodetic analyses in the mass balance years 2002/03, 2005/06 and 2006/07.

Nevertheless, a first hint for a potential reason is given by looking at the spatial mass balance distribution indicated by the altitudinal distribution of point measurements as shown in Figure 6 Fig. 5 for the exemplary year 2002/03. In all three years of the poorly matched years, glaciological point data from elevations above 3000 m a.s.l. are basically missing on Hintereisferner , but all (Fig. 6). Given the glacier-median elevation of about 3039 m a.s.l. this means that the upper half of the glacier was not covered by measurements in these years. At the same time the three years of concern are among those with the most negative ones (Figure 7). mass balances within the Hintereisferner record (Fig. 2 and Tab. 2). The reason for missing measurements in higher elevated areas in those years is the fact that no snow from the previous winter survived the warm summers at snow pit locations and hence, traditional accumulation measurements were not possible. To address the problem of a mass balance network which had not been adapted in time, ablation rates measured at the highest stakes on the flat tongue (at about 3000 m a.s.l. and lower) had been multiplied with the observed ice exposure time of the higher slopes (G. Markl, personal communication). This disregards the impact of higher solar radiation intensity on the slopes compared to the flat tongue, and the application of formerly observed "typical" spatial patterns of mass balance in the spatial extrapolations are considered to be possible reasons for the differences between the two methods in these years.

After several years of gradual degradation of the firn body, ice and older dark firn had suddenly become exposed over all altitude bands by mid of August 2003 with consequent effects on albedo and the surface energy budget. From then on, the The East and South facing high slopes of Hintereisferner had been exposed with a very low albedo exposed a low-albedo surface to high solar radiation for 6 to 7 weeks of several weeks in the exceptionally warm and dry summer 2003 (Fink et al., 2004). As a consequence, the mass loss in the former accumulation area of Hintereisferner became large and almost constant above 2800 m a.s.l. unexpectedly large in areas without ablation stakes (> 50% of the glacier area). This effect had been observed on a smaller glacier some years earlier (Kaser et al., 2001). By facing this sudden change of the mass balance regime in 2002/03 and As a consequence, well known spatial patterns of surface melt of former years used in the mass balance network not being adapted in time, ablation rates measured at the highest stakes on the flat tongue (at about 3000 m a.s.l.) had been multiplied with the observed ice exposure time of the higher slopes (G. Markl, personal communication). The thereby disregard of higher solar radiation intensity on the slopes compared to the flat tongue are considered to be a possible reason for the differences between the two methodsanalyses were no longer valid; an effect which had also been observed on a smaller glacier in the Eastern Alps some years earlier (Kaser et al., 2001).

While higher winter snow cover buried the dark ice surface far enough into the autumns of 2004 and 2005 the high glacier portions remained protected, even allowing obtaining protecting higher glacier portions and allowing for snow pits at the end of summer.In the hot July of 2006 dark ice became again exposed and , the 2002/03 problem was repeated.became evident again in summer 2006 when dark glacier surfaces were again exposed after an early-summer heat wave.

In 2006/07 when the glaciological mass balance obtains more negative values than the geodetic one we face a different situation. In During summer 2007 there was a number of snow falls leading to high fall events increased the surface albedo in the upper part of Hintereisferner while stake measurements in the lower part of the glacier indicated relatively high ablation rates. The lack of metadata We suspect that those high ablation rates were mistakenly extrapolated to higher elevations but the lack of meta-data for this particular year disables any further discussion and interpretation.In 2002/03, 2005/06 and 2006/07

However, based on our findings we argue for the geodetic data being closer to reality than the glaciological ones as recommended by Thibert et al. (2008) and Huss et al. (2009)in the years 2002/03, 2005/06 and 2006/07 (cf. Thibert et al., 2008; Huss et al., 2009). For all other years where when differences between the methods are statistically insignificant and where error bars overlap we keep the glaciological data in the record. The crucial effect of replacing the three problematic years is well emphasized in the cumulative mass balance curves shown in Figure 8.the glaciological analyses yield plausible results. This interpretation is corroborated by comparison of the mass balance of Hinteresiferner with those of other glaciers in the region (see supplementary material).

Additional confidence for our approach comes from comparing the 2002/03, 2005/06 and 2006/07 mass balances of Hintereisferner with that of Silvrettagletscher (2.7 , Switzerland, 52 away), Jamtalferner (3.7 , Austria, 45), Weißbrunnferner (0.5 , Italy, 35) and Vernagtferner (7.9 , Austria, 6). While in the years 2002/03 and 2006/07 original Hintereisferner values lay outside the spread of the other glaciers' mass balances and the reanalysed ones are inside, the 2005/06 originals are inside and the reanalysed value becomes the most negative one in Figure 9. This is of no surprise with Hintereisferner being the lowest reaching glacier of all and among the most negative result in all analysed years. A more comprehensive discussion and justification for the different relative positions in Figure 9 would require a detailed investigation on local conditions including meteorological patterns for each individual glacier and mass balance year.

7 Conclusions

Over the past decades it has become a standard procedure to review the annual glaciological data alongside with decadal geodetic mass balances from a variety of sources Kuhn et al. (e.g., 1999); Hagg et al. (e.g., 2004); Cox and March (e.g., 2004); Thibert et al. (e.g., 2008); Huss et al. (e.g., 2009); Fischer (e.g., 2011); Galos et al. (e.g., 2017). None (e.g., Kuhn et al., 1999; Hagg et al., 2004; Cox and March, 2004; Thibert et al., 2008; Huss et al., 2009; Fischer, 2011; Galos et al., 2017). However, none of the mentioned studies uses annually obtained geodetic data series. (Geist et al., 2007) high-resolution ALS-data over one decade. Geist et al. (2007) were the first and so far only authors comparing glaciological and ALS-based geodetic results on an annual timescale for time scale at Hintereisferner for the period 2001 to 2005. Their findings reveal considerable differences revealed considerable differences between the methods, especially in the year 2002/03. Yet, the study focuses on methodical issues only and does not aim at re-analysing the glaciologically obtained mass balances. It does neither include neither includes a thorough data homogenisation nor a robust uncertainty assessment and discussion.

In our review of the 2001 to 2011 Hintereisferner mass-balance record we showed that the consideration of method-inherent differencesshow that the explicit consideration of uncertainty sources, such as the presence of snow cover, survey dates and density assumptions, is mandatory for accurately calculating annual geodetic mass balances. In turnConversely, crevasses and internal processes seem not to play a key role. The largest potential source for differences between the geodetic and glaciological method on the annual scale is the presence of a snow cover . Our method allows us to correct during geodetic data acquisition. Although its reliance on a variety of raw data and meta information might limit its applicability to other sites or cases, our method allows correction for method-inherent differences for every pixel and provides an appropriate basis for detecting discrepancies in the direct glaciological method. However, our reanalysis approach requires a variety of meta-information and raw data, which can limit its applicability to other sites or cases. However, the corrected Joint analysis of glaciological and geodetic data series show shows that the glaciological method in our case successfully captures the mass change in seven out of ten mass balance years and both methods generally agree on the annual as well as on the decadal time scale.

Our analysis further shows that in years with very negative mass balances and a low extent of the accumulation area, the glaciological measurement network has to be adapted accordingly. In the case of Hintereisferner, this means that additional ablation stakes in higher parts of the glacier are needed to properly assess the mass changes in regions where snow measurements could be performed in former times. Missing these changes , a resulting lack of respective data is often tried to overcome with different If appropriate changes to the measurement network are not made in time, attempting to overcome the resultant lack of data with mass balance extrapolation approaches based on spatial patterns observed during preceding years, might be inappropriate. In the 2001 to 2011 Hintereisferner series the application of such approaches led to considerable deviations from the geodetic results in three years and the careful revision of both series gives support for favouring the geodetic dataidentifies three cases where the applied glaciological measurement set-up proves deficient. Hence, we conclude that in times of increasing availability of high resolution topographic data, geodetic mass balances can represent a valuable possibility to overcome unravel shortcomings in the glaciological measurements even on an annual scale if these data are thoroughly analysed.

Although major discrepancies between the glaciological and geodetic methods on Hintereisferner could be explained by our workflow, further glaciological work-flow, further investigations should address a better quantification of error sources, such as internal and basal processes, in both the glaciological as well as geodetic mass balances. Moreover, in times of vanishing firn areas and disconnecting glacier tributaries, existing mass balance measurement networks might have to be reassessed.

With the high-quality DTMs (e.g. ALS derived DTMs) ALS-DEMs reliably reproducing the annual mass balance the here presented workflow work-flow presented here is recommended for (i) a re-analysis of annual glaciological with annual geodetic data and (ii) as a grid based tool for grid-based tool for deriving a glacier-wide geodetic mass balance of high spatial resolution suitable for a better understanding of the nature and origin of the differences in between the two methods.

Data availability. Mass balance data related to this study are submitted to the WGMS and will hence be publicly available through their website. Additional information on study site and data are available on request at the Institute of Geography (ALS and geodetic data) and the Institute of Atmospheric and Cryospheric Science (glaciological and meteorological data), University of Innsbruck. Coarser (10 m) versions of all the ALS-DEMs are available at Pangea.de (https://doi.pangaea.de/10.1594/PANGAEA.875889).

Author contributions. CK performed the gross part of analyses, designed and wrote the paper, EB designed an early version of the study and carried out preliminary analyses, SG contributed to methodical development, writing and revised design of the paper, LN refined the paper by native-speaker editing and comments on the manuscript, RP added expert knowledge on study site and data and performed related analyses, LR was involved in handling and analysing ALS-data, RS, JS and GK are the leaders of scientific projects related to this study and contributed to study-related discussions, paper design and writing. All authors contributed to the refinement of the manuscript.

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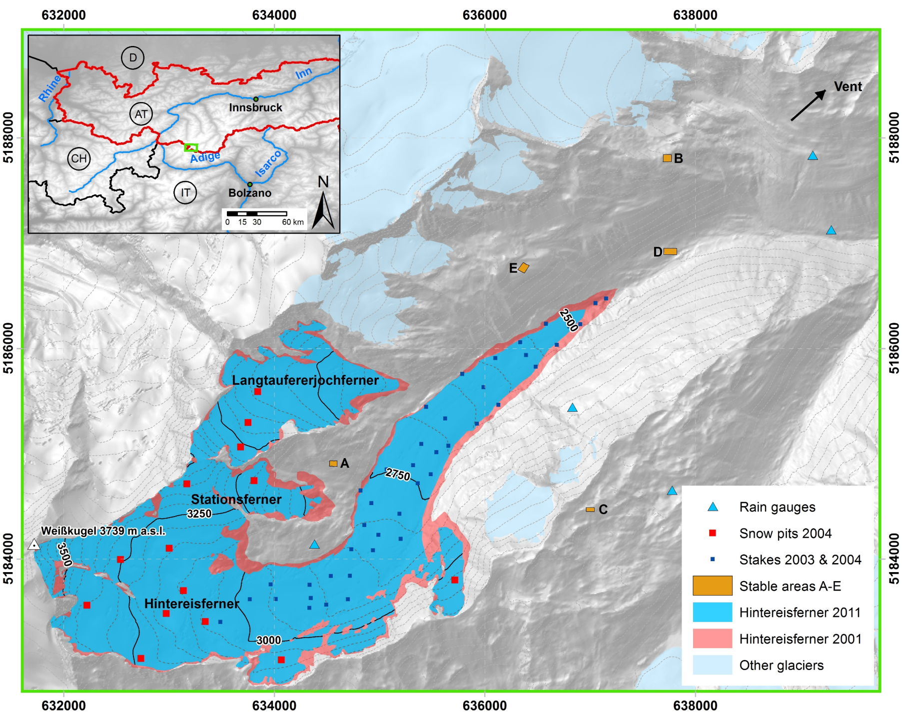

Figure 1. A map of Hintereisferner with the locations of the rain gauges and the glaciological mass balance measurement points in 2004 as an example. Also depicted are the glacier outlines for 2001 and 2011. Note that in 2003 no accumulation measurements could have been carried out due to the strongly reduced accumulation zone. Hence, only ablation stakes were available. Coordinates are in WGS84/UTM32N.

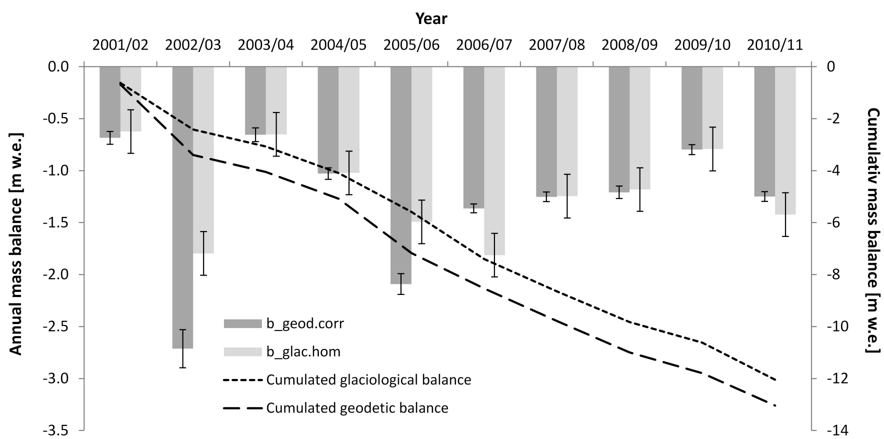

Figure 2. First order comparison Comparison of the homogenized glaciological and corrected geodetic annual and cumulative area adjusted glaciological ($b_{glac.hom}$; light mass balances of Hintereisferner over the study period. Dark grey bar bars and dotted the dashed black line) and raw indicate geodetic mass balances ($b_{geod.raw}$; dark while light grey bar bars and dashed the dotted black line) of Hintereisferner in show the period from 2001 to 2011. Method-inherent glaciological series. Vertical black lines show the annual uncertainties (σ_{DTM} for geodetic, σ_{point} σ_{glac} and $\sigma_{spatial}$ for glaciological balancesσ_{geod}) are indicated by horizontal lines, respectivelyof the two methods.

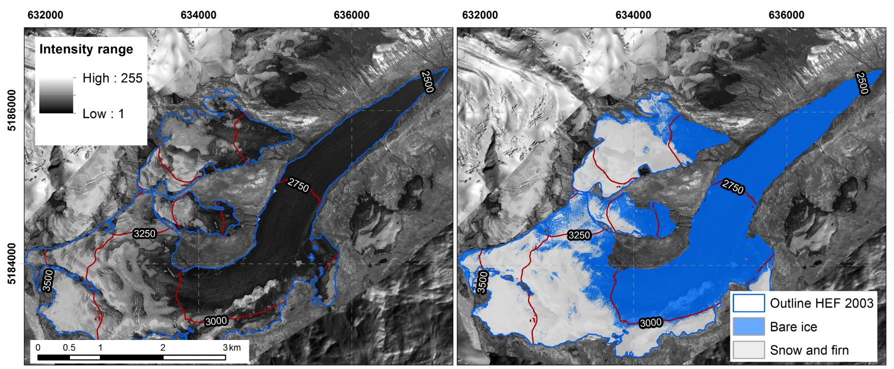

Figure 3. Intensity of the reflected laser beam of the ALS acquisition in 2008 (left) and derived surface classes (right). The classes are perennial firn with an average density of 700 $\pm$50 $\mathrm{kg\,m^{-3}}$ and bare glacier ice of 900 $\pm$17 $\mathrm{kg\,m^{-3}}$. Map coordinates are in WGS84/UTM32N.

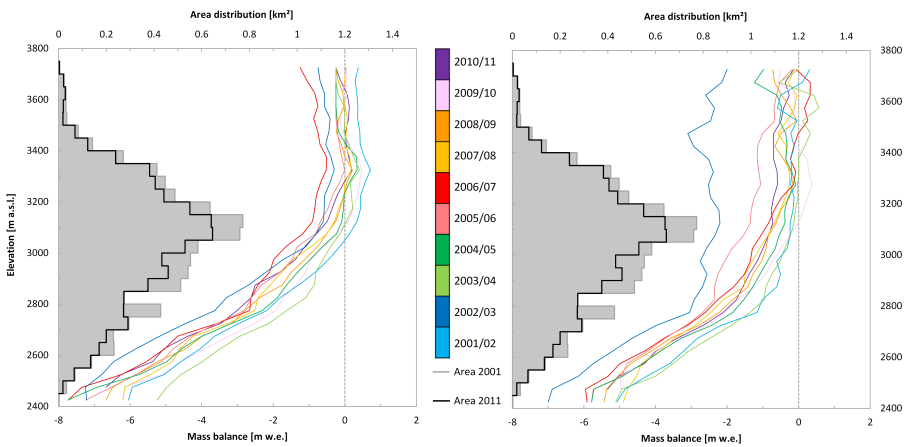

Figure 4. Corrected Altitudinal profiles of annual homogenized glaciological (left) and corrected geodetic (right) vertical mass balance profiles for balances over the study period2001/02-2010/11. Note that highest . Largest differences, which occur in the years 2002/03 (dark blue line) and 2005/06 (light red line) are also well visible in the balance profiles at elevations above 2900 m a.s.l. Note that vertical profiles of the two methods cannot be directly compared due to the effect of glacier dynamics not captured in the glaciological results.

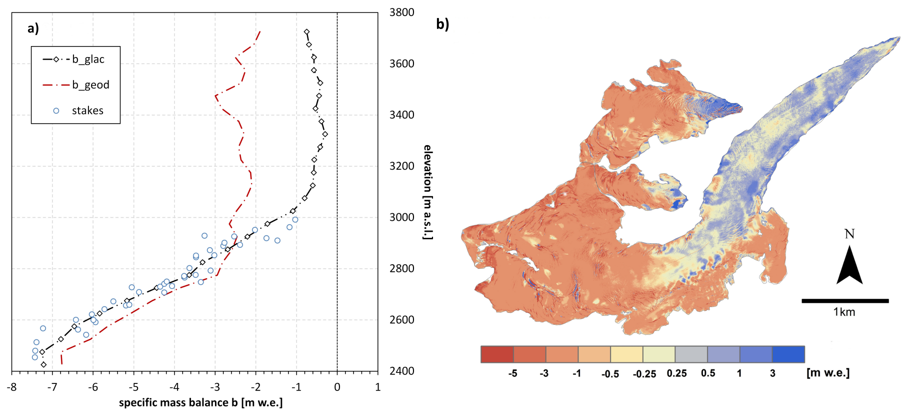

Figure 5. The extraordinary mass balance year 2002/03. (a) Comparison of vertical mass (b_{glac}balance profiles (B_{glac}; $b_{geod}$$B_{geod}$) and including the distribution of accumulation and ablation measurementsdirect measurement points over the elevation-span of the glacier. (b) Spatial Spatially distributed difference of the methodical results with main deviations between the methods above in elevations higher than 3000 m a.s.l. where in situ observations are missing. Note that vertical profiles of the two methods cannot be directly compared due to the effect of glacier dynamics which leads to more negative geodetic results (than the glaciological ones) in the higher elevated areas and vice versa in the lower glacier regions.

Annual glaciological vs. geodetic mass balance. Both series are corrected for method-inherent differences and plotted with uncertainties (grey crosses). The black diagonal line marks equal balances from both methods.

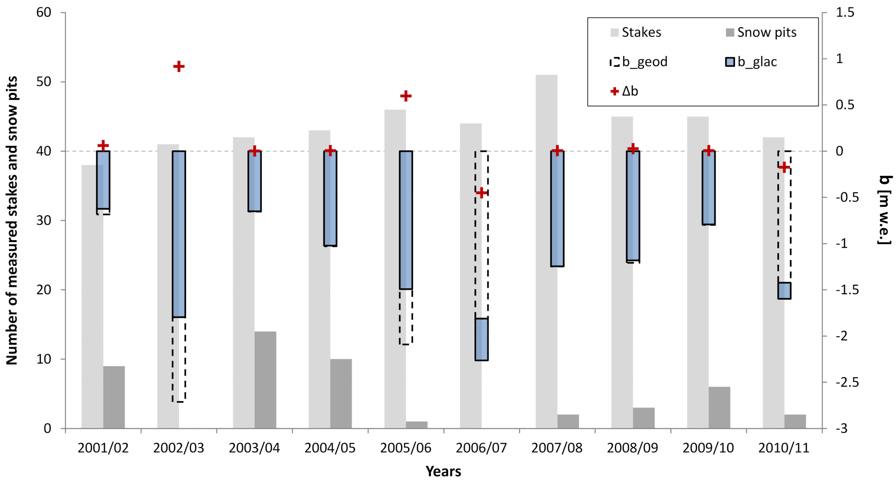

Figure 6. Comparison of mass balances (b_{glac}; b_{geod}($B_{glac.hom}$ and $B_{geod.corr}$) and their differences ($\Delta b \Delta B$) with number of accumulation and ablation and accumulation measurements. Note that in areas higher than 3000 m a.s.l. only accumulation measurements were performed.

Calibration of glaciological mass balance series for the period 2001–2011 with the geodetic surveys for Hintereisferner. Cumulative adjusted mass balance b_{glac} is calibrated with the geodetic mass change (b_{geod}) for the respective years 2002/03, 2005/06 and 2006/07 resulting in calibrated b_{glac}.

Comparison of original and reanalysed annual glaciological mass balances of Hintereisferner with different glaciers measured in the surrounding of Hintereisferner.

Table 1. Key parameters for the 11 ALS data acquisition campaigns at Hintereisferner from 2001 to 2011. Point density is averaged over the study area, while the horizontal accuracy is calculated based on a flat reference area in the vicinity of the study area.

Date of acquisition	Optech sensor	Mean height above ground	Max scanning angle [degrees] [m]	Pulse repetition frequency (Hz)	Across track overlap (%)	Average point density (points/m^2)	Vertical accuracy standard deviation (SD) (m)
11.10.2001	ALTM1225	900	20	25000	24	1.1	n.a.
18.09.2002	ALTM3033	900	20	33000	24	1	0.1
26.09.2003	ALTM1225	900	20	25000	24	1	0.06
05.10.2004	ALTM2050	1000	20	50000	24	2	0.07
12.10.2005	ALTM3100	1000	22	70000	50-75	3.4	0.07
08.10.2006	ALTM3100	1000	20	70000	37-75	2	0.08
11.10.2007	ALTM3100	1000	20	70000	37-75	3.4	0.06
09.09.2008	ALTM3100	1000	20	70000	40-45	2.2	0.06
30.09.2009	ALTM3100	1100	20	70000	31-66	2.7	0.05
08.10.2010	ALTM Gemini	1000	25	70000	62	3.6	0.03
04.10.2011	ALTM3100	1100	20	70000	25-75	2.9	0.04

Table 2. Original glaciological mass balances (B_{WGMS}), the impact of reference-area adjustment (ϵ_{ref}), the homogenized glaciological mass balance $B_{glac.hom}$ with related random uncertainties σ_{glac}, the corrected geodetic mass balances $B_{geod.corr}$ and their uncertainties $\sigma_{geod.corr}$, the difference between homogenized glaciological and corrected geodetic balances ΔB, the common variance of the two series σ_{common} and the reduced discrepancies δ. The acceptance of the null-hypothesis ($H_{0_{95}}$), indicating if the glaciological balance is statistically different from the geodetic balance or not, is evaluated on the 95% confidence level, which corresponds to δ-values inside (outside) the ± 1.96 range, respectively. β_{95} depicts the probability of fulfilling $H_{0_{95}}$ inspite of differences at the 95% confidence level. Bold entries refer to years in which $H_{0_{95}}$ is not fulfilled.

Period	B_{WGMS}	ϵ_{ref}	$B_{glac.hom} \pm \sigma_{glac}$	$B_{geod.corr} \pm \sigma_{geod.corr}$	ΔB	σ_{common}	δ	$H_{0_{95}}$	β_{95}
2001/02	-0.647	+0.023	-0.624 ±0.21	-0.685 ±0.062	0.061	0.215	0.28	yes	94
2002/03	**-1.814**	**+0.018**	**-1.796 ±0.21**	**-2713 ±0.183**	**0.917**	**0.276**	**3.33**	**no**	**9**
2003/04	-0.667	+0.016	-0.651 ±0.21	-0.654 ±0.066	0.003	0.216	0.01	yes	95
2004/05	-1.061	+0.039	-1.022 ±0.21	-1.028 ±0.056	0.006	0.213	0.03	yes	95
2005/06	**-1.516**	**+0.023**	**-1.493 ±0.21**	**-2.091 ±0.100**	**0.598**	**0.229**	**2.61**	**no**	**26**
2006/07	**-1.798**	**+0.015**	**-1.813 ±0.21**	**-1.363 ±0.042**	**-0.450**	**0.210**	**-2.14**	**no**	**43**
2007/08	-1.235	+0.011	-1.246 ±0.21	-1.252 ±0.046	0.006	0.211	0.03	yes	95
2008/09	-1.182	+0.000	-1.182 ±0.21	-1.209 ±0.060	0.027	0.215	0.13	yes	95
2009/10	-0.819	+0.027	-0.792 ±0.21	-0.798 ±0.047	0.006	0.211	0.03	yes	95
2010/11	-1.420	+0.003	-1.423 ±0.21	-1.249 ±0.047	-0.174	0.211	-0.82	yes	87
01/11	-12.159	+0.117	-12.073 ±0.65	-13.38 ±0.335	1.309	0.733	1.79	yes	57

Table 3. Method-inherent differences and uncertainties as quantified in this study. Differences related to DEM (ϵ_{DEM} and σ_{DEM}), density conversion (ϵ_{dc} and σ_{dc}), survey dates (ϵ_{sd}), internal processes (ϵ_{int} and σ_{int}) and crevasse volume (ϵ_{crev}). While the overall ϵ_{geod} accumulates from all individual differences, the overall σ_{geod} is calculated by propagating the individual uncertainties. The unit for $\overline{\rho}$ is $\mathrm{kg\,m^{-3}}$. All mass balance uncertainties are given in meter water equivalent ($\mathrm{m\,w.e.}$).

year	$\overline{\rho}$	ϵ_{DEM}	ϵ_{dc}	ϵ_{sd}	ϵ_{int}	ϵ_{crev}	ϵ_{geod}	σ_{DEM}	σ_{dc}	σ_{int}	σ_{geod}
01/02	830±30	+0.29	+0.08	-0.03	+0.05	-0.02	+0.36	±0.015	±0.04	±15	±0.062
02/03	820±45	+0.09	+0.31	+0.06	+0.05	+0.06	+0.57	±0.024	±0.18	±15	±0.183
03/04	875±20	-0.20	+0.01	+0.03	+0.05	-0.04	-0.15	±0.008	±0.01	±15	±0.066
04/05	855±30	-0.41	+0.03	-0.02	+0.05	-0.04	-0.38	±0.012	±0.02	±15	±0.056
05/06	850±35	+0.29	+0.14	-0.08	+0.05	-0.005	+0.40	±0.013	±0.10	±15	±0.100
06/07	885±20	-0.02	+0.02	-0.02	+0.05	+0.004	+0.04	±0.004	±0.01	±15	±0.042
07/08	865±25	+0.10	+0.05	-0.06	+0.05	-0.02	+0.12	±0.023	±0.04	±15	±0.046
08/09	890±20	-0.05	+0.01	-0.05	+0.05	-0.03	-0.07	±0.014	±0.02	±15	±0.060
09/10	930±20	-0.32	-0.03	-0.03	+0.05	-0.04	-0.37	±0.008	±0.02	±15	±0.047
10/11	870±25	+0.32	+0.05	+0.03	+0.05	-0.02	+0.43	±0.016	±0.04	±15	±0.047
01/11	890±20	+0.29	+0.13	-0.07	+0.50	+0.05	+0.77	±0.087	±0.27	±0.047	±0.335