Dear Prof. Hagen,

please find our responses to the comments of two referees and the author of a short comment below. While section 1 provides detailed answers to concerns raised by the two referees and the author of a short-comment, sections 2 to 4 offer a point by point response to the remarks of each referee / short comment author. The referee's comments are given in *grey italics* while our responses are in regular font.

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

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 included a discussion on the integration of meteorological data in observational series of glacier mass balance in Sect.3.2 and especially in Sect.5.4 of the revised manuscript which is fully dedicated to this topic.
- We clearly flagged all data which are affected by mass balance modeling in all tables of the paper and the supplements, as well as in the datasets submitted to the WGMS. For that reason we also changed Fig.2 and Tab.1 in a way which makes it easy to see which years and seasons are influenced by modeled values and to which extent.
- We present a stronger motivation for the choice of the presented model approach and explain why we did not rely on another (statistical) approach such as the Lliboutry model (Lliboutry, 1974) or other techniques mentioned by the two referees and the author of a short comment.

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

Best regards,
Stephan P. Galos & co-authors

1 Author's response to important concerns shared by the referees

1.1 Mass balance measurements and data modeled from atmospheric input

Both referees and the author of a short-comment address the use of modeled point mass balances in observational series which under certain circumstances may be problematic. We agree that glacier mass balance data based on meteorological variables have to be clearly flagged and implications such as a the dependence to atmospheric variables - as mentioned by the referees - have to be indicated and discussed in an appropriate matter. This was not the case in the discussion version of our paper manuscript and has been changed in the revised manuscript.

The potential of models based on meteorological data in modern glacier mass balance monitoring strategies has been outlined by a number of authors (e.g. Machguth et al., 2006; Huss et al., 2009, 2013). Consequently, during the past years many studies have made use of the benefit offered by a combination of direct measurements, observations and models. The series of published works includes the reconstruction of glacier wide mass balance series from sparse point measurements (e.g. Huss et al., 2015), the application of the model as an enhanced method for the spatial extrapolation of point measurements to unmeasured regions of the glacier (e.g. Huss et al., 2009, 2013; Sold et al., 2016), the extrapolation of measurements in time (e.g. Huss et al., 2009) and the integration of auxiliary data such as snow (line) observations (e.g. Huss et al., 2013; Barandun et al., 2015; Kronenberg et al., 2016; Sold et al., 2016).
Some of the mentioned works are explicitly presented as mass balance reanalysis studies (Barandun et al., 2015; Sold et al., 2016) and the model based techniques presented in these studies often enable the (currently) best possible estimate of glacier mass balance. This results from the fact that the performance of modern model approaches is generally superior to statistical approaches. This in turn is owed to the additional information (local topography and related implications on governing micro-climatological parameters such as temperature and radiation, snow line, snow depth and density, etc.) which is used to more accurately calculate the mass balance of a certain point or glacier.
However, the use of meteorological data to drive the models is regarded as problematic since observational series of glacier mass balance are used in investigations of glacier behaviour in response to climate forcing, which in turn is represented by atmospheric parameters. Therefore these data must be flagged and information on how the data was compiled must be provided in a fully transparent matter to enable possible data-users to decide whether the data suits their purpose or not.

In order to eradicate shortcomings in the original manuscript related to this topic we have included the following improvements in the revised version of the paper:

- The revised paper contains a clear indication of the problems associated with integrating meteorological variables in observational series of glacier mass balance
- We present a stronger motivation for the choice of the presented model approach and explain why we did not rely on another (statistical) approach such as the Lliboutry model

(Lliboutry, 1974) or other techniques mentioned by the two referees and the author of a short comment.

- We included additional references dealing with mass balance reconstruction based on statistical methods
- We critically discuss the implications of using a model approach like ours in the results section and comment on limits in the transferability of the presented method
- We changed Figure2 and Table1 in a way which makes it easy to see which years and seasons are influenced by modeled values and to which extent.

The reanalized mass balance data (point values and glacier wide averages) are meanwhile submitted to the world glacier monitoring service (WGMS). Thereby all data which are fully or partly based on modeling are clearly flagged.

1.2 Mass balance modeling

Referee Nr.1 and the author of the short-comment express their concern regarding the applied model approach with detailed comments addressing model properties/tuning, meteorological input and the transferability of the approach. Here we would like to emphasize that the goal of our study significantly differs from that of a modelling study. While energy balance models are usually applied for studying the interplay between atmosphere and glacier surface, our study does not aim to resolve physical processes behind glacier energy and mass balance. This strongly relativizes many of the concerns about model properties, extrapolation of meteorological model input or the fitting procedure of the precipitation scaling factors.
The goal of this study was to use the model as a tool to calculate the mass balance at a given point as realistically as possible. The validation of the model output against observations yields uncertainties which are markedly lower than those of other methods and hence gives us confidence that our goal was reached.

Without starting a flame war against statistical approaches, it can be argued that statistical methods relying on simplified spatial and temporal relationships (such as a temporally constant spatial mass balance gradient) suffer a number of drawbacks. Statistical methods damp the spatio-temporal variability of mass balance as they imply (linear) correlation between mass balance points or glacier parts or other simplified assumptions. As such they must be handled at least as carefully as series partly based on points modeled from atmospheric input when it comes to process oriented applications.

In the revised manuscript we discuss the above mentioned issues more explicitly to motivate our choice for the physical model. Possible restrictions in the applicability of the approach to other sites and for other purposes are discussed in the text of section 5 (Results and discussion) of the revised manuscript.

1.3 Glacier mass balance units

Both referees argue against the use of the unit $kg\ m^{-2}$ in our paper and suggest *m w.e.* instead. We would like to keep $kg\ m^{-2}$ for the following reasons:

- *kg* (mass) and *m* (length) are both part of the SI-unit system while "water equivalent" (*w.e.*) and *mm* are not
- *m w.e.* often requires at least two, in our case even three decimal digits which makes it uneasy to read
- $kg\ m^{-2}$ is easy to read and convenient since it is equivalent to *mm w.e.* which is familiar to any glaciologist
- *kg*, as a unit of mass, seems appropriate for a mass-balance study
- Finally, we follow (Cogley et al., 2011, p13, lines 37 to 40), who wrote : *"Diverging from Anonymous (1969), we have accorded primacy to mass units rather than volumetric units. This means that, although we do not discourage use of the metre and millimetre water equivalent, we consider that usage and understanding would be the better for a stronger emphasis on the difference between mass and volume"*.

It is also suggested to present annual and seasonal mass balance as a function of time. Here again we refer to Cogley et al. (2011, p.66, lines 1 to 8). The unit for specific (per unit area) mass balance is $kg\ m^{-2}$ while $kg\ m^{-2}\ yr^{-1}$ refers to a mass balance rate. The use of mass balance rates is appropriate in cases where the presented rate is valid for a longer time-span (longer than the unit of time used to give the rate itself). Hence, mass balance rates should be used when presented numbers are averaged over several years, or where they are regarded to be valid over a longer time period. This is not the case here since we present mass balances for individual years.

2 Point per point reply to referee-comment Nr.1 by E. Thibert

2.1 General Comments

S. P. Galos and co-authors provide a data reanalysis scheme applied to a ten year record (2004 to 2013) of seasonal mass balance at Langenferner glacier in the European Alps.
The approach involves homogenization of available point values and reconstruction of missing data for years and locations without measurement by the application of a process-based model constrained by snow line observations. Point mass balances are then extrapolated to the overall glacier surface to quantify the glacier-wide balance help to different extrapolation techniques and recourse of topographic data. The 2 reconstructed seasonal series differ notably from the original records. The new annual mass balance series is compared to long-term volume changes determined from airborne laser-scanning data in a rigorous error analysis and following the framework proposed by (Zemp et al., 2013). The authors find good agreement between those determinations, the residual discrepancy being explainable by the natural scattering of the data. These favourable results are to confer a significant confidence in the correctness of the re-analysed glacier-wide mass balance times-series of Langenferner glacier.
The paper employs advanced methods of mass balance computations, and geo-statistical inferences. The paper is clear, well organized, and properly focuses the scope of the journal. I think this paper is to be welcomed also as a new appropriation from the glaciological community of the guidance proposed 4 years ago by (Zemp et al., 2013).

I have two main questions regarding the model tuning for point balances, and the spatial/temporal pattern of balances:

1°) I find the calibration of the accumulation rather weakly constrained on how the precipitation scaling factors $\Gamma_{i,a}$, are allowed to vary spatially (from stake-to-stake) and with time (from year-to year).
In the present formulation, Γ is allowed to account for any deviation from the observed precipitations at all stakes and independently from what happens at other stakes. The authors mention on line 25 that the spatial pattern of $\Gamma_{i,a}$ is reasonable regarding terrain curvature and wind effects. Analysing Figure 5, it seems also that some stakes systematically have lower Γ (stakes no. 21 or 25) and on some years all stakes deviates accordingly up (2009, 2011) or down (2010, 2004). Can the authors provide a colour coded map of the mean spatial structure of Γ between 2004 and 2013 which could sustain this? Therefore one should expect a much more constrained formulation in Equation (2) when it comes to tune the model at individual stakes. Maybe the authors could reformulate Γ as $\Gamma_{i,a} = \gamma_i \, \gamma_a$., fitting 2 uncorrelated functions holding spatial and times dependencies of accumulation, and accounting for systematic deviations at some locations (γ_i) and on some years (γ_a).

We prefer not to further constrain this parameter, as we are not sure what the added value of this procedure would be. A stronger constraint would limit the allowed range of Γ which in turn would have negative impact on the model skill. We see this tuning parameter as an "inverse model", allowing us to reconstruct the mass-balance from observations of the ice (or firn) emergence. In the revised manuscript we commented more clearly on the fitting procedure of Γ and related implications for the model approach.

The role of the scaling parameter Γ is to account for local accumulation characteristics such as snow redistribution, which are strongly variable in space and time and are a priori unknown and independent from the characteristics at other (measured) stake locations. While the primary goal of the paper is not to learn about these processes, the spatio-temporal variations of Γ indeed have a lot to say about them.
As suggested, we added a color coded map to the supplementary material showing mean Γ at the locations to which the model was applied. In the same figure we also added a colour coded map of the 2005 winter balance showing that high (low) values of Γ coincide with high (low) values of local winter mass balance.

In principle we appreciate the author's suggestion, as it would provide a new way to assess the applicability of the "Lliboutry model" (the suggested constraint is very close to the underlying assumptions of Lliboutry's model). We plan to compare these strategies (Lliboutry, Contrained Γ, Free Γ) in the frame of a master thesis at ACINN.

2°) Figure 6 shows that the altitudinal profiles of balance and the way they change over time somewhat follow the time-space decomposition proposed by (Rasmussen, 2004) or (Kuhn, 1984):

$b(z,t) = f(z) + \delta b(t).$

In search of this, the authors could test if there is strong correlation between readings at the individual stakes. This feature also suggests that Lliboutry's model should work on the data set. A 10-year time series is just long enough and eminently suitable to test Lliboutry's linear model. I would therefore encourage to possibly test this analysis all the more that it could provide estimates for missing values of point balances in the accumulation area at the beginning of the record. Moreover these estimates would be free from any meteorological or glacier-to-climate assumption and safeguards the reconstructed series for an independent and unbiased analysis with climate drivers.

Again the referee's suggestion is valuable and interesting but goes beyond the scope of our paper. Lliboutry's model is a powerful tool to reconstruct mass balance values for locations and years without measurements. Nevertheless we have decided to use a different approach for several reasons: First the temporal series of several of the stake locations for which we apply our model are quite short. Some do not comprise more than three or four measured years and hence the local characteristics (α_i (e.g. Thibert and Vincent, 2009, equation 3)) are quite unreliable since loosely constrained. Apart from this the reported uncertainties for individual point mass balances calculated using the Lliboutry model are notably larger than the uncertainties of our approach which for individual points and years are in the order of 129 $kg\ m^{-2}$ (Figure7 in our paper). However, a direct comparison of the methods is outstanding and could be an interesting perspective for future research.
Please see our detailed statement in section 1 for changes which were included in the revised manuscript.

Here follow some detailed questions, comments, suggestions, and indications of minor typos in the paper. Please consider them in the same positive way in which they are proposed.

2.2 Specific Comments

Substantive comments
P1-L1. You could mention that both uncertainties (scattering) and incorrectness (biases) affect calculations.
We clearly describe the composition of uncertainties and errors, as well as their origin in section 4 of the paper. As the abstract should be short, concise and well readable it offers limited possibilities for explanations and we would prefer not to add this detail in this part of the paper.

P1-L11. Annual values for mass balance refer to changes per unit of time (rate) and should here and throughout the manuscript expressed per year (yr^{-1}). Although there is not uniformity of units regarding specific mass balance (per unit of area), the authors could use the convenient, numerically equivalent and more meaningful mm w.e. or, alternatively, the SI unit m w.e. instead of kg m^{-2}.
Please see our detailed statement in section 1.3

P1-L19. Don't you think that a more direct (physically-based) driver is rather the surface energy balance?
Although the surface energy balance of glaciers enables understanding of many processes behind glacier changes it does in the end not provide information on whether a glacier is losing or gaining mass because it does not allow conclusions on accumulation processes. In contrast, the (surface) mass balance of a glacier accounts for both accumulation and ablation processes - which are both equally important for glacier behaviour - while the energy balance mainly allows to deduce ablation processes.

P3-L21. Again please express rate units per year (yr^{-1}).
Please see our detailed statement in section 1.3

P4-L10. You mean that these stakes couldn't be measured any longer?
Yes, exactly. The locations became free of ice during the study period. We changed the sentence to clarify.

P4-L26. Please use when relevant "glacier-wide balance" terminology to fit Cogley et al.(2010) glossary.
In this special case the terminology is OK since we did not only submit glacier wide balances but also point balance and mass balance versus altitude (annual and seasonal specific mass balance for individual 50 m altitude bands) information. However, we generally tried hard to follow Cogley et al. (2011) wherever possible and therefore clarified the terminology wherever we felt that there could be a flaw.

P5-L24. A bit more needs to be say on how single out definitely areas outside the glacier subject to elevation loss (erosion in moraine terrain) and area on the glacier subject to reduce ablation (thick debris)?

Debris cover and related problems/processes play a minor role at Langenferner since only a few percent of the glacier is debris covered. Especially for the glacier wide mass balance the influence of debris cover is negligible. However, we briefly discuss this point in the revised manuscript and added an orthophoto-map to the supplementary material of the paper where (the small) debris covered areas are indicated.

P7-L19. A 10-year time series is just long enough to test Lliboutry's linear model as the spatial terms generally converge to steady values over this time scale.
For many of the stake locations where the model was applied to we only have five years of measurements, for some even only three or four. Please see our statements in section 1 and our explanations regarding point 2°) of section 2.1.

P8-L15. At which spatial scale does ERA-Interim provides time series for atmospheric pressure?
"The spatial resolution of the data set is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa." from: http://www.ecmwf.int/en/research/climate-reanalysis/era-interim.
We added the distance of the nearest grid-point from the glacier to the paper text.

P8-L26 to P9L8. How ranges the pre-calibrated scaling factor Γ_0 compared to the altitudinal gradient of precipitations?
We did not investigate this explicitly since it is not relevant for the paper (see our statement addressing 1°) in section 2.1). But when having a closer look to the range of $\Gamma_{i,a}$ it is obvious that Γ is determined by accumulation re-deposition (mainly due to wind) rather than an altitudinal precipitation gradient. We all know this also from field observations where certain locations "always" show very shallow snow cover or even bare ice while other locations are burried by meters of snow. To a certain extend such patterns re-occur every year, but still there can be differences depending on absolute snow amount, prevailing wind directions, storm events, timing and strength of melt or rain events, etc.

P9-L10 to 28. As mentioned above, the calibration is very weakly constrained on how $\Gamma_{i,a}$ is allowed to vary spatially and with time and one should expect a much more constrained formulation in Equation (2). Please refer to my general comment ahead.
We did refer to the referee's general comment in our statement addressing 1°) in section 2.1.

P10-L29. I suspect a 1x1m resolution grid to be an oversampled interpolation. Considering 250 kg m-2 contour-lines and analysing Figures 4 and 6 suggests that just 4 to 5 contour-lines should cover the altitude range [3125-3375 m] over nearly 1 km in the accumulation area. Which means that a 100x100 m would be the right sampling scale adopting a maximum of 2 grid cells between contourlines.
We used the high resolution of 1 m because this enabled us to accurately derive glacier outlines/margins. All calculations in the paper, except for the boot-strap uncertainty calculations (where a 5 m grid was used for reasons of computational effort), were performed using a 1x1 m grid resolution. This was also done as the surface mass balance grids served as input for the calculation of glacier outlines in years without ALS or orthophoto data (paper section 3.5). For this application a high resolution is a precondition. Of course a 1m resolution grid is subject

to noise but (i) due to the high point density of ALS measurements this noise is limited and (ii) for spatial integrations stochastic errors related to the high resolution do not have an impact. When smoother grids are needed for whatever application they can easily be resampled from the 1 m raster.
The density of contour lines can by the way not be deduced from Figure 6 since the Figure shows mass balance averages over 50 m altitude bands which does not say anything about local mass balance gradients resolved in the manual 2-D analyses. We added a Figure to the supplementary material showing the contour lines used to calculate the mass balance. We are aware of the fact that the high degree of resolved details is not necessary to calculate spacial averages but it may be the basis for studies on physical processes related to surface mass balance and its spatial distribution.

P11-L25. Don't you think it should be better to adjust field data to preserve the independency of the geodetic balance as a reference control?
Yes, of course those values should be preserved, but this is also valid for the field data. Therefore we applied the correction only to make a comparison between the direct and the geodetic methods possible and reasonable. The original values for the time period between the ALS campaigns without any corrections are presented in Table 3 and in the text of section 5.4 of the paper just besides the corrected ones. However, we included the value for the snow (density) corrected results in Table 3 to have all three relevant numbers (uncorrected, corrected for snow, corrected for snow and time difference) present in the revised manuscript.

P13-L15. Looks like my comment on P5-L24 on how single out areas outside the glacier subject to erosion and area on the glacier subject to low ablation.
Please see our comments concerning the similar issue on P5-L24.

P15-L5. Here and in section 4.2, I am not sure if 3 levels of subsections are worth.
The comment is understandable since the individual sub-sub-sections are quite short. But we chose this structure to make it more easy to follow and for someone who may use this part of the paper as a guideline, it is easier to follow since each of the sub-sub-sections describes one of the terms in equations 14 and 15.

P14-Equation 14. Here you assume errors to be uncorrelated to combine them quadraticaly. To some extent, this general formulation from Zemp et al. (2013) does not account that errors at a point and errors associated to the spatial integration are combined through weighting coefficients in the spatial averaging. Make here an explicit referral to the supplement S2.1 where details can be found about error calculations.
Done. We also added a comment on this in the revised version of the paper since this issue is something which many people seem to disregard.

P16-L12. Unit kg m^{-2} yr^{-1}?
No, not per year. This value is independent from the duration of the period of interest. It refers to the uncertainties related to differences in snow cover between the two ALS-acquisition dates and to differences in survey dates between the glaciological and the geodetic method. These uncertainties result from the inaccuracy of assumptions related to the described issues and af-

fect the geodetic balance over a whole period.

P17-L5. How do you think your re-analysis model will perform in case of systematic positive balances over few years? Would you have to recalibrate it? Or to reformulated the approach?
As stated in the manuscript, in case of clearly positive mass balance the approach cannot be applied in the presented way as it relies on information on the date of ice (firn) emergence. However, it could for instance be applied to extrapolate snow measurements in time and to calculate the fixed date balance based on a measurement performed at a random date in summer. We do not think that the performance of the model is dependent on the absolute value of the mass balance at a certain point but rather depends on the amount and strength of summer snow fall events (with temperatures around the threshold distinguishing liquid and solid precipitation) between the measurement taken and the end of the hydrological year or the reference date to which the mass balance information should be extrapolated by the model.

P17-L8. Title section 5.2: Mean (specific) glacier-wide annual balance Specific means per unit area, not averaged at the glacier scale.
According to Cogley et al. (2011, p63, specific mass balance) this is not totally correct. Although we use the term "*specific mass balance*" as proposed by the referee, we have to point out that "*mean specific*" can very well be used for mass balances averaged over the glacier area. However, we changed the title to "Glacier wide specific annual mass balance".

P17-L9. Can you estimate the spatial variability of the mass balance at the glacier scale from the five different extrapolation methods? And for winter and summer balance as well?
We are not sure whether we correctly understood the question. The spatial variability of surface mass balance is of course best reflected by the contour line based methods. This issue is discussed in paper section 5.2 and indirectly in paper section 3.3.1 where the benefits of the contour line method are listed. Apart from that , the total range of observed point balances (max-min) is preserved by all methods, except for the profile method which tends to underestimate total variability.
We added a statement to section 5.2 of the revised paper version which discusses the matter of spatial mass balance patterns more clearly. We did not include a quantification of differences between the mass balances calculated from the different methods at a certain unmeasured point or area since this goes beyond the scope of the present study.

P17-L20. Biases units kg m^{-2} yr^{-1}?
Please see our statement in section 1.3.

P20-L10. It would be helpful to remind the reader that you did not correct for such internal processes.
Done, we inserted a reminder a few lines earlier in the second sentence of the subsection.

Tables
Table 4. Legend. Remove "s" after δ.
Done.

Figures
Figure 6. I don't find where the main text refers to Figure 6

It is in section 3.5 where we refer to ”Fig. 4 and 6”.

Figure 7. I suggest to add the 1:1 line and the fitted line with the equation terms providing intercept (bias) and slope.
Done.

Figure 10. Is it possible to plot error bars (one sigma) on cumulative balances.
In the three upper panels we did it for geodetic and and reference method. In the lower panel we tried out plotting the accumulated random errors as calculated in paper section 4 but they were not visible since uncertainty bars are smaller or at the end of the period only slightly larger than the markers (less visible than in the rightmost of the upper sub-plots for 2011-2013). For style reasons we omitted them.

Supplement
In the main text of the paper, provide much more explicit referrals to the supplement when needed.
Done. Please note that the supplementary was substantially improved in the revised version.

Stylistic/flaw/typos
P5-L5. The “glacier” surface energy balance, not glacial
Thanks, ⇒ done.

P9-L14. Therefore
Changed.

P12-L6. Therefore
Changed.

P20-L12. Point to be deleted after “shown”
Done.

P21-L33. Add a space bar “52 kg m^{-2} for winter”

Done.

3 Point per point reply to referee-comment Nr.2 by L. Andreassen

3.1 General Comments

The authors reanalyze a 10-year record of mass balance of a small glacier in the Italian Alps. They use previously applied approaches combined with new approaches. They present a thorough error calculation. The methods and results are in general carefully described. They make use of pseudo-observations to reanalyze the data and calculate the glacier wide mass balance. This study is thus not only a modelling experiment, but presented as a reanalysis of mass balance providing updated series of glacier mass balance. Such mixing of modelling and field-data is not unproblematic, but the authors do not discuss this. I miss a section in the paper discussing this choice. Furthermore, I miss a paragraph where the authors discuss the implementation of their results and flagging of the series.

The referee's remark is correct. Please see our detailed statement in section 1.

Information on number of pseudo stakes used for every year and which years that used modelled pseudo points in the calculation is lacking from the table. If some years need to be modelled and not others, this should be more clearly stated and flagged in the paper and resulting tables. A comment field in the table could be useful to so the series are marked with reanalysis and comment on modelling degree.

We present an improved Table 1 which focuses more on the differences in glaciological variables between the original record and the reanalized series and providing information on the degree of modeling involved in the mass balance of individual years and seasons.

Fig 2 could be extended with all 10 years so the data sources are shown.

We followed this suggestion by changing Figure 2 to a nine-year panel showing the data sources for the years 2004 to 2012. The set up for the annual mass balance 2013 can now be seen in Figure S2 of the supplementary material.

Data availability
According to TC journal instructions, "Authors are required to provide a statement on how their underlying research data can be accessed". A section on Data availability therefore needs to be added to the paper with information on where to find the underlying data. The World Glacier Monitoring Service is the appropriate data service for much of the glaciological data.

The required statement was added and the data has been submitted to the world glacier monitoring service.

3.2 Specific Comments

Units. I suggest using m w.e. or m w.e. a-1 instead of kg/m2. Alternatively, mm w.e. Kg/m2 is not standard in the literature.
Please see our detailed statement in section 1.3.

P2. L30. Very long sentence.
The long sentence was split in two.

P3. Study site and data could be divided in 2 chapters.
Well, this is true. But on the other hand they are not so easy to separate since some information (e.g. section 2.2 Glaciological measurements) which is relevant for the data is strongly related to the study site and vice versa. As a compromise and for a better overview we changed the structure by inserting a subsection named ”Langenferner” which comprises all information which is just about the glacier itself.

P3. L27. Could mention the mean value for the period.
Please note that the paper is already quite long and for this reason the interested reader is referred to the references cited in the paper where she/he can find further information. Nevertheless, we changed the sentence and included the information as suggested by the referee.

P4.'The current stake network October 2016' is not that relevant here as the study period is up to and including 2013. Rather give the information for 2013. In 2.1. or in the introduction objectives (P3) the study period could be mentioned explicitly.
We followed both remarks. We changed the information on the stake network and included information on the study period in the introduction.

P4. 15. Add 'of remaining snow from the previous winter' or something similar to be clear to not mix up with winter balance/accumulation. Same for L18. Could mention how large area (in %) that had snow remaining in 2010 and 2013.
We included information about the areal extent of accumulation areas in both years but the accumulation area at the end of the hydrological year does not necessarily refer to areas with remaining snow from the previous winter. Instead, it refers to areas with positive mass balance. Especially in the year 2010 large areas in the upper parts of Langenferner had undergone only moderate ice melt in July and were covered by a relative thick layer of snow in August and September. This led to a positive fixed date mass balance at those locations although no snow of the previous winter could remain throughout the summer there. Hence, the proposed phrase ”remaining snow from the previous winter” is in this special case not appropriate and would introduce misinformation instead of clarity. We used the term ”annual net accumulation” to avoid confusion with winter accumulation or accumulation at any date other than the end of the hydrological year.

P4. L26. Mention the first mass balance year reported, e.g. 2003/2004, it may not be very clear since measurements began in 20002 (L5).
We added ”since the beginning of measurements in the year 2003/04.” to the last sentence of the paragraph.

P5. L12. On 'Around', I assume also on the glacier since this is not specified. Replace around with covering or take out and just state the point density. Would it be better to resample to a 5 m model? The section 2.3 was quite brief.
Yes, the mentioned point density also refers to the glacier itself. We changed the phrasing to

”on and around Langenferner”.
Indeed the section is quite brief. But again the reader is (now more clearly) referred to another study where the DTMs are described in more detail if this kind of information is regarded as relevant. More info could be added in case of more specific comments on that.
DTM-resolution: We used the high resolution of 1 m because this enabled us to more accurately derive glacier outlines/margins. All calculations in the paper (except for the boot-strap uncertainty calculations where a 5 m grid was used for reasons of computational effort) were performed using a 1x1 m grid resolution. This was also done as the surface mass balance grids served as input for the calculation of glacier outlines in years without ALS or orthophoto data. For this application a high resolution is beneficial. Of course a 1m resolution grid is subject to noise but (i) due to the high point density of ALS measurements this noise is limited and (ii) for spatial integrations stochastic errors related to the high resolution do not have an impact. If a smoother 5 m grid is needed for whatever application it can easily be resampled from the 1 m raster.

P5. GPS should probably replace with GNSS (Global Navigation Satellite System) throughout the manuscript.
Done.

P5. L23. How much of the glacier is debris covered? This is not stated here or in chapter 2. A picture or aerial photo could have been a nice addition to the paper. Orthophotos are available according to the text. Could be added in an improved figure 1. The section and the referencing is a bit unclear to me, was the approach done following Abermann et al (2010) or was is it done by Abermann et al (2010).
Debris Cover: Only a minor fraction of the glacier’s lower part is debris covered.
We added a comment in the text and referred to the supplementary material where an orthophoto-map was added which gives information on debris cover.
Orthofoto and Figure 1: Figure 1 was improved according to your suggestions but we did not include an othophoto as when we tried including an OF as a base map the result was an overloaded figure. Instead, we added an orthophoto-map of the glacier to the supplementary material of the paper showing the measurement set-up for the annual mass balance 2013 which was cut from figure 2 for reasons of readability (Panel of 9 years better fits to a whole page figure). This map also provides information on debris covered areas (indicated by red arrows).
Method and referencing: Both citations refer to the same paper (Abermann et al., 2010). However, the two (somehow confusing) respective sentences were changed for clarity.

P5. L28. Changes in ice divide is negligible. Could this be quantified?
It depends on if you regard the surface topography as a satisfying proxy for the ice flow direction. Differences between the DTMs of 2005, 2011 and 2013 are quite small (order of meters) and could also be due to differences in snow cover (2013). Hence, we did not discuss this issue in detail as it is not in the focus of the current paper.

P6. Ch 2.5. Could the extraction of snow line information be illustrated. Maybe add a table to the supplementary material? How were the imagery geo-referenced and stakes identified on the imagery? Some more information could be added.

As stated in the paper this was done manually without any geo-referencing of the images. The glacier is quite small and not too homogenous, consequently the location of stakes can quite easily be identified by someone who knows the glacier well. Nevertheless this issue is an important one, also limiting the 1:1 transferabilty of the method to other sites. Therefore we added a more critical discussion of this point in the results section and added an explaining section to the supplementary material.

P6. L21. Write what you did instead of 'we accounted for this problem' to be specific.
Done.

P6. L28. This issue → this melt . . . L29. Respectively → for the additional melt We think that the first case is a matter of writing style and it is clear for the reader that the word "issue" is referring to the problem of ice melt. In the following sentence "respectively" was replaced by "late autumn ice melt".

P7.L2-3 Unclear, do you mean that 'Whereas measurements were carried out close to the . . . and thus reported as fixed date in the original data, the. . . .
The sentence was changed for clarity.

P7. L10. When correcting accumulation: How are melting episodes accounted for?
Melting epsodes were not accounted for. They only have to be accounted for if the melt water drains from the glacier during the correction period (i.e. between April 30^{th} and the date of winter balance measurement in early May) which at Langenferner is hardly ever the case in that time of the year. Snow pits dug for winter balance measurements indicate that the snow pack was never saturated with melt water, except for the extraordinary year 2007 when the snow pack in the lower glacier sections was saturated due to very warm weather in April. But even in that year conditions in early May were colder again leading to the assumption that even in 2007 melt water run-off can be neglected in this regard. Note that the applied correction method only corrects for the date difference between the end of the hydrological winter (April 30^{th} and the date of measurement). The reason for larger delays in measurements has always been unfavourable weather which in early May at altitudes of more than 2700 m (terminus of Langenferner) is commonly related to snow fall rather than significant melt.
However, we added an explaining sentence to the respective subsection in the paper and referred the reader to the supplementary material where we explain the assumption and resulting restrictions in the transferability of the method.

P7. L17. L 21. L23. Is → was
Changed according to reviewer's suggestion.

L32. Add that is also justified by available data to run the model (this is not always the case)
A statement was included in the improved motivation section.

L29 Generated (use past tense on work carried out in this study)
Probably referring to L19 (not 29)...changed according to referee's suggestion.

L1. Provide to whom? 'Instead of . . . only' → 'in addition to glacier wide balances' One must be care-

ful not mixing measured and modelled point data as this can add confusion, data should be clearly marked.
Done. Text changed according to reviewer's suggestion. The issue of data flagging is now clearly discussed in the paper (see also section 1of this document).

L33. What does 'After the individual extrapolation of point measurements mean here? Interpolation could be a better word.
This point is not that trivial. While 'interpolation' refers to space or time between known (measured) points, extrapolation refers to space or time outside or beyond data points. In the case of mass balance calculation we actually deal with both (Zemp et al., 2013). Hence, the truth is actually that neither interpolation nor extrapolation is the fully correct term. It is true that the *topo to raster* tool is often called an interpolation tool, nevertheless it is also used to extrapolate data values for regions outside the measured area. Another example: For annual balance we often rely on firn density from one snow pit. In this case the density is definitely not interpolated. Similar is true for other situations.
As neither the one nor the other term is fully correct, we decided to go on with "extrapolation" in the revised paper for reasons of simplicity.

L26. Mean manually drawn? Add this information.to be clear.
Changed according to referee's suggestion.

L28. What does the latter method refer to here? Specify the method to be clear.
The method specified as 'the latter' refers to the last method described in the previous sentence and it is obvious from the content which method is resulting in rasters. For this reason we kept the sentence unchanged.

P11. Suggest to call this paragraph be called interpolation. Usually one refer to interpolation methods in general, not extrapolation methods. E.g., the Topo to Raster tool is an interpolation method
See above comment on the use of interpolation versus extrapolation.

P11. L15. Why the e.g. reference here, unclear.as follows (Zemp et al., 2013) → following Zemp et al. (2013).
Both issues changed.

P11. L19. Is → was
Changed.

P13. L13. Serves → served
Changed.

P14. L29. Substitute 'the above problem' with 'uncertainties in points'
Replaced by "the propagation of point scale uncertainties".

P14. L10-12. Rough surface topography may give errors when measured differently by field observers. Uncertainties in identifying summer surface gives also uncertainties in point data.
Reading errors and errors related to surface roughness are treated separately in our study. From time to time we perform reading experiments with student groups. Even in areas with

high surface roughness typical reading errors are in the order of 3 cm. Note that errors are expressed as standard deviations and that larger values can occur but are not too common. Uncertainties in identifying the summer surface are discussed in the paper. In our case they are only concering snow probings since in snow pits the summer horizon is easy to identify due to the very negative mass balances and the strong surface melt and resulting dirt accumulation at the surface throughout the study period.

P14. Line 29. Instead of starting a subchapter 'Similar to the above problem', state what the problem is.
Done, we changed the sentence.

P15. L10 due to the fact that it.. → as it..
Changed.

P15. 4.2.1. Could give some more details on the coregistration.
We changed the subsection by adding all information relevant for the paper.

P17. L5. Specify why it could not be used.
Done.

P20. L20. Than → as
Changed.

P18. Line 8. Are the original ELA and AAR values changed from the original record? Please make a comment addressing changes in ELA and AAR and add the original values to Table 1 if changed.
Yes, also the ELA and AAR of the reanalized series changed. This is now visible from an improved Table1 which - following the referee's suggestion - puts more focus on changes between original and reanalized reference series, as well as information on degree of modeling involved in the mass balance of the respective season or year.

P19. L14. Add the value found by Galos et al. (2015).
Done.

P19. L15. Could add some results in the text for the short periods, not just referring to the table. Comment on the density conversion factor and uncertainty used for the short period, as short periods (1-3 yr) may have a different conversion factor. (Huss, 2013)
We added results for the shorter periods.
Density conversion: we explained in detail how the geodetic mass balances were calculated. Thereby we also explain that we distinguish between fresh snow, snow from previous winter and ice. We applied the density conversion factor of 850 kg m^3 to the ice part of the glacier and used different densities for fresh snow and snow from the previous winter. The changing conversion factors for short observation periods as discussed in Huss (2013) refer to calculations where different densities (of snow and ice) are not explicitly accounted for.

P20. L4. What do you mean with further calibration, do you consider some of the presented work as calibration?
Not in the sense of mass balance calibration. We removed "further".

P20. L20. Than → as
Changed.

L21. Specify by adding 'reanalysed' summer balance values?
Done.

L23. Add 'total', thus 'a total value
Done. Also changed two sentences later.

L25. Specify what you mean with individual contributors.
Done.

P20. L28. Could add 'reduced discrepancy' after recalculating.
Done.

P20. L31. Name the two methods. What does it mean not acceptable.
Changed to: 'do not fulfill the [...] criteria'

P21. L1. Specify where you recommend it to be used.
Since the referee did not specify what she means with "it", we just assumed that "it" refers to the method in general. We added a more critical discussion on the applied approach to the revised version of the paper commenting on implication and limits regarding transferabilitya and possible alternatives.

P21. L4. Is it not the glacier wide averages that are calculated based on pseudo observations? Check L2-5.
We changed the sentence to make it clearer.

P22. L8. As well as related → of. Inter-annual mass balance variability has indeed been considered before. Suggest rewriting.
We do not state that inter-annual mass balance variability has not been addressed before but we changed the sentence.

Figure 1. Add source and year of glacier outlines. The map should be fitted to either one-column or two-column width. Could be extended in east to allow some more space around Weissbrunnferner. Borderline on inset could be refined and the inset would probably look better without the shaded background.
Source and year of glacier outlines: Done.
Figure width: The width of figure 1 is two column. For the submission of the manuscript we used the latest LATEX-template provided by *The Cryopsphere* where the figure and table widths are default for both one-column (8.3 cm) and two-column figures (12.0 cm) and tables. In the final version the sizes will meet the Journals requirements.

Figure 2. Same comment as 1, could be extend to 2-column width. The dense outer outline could be thinned.0,5 → 0.5 Suggest to add all years here.
Figure width: see above comment. More years: We have added all years from 2004 to 2012 and show the 2013 set-up in the supplementary material.

Figure 7. Add 1:1 line Figure 8. Add (orig) and (ref) to the text.
We added the 1:1 line as suggested. ”orig” and ”ref” is not appropriate here since modelled point values which were used for this validation are not used in the reanalysis. The shown validation is only possible for years and locations with modelled and measured values and in such a case the measured values were given priority in the reanalysis.

Table 1. Add ELA and AAR if different from the original record. Add Area used in the original record. Add a comment field stating if modelled pseudo stakes are used for each year. Suggest having an additional table stating the data source available for each year including pseudo stakes used.
Table 1 was changed following the referee’s suggestions.

In general, there are numerous ‘in order to’ in the manuscript. ‘in order to’ can be replaced by ‘to’ in many (if not all) occurrences.
We replaced some of them.

4 Point per point reply to short-comment Nr.1 by L. Carturan

4.1 General Comments

The paper from Galos et al. presents a valuable contribution in the field of glacier mass balance monitoring, implementing reanalysis procedures optimized in the framework of the World Glacier Monitoring Service (Zemp et al., 2013). In particular, the field measurement efforts, the completeness of the reanalysis and the detailed quantification of uncertainties are appreciable.

Due to logistical issues and/or to the peculiar characteristics of monitored glaciers, it is often impossible to setup point monitoring networks that are evenly distributed and cover the entire surface of the glaciers. Therefore, there is usually the need for interpolating and extrapolating point measurements over unmeasured areas, which often have high lateral gradients of mass balance. In such circumstances, the analyst's knowledge of the monitored glacier becomes decisive, and greatly benefit from repeat observations of snow cover patterns during the ablation season, over several years. The Authors of this paper make extensive use of this information for mapping the mass balance distribution over Langenferner, which in my opinion is another added value of this work.

However, I have one point to highlight, which is the calculation of so-called pseudo-observations in the upper part of the glacier for years without direct measurements in that area. Galos et al. use a physically based energy and mass balance model to do that, starting from meteorological data recorded by weather stations located in the proximity of the glacier. There are some weak points on the way the model has been applied and the transfer function for meteorological variables have been calculated (see detailed comments); apart from this, my principal criticism concerns the use of mass balance models for calculating artificial point measurements, which are required in usampled areas for completing glacier-wide mass balance computations.

Because the high value of mass balance records lies, among others, in their useability as sensitive climatic indicators and for improved understanding of glacier-climate interactions, using pseudo-measurements modelled from meteorological data is a sort of circular procedure.

Previous works by e.g. Haefeli (1962); Jansson (1999); Carturan et al. (2009), and Kuhn et al. (2009) proposed extrapolation procedures that are independent from meteorological observations. In my paper on the mass balance series of the neighbouring La Mare Glacier (Carturan, 2016), I tried implementing these procedures for mass balance extrapolation, combining point measurements and snow cover pattern observations.

Therefore, I recommend at least mentioning these works in the Introduction section, clearly stating why a mass balance model has been preferred for mass balance calculations in unsampled areas, and discussing the limitations of this approach. In particular, I suggest discussing the generalizability of the method (e.g. for glaciers with few or absent meteorological data, indispensable for calculating transfer functions of meteorological variables, glacier cooling effect, etc), and the fields of application of mass balance series that are partly derived from meteorological data (ok e.g. for estimating contribution to sea level rise and management of regional water supplies, but maybe less reliable for early-detection strategies of climate change and process understanding).

The author of the short-comment addresses points which have already been raised by the referees. Those are:

- the use of point mass balances modeled based on atmospheric input
- alleged weak-points in the application of the used model
- a missing discussion of previous works using statistical approaches to estimate the mass balance in unmeasured areas and
- a better motivation why the presented approach was used.

We address all those points in the detailed statements in section 1 and apart from that, we reply to the short-comment author's detailed comments below.

4.2 Specific Comments

Page 2, Line 15-25: In the Introduction, I suggest mentioning published works dealing with point mass balance extrapolation methods that are independent from meteorological data (e.g. mass balance vs. altitude). See references in the general comments.
We included a number of the presented references in an enhanced motivation discussing the choice of our approach in favour to other methods.

Page 4, line 15: extensive net accumulation measurement. Also in the following I suggest specifying net accumulation where required.
We changed the term to "annual accumulation" which is defined in (Cogley et al., 2011).

Page 4, line 26: I suggest writing here which time system is used (fixed date)
We did not follow this suggestion since annual mass balance where reported as fixed-date, but seasonal balances before the reanalysis were floating-date balances actually. The point is addressed in detail in section 3 of the manuscript.

Page 5, line 26-29: did the Authors consider the possibility of using the bedrock topography, as obtained from geophysical measurements, instead of the surface topography, for identifying the divides?
The GPR-campaign mentioned in the text of the paper allowed for an estimate of total glacier volume, but the spatial resolution in the upper glacier part is not suited to derive the glacier bed in a sufficiently accurate matter.

Page 6, line 21: how did the Authors account for this problem? Here and in other parts of the paper the reader is left (temporarily) without explanations
We inserted a cross reference to manuscript section 3.13 where the corresponding method is explained in detail.

Page 7, line 3: stratigraphic correction only for snow cover (is it fresh snow after measurement?) and not for ablation? How was it done?
We changed the text of the paragraph to make the purpose of this correction more obvious.
Melt (and other) ablation was neglected since it must only be accounted for if the melt water

drains from the glacier during the correction period (i.e. between April 30^{th} and the date of winter balance measurement in early May). This was never observed at Langenferner at that time of the year. Snow pits dug for winter balance measurements indicate that the snow pack was never saturated with melt water, except for the extraordinary year 2007 when the snow pack in the lower glacier sections was saturated due to very warm weather in April. But even in that year conditions in early May were colder again leading to the assumption that even in 2007 melt water run-off can be neglected in this regard. Note that the applied correction method only corrects for the date difference between the end of the hydrological winter (April 30^{th} and the date of measurement). The reason for larger delays in measurements has always been unfavourable weather which in early May at altitudes of more than 2700 m (terminus of Langenferner) is commonly related to snow fall rather than significant melt.
We added an explanatory sentence to the respective subsection in the paper and referred the reader to the supplementary material where we explain the assumption and resulting restrictions in the transferability of the method.

Page 7, line 12: raw precipitation or (gauge-undercatch) bias-corrected precipitation? Possible impact on calculations?
Unless not explicitly stated otherwise, "precipitation" refers to raw measurements. Hardly any impact can be expected on mass balance calculations since the precipitation measurements are taken at a relatively wind sheltered location in a valley at 1851 m a.s.l. Furthermore, the model approach fits accumulation to observations for each year and location individually. Measurement errors would hence impact precipitation scaling factors, rather than the mass balance results which are in any case validated against observations.

Page 7, line 29-31: it is a fact that the spatial variability of the mass balance is large, and largely dependent on the spatial variability of micro-meteorological variables and local topography. Does the model fully account for these factors? Maybe the Authors should briefly recall here the main processes accounted for in the model. Moreover, physically based energy and mass balance models strongly rely on accurate spatially distributed fields (or in situ measurements) of several meteorological variables for their application. Because this is not the case of Langenferner, as stated at line 27 and in Section 3.2.1, there is the need for spatially flexible model tuning for the choice of the optimal parameters at the individual points, based on summer snowline observations. In my opinion, such use of a physically-based energy and mass balance model, instead of simple statistical relationships applied to measured point mass balances and observed snow lines (i.e. independent from meteorological observations, e.g. Carturan, 2016) is questionable and should be better motivated by the Authors.
The applied method accounts for spatial and temporal variations of the most important mass balance drivers: short and long wave radiation, sensible heat flux and accumulation, as well as feedbacks related to it (surface albedo, etc) to which we devote special attention in our study by the flexible tuning of the precipitation scaling factor Γ.
Again we have to mention that our study does not aim to resolve physical processes behind glacier energy and mass balance but at simulating the mass balance at a given point as realistically as possible. Certainly accurate micro-meteorological fields as model input are of great importance when the goal is an enhanced understanding of physical processes. This issue is addressed, using Langenferner as the case study, in a recently published paper (Sauter and Ga-

los, 2016). But for this study such problems are of minor importance for the reasons mentioned above.
Nevertheless, we included an enhanced motivation and discussion in the introduction of the revised paper.

Page 7, line 31 to Page 8, Line 2: I think that actual measurements, instead of pseudo-observations derived from climatic/meteorological data, should be preferably used in investigations concerning glacier-climate interactions (there is a risk of circular reasoning).
Please see our statements in section 1 of this document.

Page 8, line 7-8: fixed lapse rates and fixed offsets of temperature imply fixed glacier cooling/damping effects and simple air temperature distribution, whereas in the recent literature there is evidence of a significant variability of these processes within/among glaciers (e.g. Greuell and Böhm, 1998; Shea and Moore, 2010; Petersen and Pellicciotti, 2011; Petersen et al., 2013; Carturan et al., 2015). The same is valid for the other meteorological variables, which have been calculated using transfer functions derived at one point over the glacier. I suggest at least discussing this issue.

We apply the fixed temperature lapse rate which was also used by Carturan et al. (2012) and many other studies which aim to enhance process understanding related to glacier mass balance. In our study the applied temperature gradient is justified by on-glacier measurements at a weather station close to stake 22 for which the Monte Carlo optimization was performed. Besides that, we repeat that our study does not focus on individual processes contributing to the mass balance. Please also see our detailed statements in section 1 of this document and our replies to a series of similar comments above.

Page 8, line 24: I think the main reason for this improvement lies on a better calculation of the liquid vs. solid precipitation fractions. Do the Authors agree?
Not only. This also for example allows a snow pack to build up during favourable conditions in a certain period of the day, while the small amounts of equally distributed hourly snow fall would eventually melt during the same time step. The consequence is a change in albedo and other feedbacks which can be decisive for whether or not melt conditions occur.

Page 8, line 28: Γ_0 therefore mainly accounts for gauge under-catch errors, precipitation vertical and horizontal gradients, and snow redistribution (and possibly ablation?). I suggest commenting on this.
It accounts for the local accumulation characteristics which is explained in the following paper section 3.2.3. Please also see our above comment referring to Page 7, line 29-31.

Page 9, line 16-18: this tuning procedure is based on the assumption that the parameters controlling ablation processes, tuned at stake 22, are also valid elsewhere and that there are no significant biases in the calculation of spatial fields of meteorological variables, because otherwise there could be compensating effects from errors in modelling accumulation and ablation processes. My suggestion is to briefly discuss this aspect. In addition, I suggest better clarifying and repeating here for which stakes and in which years the model calculations have been done.

The tuning procedure is based on the assumption that the model setting after the Monte Carlo optimization is valid for the surrounding stakes which are all located in the upper half of the glacier at similar altitudes (approximately 3125 to 3360 m a.s.l., stake 22: 3220 m a.s.l). This does not mean that the physical processes governing the mass balance have to be the same since the model resolves local topography and its impact on insolation, altitudinal variations in air temperature and related feedbacks with long wave radiation and - especially important - local characteristics of accumulation. The set of 33 observations which is used to validate the approach comprises measurements of annual point balances ranging from -1900 $kg\ m^{-2}$ to slightly positive values and there is no detectable dependence of the model skill to the actual value of measured point balance. Even if there were compensating effects in the modeling of ablation and accumulation processes - which is so far nothing but an unqualified suspicion - it would not matter since this study does not aim at studying physical processes and the only interest is the skill of the modeled mass balance values.
The revised paper version includes a stronger motivation regarding the chosen approach including a discussion of alternatives. We have also tried to more clearly delineate the present study from works which focus on enhanced understanding of mass and energy balance processes. We clearly discuss the transferability of the model and its limitations in the introduction, as well as in section 5 (Results and Discussion). The number of modeled point values used in the calculations of glacier wide balances for individual years and seasons is now visible in a revised Figure 2 and an improved Table 1.

Page 15, line 31: is this assessment bases on the procedure proposed by Rolstad et al. (2009)? If so, I suggest adding this reference here.
Is is not explicitly based on Rolstad et al. (2009) but rather follows Joerg et al. (2012).
The reference was added.

Page 16, line 5. Compared to the period from 2005 to 2012, in 2013 the AAR was significantly larger in most glaciers of the Ortles-Cevedale. The effects on the mean glacier density were likely small or negligible, but maybe the Authors could shortly comment on that.
This issue is mentioned in paper section 3.4.
The effects are not negligible for short periods (2011 to 2013) which is now stated in section 5.4 of the revised manuscript.

Page 17, line 26: maybe here the Authors could replace objective with automatic extrapolations. Here and elsewhere, specify net (accumulation) where required.
Done.

Page 19, line 23-24: in my opinion this is a key point and an essential prerequisite for reliable mass balance mapping and calculations. The Authors should mention here previous works highlighting the importance of observations regarding the snow cover pattern (e.g. Kaser et al., 2003; Østrem and Brugman, 1991).
Done.

Page 21, line 17-18: this good agreement is largely dependent on snow line observations, which have been used as constrains for model calibration at individual points, and on the representative location

of stake 22 (where the model has been optimized) compared to the location of the modelled stakes. Given also the simplified transfer functions used for the meteorological variables, I wonder how much generalizable the proposed method is, what is its added value in comparison to statistical procedures based only on observations (point measurements and snow line mapping), and how to consider mass balance pseudo-observations derived from climatic data used alongside actual observations. In my opinion, the implementation of such combined (measured + modelled from meteorological data) mass balance datasets poses some limitations to their use for process-understanding or as key variables in monitoring strategies of the Earth climate (Zemp and others, 2005; WGMS, 2008). This is because the climatic indicator (glacier mass balance) becomes dependent on the same climatic variables it should be a proxy of.
Again please see our comments in the detailed statements in section 1 of this document and our replies to a series of similar comments above.

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Figure 2: it is unclear if the snow probings refer to winter mass balance measurements or to annual net accumulation measurements. In the second case, the location of winter balance measurements should be added.
The figure caption was changed for clarity.

Figure 7: I suggest adding the 1:1 line
Done.

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Reanalysis of a ten year record (2004-2013) of seasonal mass balances at Langenferner / Vedretta Lunga, Ortler-Alps, Italy

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Abstract. Records of glacier mass balance represent important data in climate science and their uncertainties affect calculations of sea level rise and other societally relevant environmental projections. In order to reduce and quantify uncertainties in mass balance series obtained by direct glaciological measurements, we present a detailed reanalysis work-flow which was applied to the ten year record (2004 to 2013) of seasonal mass balance of Langenferner, a small glacier in the European Eastern Alps. The approach involves a methodological homogenization of available point values and the creation of pseudo-observations of point mass balance for years and locations without measurements by the application of a process-based model constrained by snow line observations. We examine the uncertainties related to the extrapolation of point data using a variety of methods, and consequently present a more rigorous uncertainty assessment than is usually reported in the literature.

Results reveal that the reanalyzed balance record considerably differs from the original one mainly for the first half of the observation period. For annual balances these misfits reach the order of >300 $\mathrm{kg\,m^{-2}}$ and could primarily be attributed to a lack of measurements in the upper glacier part and to the use of outdated glacier outlines. For winter balances respective differences are smaller (up to 233 $\mathrm{kg\,m^{-2}}$) and they originate primarily from methodological inhomogeneities in the original series. Remaining random uncertainties in the ~~reanalized~~ reanalyzed series are mainly determined by the extrapolation of point data to the glacier scale and are in the order of ± ~~80~~ 79 $\mathrm{kg\,m^{-2}}$ for annual and ± 52 $\mathrm{kg\,m^{-2}}$ for winter balances with values for single years / seasons reaching ± 136 $\mathrm{kg\,m^{-2}}$. A comparison of the glaciological results to those obtained by the geodetic method for the period 2005 to 2013 based on airborne laser scanning data, reveals that no significant bias of the reanalyzed record is detectable.

1 Introduction

Long term records of glacier mass balance are of particular interest to the scientific community as they reflect the most direct link between observed glacier changes and the underlying atmospheric drivers (e.g., Hoinkes et al., 1967; Dyurgerov and Meier, 2000; Kaser et al., 2006; Mölg et al., 2009a). During the past decades, considerable effort has been made to establish programs which provide mass balance information of individual glaciers from all over the world (e.g., Zemp et al., 2009; WGMS, 2015).

These records are undoubtedly valuable ~~,~~ and, among others, form the basis for the assessment of glacier contribution to current sea level rise (Church et al., 2013). However, their usefulness is bounded by inhomogeneities and unquantified uncertainties in the limited number of available records (e.g., Cogley, 2009; Gardner et al., 2013; Zemp et al., 2009, 2015).

~~During recent years~~ Recently, a number of studies have addressed the topic of inhomogeneous, biased and erroneous glacier mass balance records (e.g., Rolstad et al., 2009; Koblet et al., 2010; Zemp et al., 2010; Andreassen et al., 2012). ~~While the number of measurement points~~ The number of point measurements needed to derive glacier-wide mass balance was discussed by Fountain and Vecchia (1999) and Pelto (2000), while Jansson (1999) investigated the uncertainties related to direct measurement techniques and the appropriate number of measurement points at Storglaciären. Several studies have attempted to quantify how different methods of extrapolating point measurements to the glacier scale affect the resultant glacier mass balance (e.g., Funk et al., 1997; Hock and Jensen, 1999; Sold et al., 2016)~~, while others~~ . Others focused on statistical approaches to evaluate annual or seasonal glacier mass balance and their associated confidence level (e.g., Lliboutry, 1974; Thibert and Vincent, 2009; Eckert et al., 2011). But despite the relatively high number of studies dedicated to the reanalysis of glacier mass balance records, few of them (e.g., Thibert et al., 2008; Eckert et al., 2011) include a rigorous uncertainty analysis. Consequently, error assessment and reanalysis of glaciological data is of central interest to both the glaciological and climatological community (Zemp et al., 2013, 2015).

Zemp et al. (2013) provided a general concept for reanalyzing glacier mass balance series and the quantification of related uncertainties in the context of comparisons between directly measured and geodetically derived mass balance ~~, which is~~ which are commonly undertaken to cross-check the in-situ glaciological data (e.g., Funk et al., 1997; Østrem and Haakensen, 1999; Cox and March, 2004; Thibert et al., 2008; Cogley, 2009).

~~In addition, the~~ Since many records of glacier mass balance suffer from data gaps affecting certain time periods or areas without measurements, a series of methods have been developed to complete the respective data sets. Such reconstructions are often based on the assumption that glacier mass balance gradients are transferable in space or time (e.g., Haefeli, 1962; Rasmussen, 2004; K on other statistical relationships of varying complexity (e.g., Lliboutry, 1974; Carturan et al., 2009; Thibert and Vincent, 2009). However, all those methods rely on statistical relationships which are assumed to be stationary in time or space. This in turn limits the performance of such approaches as they are not able to depict the full natural variability of glacier mass balance.

As a consequence, the use of subsidiary tools ~~,~~ such as distributed surface mass balance models, extensive accumulation measurements and auxiliary imagery have become more commonly used components of mass balance (re-)analyses. Mass balance models have been used to extrapolate point measurements to the glacier scale (e.g., Huss et al., 2009, 2013; Sold et al., 2016), to homogenize annual or seasonal mass balance with respect to the fixed date method (Huss et al., 2009), or to investigate the impact of changing glacier area and hypsometry to values of mean specific mass balance (Paul, 2010; Huss et al., 2012). Extensive accumulation measurements (e.g., Sold et al., 2016) provide detailed information on the intractable problem of spatial variability of snow accumulation while additional optical imagery ~~provides~~ gives information on the evolving snow cover (e.g., Huss et al., 2013; Barandun et al., 2015; Kronenberg et al., 2016).

~~Despite the relatively high number of existing studies related to the reanalysis of glacier mass balance records, few of them (e.g., Thibert et al., 2008; Eckert et al., 2011) include a rigorous uncertainty analysis. Consequently, error assessment and~~

~~reanalysis of glaciological data is of central interest to both the glaciological and climatological community (Zemp et al., 2013, 2015).~~

In this paper we present a reanalysis of the mass balance record of a small alpine glacier over the ten year period 2004 to 2013 including a thorough uncertainty assessment. The example glacier is a particularly useful case as, like for many other glacier mass balance records, the measurement network has changed over time and the data record suffers from inconsistencies that must be tackled in order to create a consistent homogenized time series. Thus, developing a reanalyzed record and providing a detailed analysis of the uncertainty associated with this record showcases a method that can be applied to glacier data-sets suffering from similar inconsistencies~~and~~. Furthermore it provides insights into the reliability of existing glacier mass balance series for which such error analyses are ~~no longer~~ not possible or practical. The reanalysis presented here involves:

- (i) The creation of a complete and consistent set of point mass balance by correcting for methodological shortcomings in the original data and ~~by generating~~ the creation of pseudo point measurements for years and locations without measurements applying a ~~physically-based surface~~ physical mass balance model ensuring maximum skill by integrating available snow line observations into the reanalyzed record.

- (ii) The re-calculation of glacier wide mass balance based on a variety of extrapolation techniques and the integration of new topographic data from ortho-images and airborne laser-scanning (ALS) in order to minimize the effect of changing glacier outlines on the glacier wide mass balance.

- (iii) A sound uncertainty assessment regarding the results of this study including a comparison of the reanalyzed cumulative mass balance to the mass change obtained from the geodetic method based on airborne laser-scanning data.

2 Study site and data

2.1 Langenferner

Langenferner (Vedretta Lunga) is a small valley glacier situated at the head of the Martell Valley (46.46° N, 10.61° E) in the Ortler-Cevedale Group, Autonomous Province of Bozen, Italy (Fig. 1). It covers an area of ~~1.61~~ 1.6 km^2 (2013) and the highest point of the glacier is an ice divide at around 3370 $\mathrm{m\,a.s.l.}$ The terminus elevation is 2711 $\mathrm{m\,a.s.l.}$ and the median altitude is 3143 $\mathrm{m\,a.s.l.}$ (Galos et al., 2015). The upper glacier part is mainly exposed to the north while the lower sections face east. Only a minor fraction ($<$ 3 %) of the glacier surface is debris-covered. Ground penetrating radar measurements in spring 2010 gave a glacier volume of approximately 0.08 km^3, with a maximum thickness of more than 100 m in the upper glacier part. The glacier runoff feeds the river Plima which is a tributary to the river Etsch (Adige).

Langenferner is situated at the southern periphery of the inner alpine dry zone, thus the climate is shaped by relatively dry conditions due to precipitation shadow effects from surrounding mountain ranges. The largest part of annual precipitation is associated with air-flow from southern directions, often resulting from cyclonic activity over the Mediterranean, while the location south of the main Alpine divide means that fronts from the North are of only minor importance. Mean annual precipitation rates in the region range from about 500 $\mathrm{kg\,m^{-2}}$ at the bottom of the Vinschgau (Valle Venosta) to ~~-~~about 800 $\mathrm{kg\,m^{-2}}$ at Zufritt Reservoir (1851 m a.s.l.), up to approximately 1200 $\mathrm{kg\,m^{-2}}$ at Careser Reservoir Station, 2605 m a.s.l. (Carturan et al., 2012). During the study period the mean zero degree level as inferred from the AWSs used in this study was at an altitude of 2500 m a.s.l. As in most regions of the Eastern Alps, glaciers in the Ortler-Alps have been far from equilibrium during the past decade and have hence experienced drastic ~~losses~~ loss in mass, area and volume ~~(e.g., Carturan et al., 2013a, b; D'Agata et al., 2014) and~~ (e.g., Carturan et al., 2013b; D'Agata et al., 2014). A comparison of the geodetic mass balance of Langenferner (-9.4×10^{3} $\mathrm{kg\,m^{-2}}$) to those of about 90 other glaciers in the Etsch-Catchment (sample mean: -6.0×10^{3} $\mathrm{kg\,m^{-2}}$) shows that at least during the period 2005 to 2013 Langenferner was amongst the glaciers with the most negative ~~mean~~ glacier wide specific mass balances ~~of the Etsch-Catchment~~ in the region (Galos et al., 2015).

2.2 Glaciological measurements

Direct glaciological measurements at Langenferner were initiated by the University of Innsbruck on behalf of the Hydrological Office of the Autonomous Province of Bozen / Bolzano (HOB) in the hydrological year 2004. The program was established as a supplement to the mass balance program at ~~Weißbrunnferner~~ Weißbrunnferner / Fontana Bianca which was considered (i) as potentially threatened by rapid glacier retreat and (ii) deemed to be not representative for the region due to the specific setting of the glacier (Kaser et al., 1995). Since the start of the program, the initially provisional measurement network has gradually evolved (Fig. 2) and hence, has changed substantially over time, especially in terms of spatial stake distribution, which poses a particular challenge for understanding the spatio-temporal variability of the glacier mass balance.

In fall 2002, a number of ablation stakes was installed in the lower part of Langenferner and systematic readings began in October 2003, when additional stakes were drilled, still only covering the lover half of the glacier. In August 2005, the stake network was extended to the upper glacier sections by adding seven more stakes, the position of which was initially not accurately recorded. Systematic readings of the stakes in the upper glacier part at the end of the hydrological year were not performed regularly until the year 2009, when the measurement network was further refined by adding five additional stakes to the upper glacier sections. In the course of the study period four stakes in the lower most glacier part were removed ~~due to drastic glacier retreat~~after the respective locations became free of ice. The position of stake 13 in the middle part of the glacier had to be changed in 2011 due to outcropping rock at the original location. ~~The current stake network (October 2016) is~~

The stake network at the and of the study period (2013) was made up of ~~28~~ 30 ablation stakes which consist of elastic white PVC-tubes of roughly 2 m length, connected by a piece of rubber-hose. Drilling depths vary between 4 m in the uppermost glacier part and 12 m in the lower sections. ~~Stake readings are~~ During the study period stake readings were performed once to six times a year, depending on the local conditions at the individual stake. ~~During the study period extensive accumulation measurements~~ Extensive measurements of annual net accumulation at the end of summer were only necessary in the years 2010 and 2013 ~~since net accumulation was restricted to about 10~~ when the accumulation area ratio (AAR) made up for about 37 and 50 % of the ~~glacier area in~~ total glacier area respectively. In the other observation years ~~.~~ accumulation areas were restricted to only a few percent of the total glacier area (see Tab. 1). Up to the year 2007 no ~~accumulation measurements at the end of the hydrological year were performedand from~~ measurements of annual net accumulation were performed. From 2008 to 2013, annual net accumulation was measured at the end of the hydrological year by means of one ~~or two~~ to four snow pits at more or less arbitrarily chosen locations and, if necessary, by a varying number of snow depth probings.

Winter balance measurements have been carried out annually in the first half of May performing numerous snow depth probings and four (or three) snow pits distributed over the glacier surface in each of which the bulk density of the snow pack was measured gravimetrically. While the number and location of the snow depth probings was not fixed throughout the observation period, the number and positions of the pits were more or less kept constant, except for the year 2009 when the large amount of winter accumulation resulted in omitting pit 3. Locations of point measurements used for annual mass balance are shown in Fig. 2, measurement locations for winter balance and all measurement dates are shown in the supplementary material of this paper.

Since the year 2013, the observational set-up includes two automatic weather stations (~~AWSs~~AWS) on and near the glacier and in spring 2014 a run-off gauge was installed 3 km down-stream of the glacier terminus. Seasonal and annual mass balances are regularly submitted to the World Glacier Monitoring Service (WGMS) ~~.~~ since the beginning of measurements in the year 2003/04.

2.3 Meteorological data

The mass balance model used in this study requires meteorological data as input. These data originate from ~~AWSs~~ AWS (1851 to 3325 m a.s.l.) in the vicinity of the glacier (Fig. 1) and were provided by the HOB. Hourly values of air temperature, relative humidity, and global radiation were taken from the station Sulden Madritsch, 2825 m a.s.l., located in an alpine rock cirque some 2.5 km north of Langenferner. The other three required meteorological input variables are wind speed, precipitation and atmospheric air pressure. Those data were not available at Sulden Madritsch for the entire study period. Consequently wind speed data was taken from the station at Schöntaufspitze, 3325 m a.s.l., 5 km north of Langenferner. Air pressure was down-scaled from ERA-Interim reanalysis data of the nearest surface grid point (47°N|11°E). Daily precipitation sums originate from the station at the dam of Zufritt Reservoir, 1851 m a.s.l. in the Martell Valley, approximately 11 km northeast of the glacier (Fig. 1).

Since 2013 the Institute of Atmospheric and Cryospheric Sciences, University of Innsbruck (ACINN) operates two ~~AWSs~~ AWS at Langenferner. One station is drilled into the ice of the upper glacier part at an altitude of 3238 m a.s.l. and is designed to measure all meteorological parameters needed to calculate the ~~glacial~~ glacier surface energy balance. The second station was installed on solid rock ground close to the middle part of the glacier serving as a robust back up to bridge possible data gaps of the ice station. Data of those two stations were used to derive spatial gradients and transfer functions of meteorological data, as well as to optimize the radiation scheme of the applied mass balance model.

2.4 Digital terrain models from airborne laser-scanning

Data from three ALS-campaigns were used for this study. Respective surveys were conducted around September 14^{th}, 2005, on October 4^{th}, 2011 and on September 22^{nd}, 2013. For the area on and around Langenferner the point density of the 2005 and 2013 data sets is 1.06 and 2.65 points per m^2 respectively ~~(Galos et al., 2015)~~ and the density of the 2011 data set is 2.84

points per m^2. High resolution ($1\mathrm{m}$) digital terrain models (~~DTMs~~DTM) of the study area were calculated from the original ALS point data for all three data sets, where the mean value of all points lying in a raster cell was used as the elevation value for the cell and cells without measurements were interpolated from surrounding grid cells. For more details on the ALS data and resulting DTM the reader is referred to Galos et al. (2015).

2.5 Glacier outlines from ortho-images, ALS and ~~GPS~~Global Navigation Satellite System

Orthophotos from four acquisitions were used for updating the glacier area of Langenferner. Orthophotos for the years 2003, 2006 and 2008 were provided by the Autonomous Province of Bozen / Südtirol, while data for the year 2012 were available as a base-map within Esri-ArcGIS. The delineation of glacier area was done manually, which, for this small and well-known glacier, ensures the maximum accuracy. Outlines for the years 2005, 2011 and 2013 were derived from ALS data using high resolution hill-shades and DEM-differencing ~~(Abermann et al., 2010). ALS data also provided valuable information for~~ following the approach of Abermann et al. (2010). This method also enabled the delineation of debris-covered glacier margins as areas which had undergone no change in surface elevation between two acquisition dates could be classified as ice-free while debris-covered ice was still subject to some lowering~~(Abermann et al., 2010).~~. However, debris cover is a minor issue at Langenferner since only a few percent of the lower glacier part are covered by debris. The glacier outline of 2010 was assessed from extensive differential ~~GPS~~ Global Navigation Satellite System (GNSS) measurements in early October 2010.

In the uppermost part of the glacier the outlines are confined by ice divides which were derived applying a watershed algorithm to the ALS-DEM 2005. Although the glacier surface topography in this area changed during the observation period, the impacts on the glacier flow direction are negligible and the outlines of the uppermost glacier part were consequently kept constant throughout the study period.

2.6 Snow line from terrestrial photographs and satellite images

Information on snow cover extent was used to tune the mass balance model for individual points on the glacier. In order to map the evolution of the transient snowline at Langenferner during the ablation period, we made recourse of an extensive set of terrestrial and aerial images mainly recorded during the field campaigns on the glacier. We used photos from more than 70 field work campaigns, private visits and dated photographs from the internet. A small number of Landsat scenes from different dates provided additional information on the snow cover extent on the glacier. These data were used to manually determine the approximate date when the snow of the previous winter had melted entirely at each given stake location. In most cases the date of snow melt could be determined with an estimated accuracy of ± five days, and in many cases probably even better.

3 Homogenization of data and methods

3.1 Point measurements

Besides a sparse and unevenly distributed measurement set-up during the first half of the study period affecting annual mass balances, the original record of winter balances was influenced by methodological inhomogeneities concerning the attribution of snow accumulation and ice ablation to the correct reference year or season. These problems have to be addressed in order to create a consistent and comparable record of annual and seasonal mass balance according to the fixed date system (e.g., Cogley et al., 2011).

3.1.1 Stratigraphic correction of snow measurements

Accumulation of snow or firn is measured by means of snow probings and snow pits. Both techniques record the entire snow pack down to a characteristic reference layer which is typically given by the ice surface at the end of the previous ablation season or the firn surface at the date of the last local mass minimum. Hence, there is a need to correct the snow depth measurements in spring for snow fallen during the previous hydrological year (i.e. before October, 1^{st}) in order to obtain values corresponding to the fixed date period. As part of the ~~re-analysis~~ reanalysis process we accounted for this problem (which was not considered in the original analyses up to the year ~~2008.~~ 2008) by subtracting the respective snow water-equivalent which for all years was measured at the stake locations at the end of the previous hydrological year.

3.1.2 Ice ablation in the hydrological winter period

While incorrect attribution of summer snow can affect both annual and seasonal mass balance, ice ablation in late autumn (after September 30^{th}) only affects the seasonal mass balances. In most years of the study period ice ablation during late autumn at Langenferner was negligible since low elevated areas at the tongue are relatively small and receive only little insolation during that time of the year. Nevertheless, in October / November of the years 2004 and 2006 considerable melt took place in the middle and lower parts of Langenferner. While in the original analyses this issue was not considered, although stake data from late autumn field work were available, the point winter balances were corrected ~~respectively~~ for late autumn ice melt during the reanalysis process.

3.1.3 Fixed date versus floating date

Measurements for ~~the~~ annual mass balance were ~~always~~ in all years carried out very close to end of the hydrological year and, if necessary, stratigraphic corrections for snow cover were applied~~in order to meet the fixed date criteria~~. Hence original annual balances were reported as fixed date balances and thus no additional correction was applied during the reanalysis. Original winter mass balances on the contrary were calculated following the floating date approach meaning that the water equivalent of the snow pack accumulated since the preceding summer was measured during a field campaign in the first half of May and no further corrections were applied. In order to make the results of the seasonal balances comparable, we calculated the fixed date winter mass balance by scaling the measured and corrected point values of winter balance in order to obtain the water equivalent of snow at the end of the hydrological winter season (April 30^{th}). This was done based on precipitation measurements at Zufritt Reservoir and on the ratio of accumulated precipitation during the measurement period (floating date) and during the hydrological winter season (fixed date) as follows:

$$b_{fix} = b_{fld} \cdot \frac{\sum P_{fix}}{\sum P_{fld}}, \quad (1)$$

where b_{fix} and b_{fld} are the fixed date and floating date point values of winter balance and $\sum P_{fix}$ and $\sum P_{fld}$ are the precipitation sums recorded at Zufritt Reservoir during the fixed date and the floating date period respectively. Note that this approach is based on the assumption that no melt water drains from the glacier during the hydrological winter period which is a reasonable assumption for Langenferner (see supplementary material for a more detailed discussion).

3.2 Point mass balance modeling

A major shortcoming of the original mass balance record at Langenferner is the lack of observation points in the upper glacier part during the first years of the study period. This affects the calculations of annual mass balance in the early observation years and the temporal consistency of the record. Therefore, ~~the~~ a central aim of this study ~~is~~ was to create a spatially and temporally consistent set of point annual mass balance. ~~Due to the relatively short and inconsistent set of existing measurements, existing statistical approaches (e.g., Lliboutry, 1974; Thibert and Vincent, 2009; Eckert et al., 2011) are inapplicable. Instead we generate~~ To achieve this we generated artificial measurement points in the poorly-represented upper glacier section by applying a physically based energy and mass balance model (Mölg et al., 2012). ~~The~~ We have chosen a physical approach since reconstructions based on the spatial or temporal transfer of known mass balance gradients or altitudinal profiles (e.g., Carturan et al., 2009; I show limited performance. More comprehensive statistical approaches such as presented by Lliboutry (1974), Thibert and Vincent (2009) o Eckert et al. (2011) were not applicable due to the short series of available data (at some locations five years or less). However, the performance of modern model approaches is generally expected to be superior to statistical approaches. This is due to the integration of additional information such as the influence of local topography and related implications on governing micro-climatological parameters like temperature and radiation, snow line, snow depth and density, etc. which enables a more accurate calculation of the local mass balance. In contrast, statistical methods damp the spatio-temporal variability of mass balance as they imply (linear) correlation between measurement points or glacier parts. Nevertheless, the use of models driven with meteorological data in glacier mass balance series can be problematic (see Sect. 5.4). For this reason we clearly flag all results related to modeling and provide full methodical transparency in order to enable possible data-users to decide whether the data suits their purpose or not.

The applied model was run in its point configuration as the purpose of this study is not to use a model for the spatial extrapolation of point measurements on the glacier wide scale as done in a number of other studies (Huss et al., 2013; Barandun et al., 2015; Kronenberg et al., 2016; Sold et al., 2016), but is to reproduce a best possible estimate of annual balance values for point locations where ablation stakes were placed in the subsequent years. In this configuration, the model performance can be validated directly using data from available stake measurements. A spatially distributed model set up would introduce larger errors regarding the mass balance at selected points, while the point model allows for a spatially flexible model tuning and strongly reduces errors due to shortcomings in the spatial extrapolation of meteorological variables (e.g., Carturan et al., 2015; Sauter and Galos, 2016; Shaw et al., 2016) and the choice of the optimal parameter setting (e.g., MacDougall and Flowers, 2011; Gurgiser et al., 2013). The application of a relatively complex physical model is justified by the dominant influence of ~~micro-meteorological variability,~~ local topographic factors on micro-meteorological variability and the resultant large spatial variability of the surface mass balance ~~,~~ which can only be resolved in a sufficient way by a process based model. Furthermore, we aim at ~~providing~~ creating a set of homogenized point mass balances ~~instead~~ in addition to of glacier wide balances~~only~~, since point balances have proven to be valuable information sources for investigations on glacier-climate interactions (e.g., Huss and Bauder, 2009).

3.2.1 Transfer of meteorological variables

~~Meteorological variables (Section 2.3) were extrapolated to the glacier using spatial transfer functions. Those functions were obtained~~ Although our study does not aim to explicitly resolve individual energy fluxes, we extrapolated meteorological variables using techniques which have also been applied in process oriented studies since insufficient extrapolation of meteorological input data is often a dominant error source in the application of physical glacier mass balance models (e.g., Gurgiser et al., 2013; Shaw et al. The extrapolation techniques used here were optimized using data from the on-glacier weather station in the upper part of the glacier for the period July 2013 to August 2015, a period when measurements at all AWS were available. Air temperature from Sulden Madritsch was extrapolated to the glacier applying an altitudinal lapse rate of ~~$6.5x10^{-3} K/m$~~ $6.5 \times 10^{-3}\ \mathrm{K\,m^{-1}}$ and an offset of -0.56 K reflecting the different ~~microclimates~~ micro-climates over rock (Sulden Madritsch) and the on-glacier station. Both values were derived from a linear regression between measurements at Madritsch and the glacier station during the summers 2013 and 2014. Relative humidity was corrected for saturation over ice for below-freezing temperatures but the data was not further modified since no clear spatial pattern was detectable in the ~~analysed~~ analyzed data sets. Global radiation was used to calculate a cloud factor (e.g., Mölg et al., 2009b; Haberkorn et al., 2015) which was assumed to be spatially constant over the study area. This factor was used to drive the radiation scheme of the mass balance model which was optimized for the glacier using short- and long wave radiation data from the glacier. Wind speed from Schöntaufspitze was linearly scaled to match ~~the~~ observed wind speeds at the glacier station using a scaling factor of 0.67. ERA-Interim atmospheric air pressure from the nearest surface grid point (46.5°N, 10.5°E, 8.5 km from the glacier) was reduced to the altitude of the stake locations by the barometric equation, and since the mass balance model is relatively insensitive to small changes in air pressure, the temporal resolution of one hour was achieved by linear interpolation of the six hourly reanalysis data. Daily precipitation sums measured at Zufritt Reservoir (1851 m a.s.l., 11 km from the glacier) were used to assess hourly precipitation at the glacier, whereby the daily sums were temporally redistributed according to the course of relative humidity during the measurement day. Precipitation was only assigned to time steps when humidity exceeded the threshold of 93 % and the amount for a single time step was then scaled according to the magnitude of exceedance. If this threshold was not reached throughout the day but precipitation was measured, the threshold was lowered by steps of 5 %. This procedure was found to have a remarkable positive impact on the model performance. The sensitivity of modeled point mass balance to this correction can easily reach about $\pm$ $100\,\mathrm{kg\,m^{-2}}$ on the annual scale compared to a model driven with daily precipitation sums equally distributed over 24 hours.

3.2.2 Monte Carlo optimization of model parameters

The mass balance model approach was set up as follows (Fig. 3): first the model was pre-calibrated applying realistic values for the model parameters which were either taken from the literature or from direct meteorological observations in the study area. The first guess model precipitation $P_{0_{model}}$ was generated applying a precipitation scaling factor Γ_0 to the measured and temporally re-distributed record of Zufritt $P_{obs.red.}$ in order to fit the model to the observed values of winter mass balance (~~Equation 2)~~Eq. (2)).

$$P_{0_{model}} = P_{obs.red} \cdot \Gamma_0, \tag{2}$$

This pre-calibration was done for the location of stake 22 (Fig. 4), a stake situated in the upper glacier part, ~~near~~ in the center of the area where the point modeling was carried out. This stake was chosen as the relatively homogeneous ~~terrain surrounding it~~ surrounding makes it representative for a wider region of the glacier and it offers by far the highest number of stake readings in the upper region of Langenferner. It is hence the best choice for the optimization of model parameters, which was done applying a Monte-Carlo approach (e.g., Machguth et al., 2008; Mölg et al., 2012) performing 1000 model runs with different parameter combinations in order to find the best model setting for the local conditions. The optimal parameter combination was then applied to all stake locations in the upper glacier part. An individual Monte Carlo optimization for each stake was not possible due to the low number of available readings at some stakes.

3.2.3 Model tuning for individual stakes and years

Large uncertainties in process-based studies of glacier mass balance are commonly related to accumulation and its spatial distribution: altitudinal precipitation gradient, redistribution of snow due to wind and its large influence on spatial accumulation patterns, the temporal evolution of surface albedo and hence net radiation, etc. (e.g., Gurgiser et al., 2013; Machguth et al., 2008). In order to minimize ~~uncertainties related to the unsatisfactory representation of local accumulation~~ respective uncertainties in the mass balance model, we made recourse of a calibration procedure which integrates available snow information. ~~Therefor~~For this purpose, the mass balance model with the optimized parameter setting was tuned by replacing Γ_0 in ~~equation 2~~Eq. (2) by the individual (for stake i and year a) scaling factor $\Gamma_{i,a}$ which accounts for all site-specific properties related to accumulation. ~~This~~ $\Gamma_{i,a}$ should hence not be seen as a precipitation scaling factor but rather as a way to correct for the unresolved accumulation processes listed above. These processes are highly variable in space and time, therefore $\Gamma_{i,a}$ is allowed to vary freely, ensuring a high model skill as it enables the model to account for the full spectrum of natural mass balance variability (see Sect. 5.1). This stake and year individual tuning procedure was performed ~~for every stake and year individually and~~ in a way that the observed date of the emergence of the ice surface at the respective location was correctly reproduced by the model. An automated iterative approach ensured that the modeled date did not differ by more than one day from the observed date. ~~Note that this~~

Note that the present approach is not applicable in years with a persisting snow cover at the stake location. But during the first observation years (2004 to 2008) when measurements were partly missing, annual mass balances at Langenferner were very negative and accumulation at the end of the year was restricted to a few percent of the glacier area. For the few years and stakes with missing measurements and snow cover persisting throughout the ablation season, $\Gamma_{i,a}$ was derived based on linear regression with Γ_i-series of ~~neighboring~~ neighbouring stakes. Values for $\Gamma_{i,a}$ vary in the range of 1.1 to 4.7 (Fig. 5), and curvature of the terrain and other wind related factors are clearly reflected in the spatial $\Gamma_{i,a}$-patterns, while inter-annual variability seems to be determined by meteorological phenomena, such as number and strength of storm events, dominant flow direction during the accumulation period or the absolute amount of accumulation since years with lower accumulation amounts tend towards larger $\Gamma_{i,a}$-values.

3.3 ~~Extrapolation from~~ Spatial integration of point ~~to glacier scale~~data

Five different methods were applied to ~~extrapolate~~ spatially integrate the reanalyzed values of annual and winter point mass balance ~~to the glacier wide scale~~ in order to obtain mean specific glacier wide balances. We applied the traditional contour line method in two different ways and additionally made recourse of three ~~purely objective~~ automatic methods in order to assess and investigate possible differences and uncertainties due to the applied analysis method. After the ~~individual~~ method-individual extrapolation of point measurements, all applied methods calculate the total mass change ΔM by spatial integration of the specific mass change b over the area S based on the following equation:

$$\Delta M = \int_S b \cdot dS. \tag{3}$$

The mean specific mass balance B is then calculated as follows:

$$B = \frac{\Delta M}{S}. \tag{4}$$

Equations ~~3 and 4~~ (3) and (4) can be applied to the entire glacier area to obtain the ~~mean~~ glacier wide specific glacier mass balance, or to each single 50 m ~~altitude band in order~~ altitude-band to calculate the altitudinal mass balance profile and subsequently the equilibrium line altitude (ELA). The latter is calculated as the lower most intersection of the altitudinal mass balance profile with the $b = 0$ axis (Cogley et al., 2011). While annual (B_a) and winter (B_w) mass balances are based on measurements, summer mass balances are calculated as a residual:

$$B_s = B_a - B_w. \tag{5}$$

For comparisons with the geodetic method there is the need for direct glaciological balances over the geodetic survey period. These are calculated summing up the annual glaciological mass changes (ΔM_a) from the beginning (t_0) to the end (t_1) of the period of record (PoR) and dividing the result by the average glacier area S ~~through~~ during that period (~~equation 6)~~Eq. (6)).

$$B_{glac.PoR} = \frac{\sum_{t_0}^{t_1} \Delta M_a}{\frac{1}{2} \cdot (S_{t_0} + S_{t_1})}, \tag{6}$$

3.3.1 Contour Line based extrapolations

The contour line method (e.g., Østrem and Brugman, 1991) is an often used approach for the determination of glacier mass balance. It is based on manually derived lines of equal mass balance based on point measurements and has the advantage that the spatial pattern of surface mass change is relatively well reflected in the analysis if the method is applied thoroughly. The manual generation of contour lines often incorporates the integration of further observational information such as the position of the snowline, date of ice emergence at individual locations, meteorological conditions on the glacier and other expert knowledge such as typical spatial patterns etc. This kind of information is difficult to capture in a purely objective or mathematical sense, nevertheless it often enhances the quality of the results and the spatial resolution of mass balance information.

Mass balance contour lines are then used to derive areas of equal mass balance where the mean value of the contour lines is assigned to the area between the lines. However, for this study we applied the contour line method in two different ways: Once in its purely traditional form creating areas of equal mass balance between the manually drawn contour lines of 250 $\mathrm{kg\,m^{-2}}$ equidistance, and once applying the Esri-ArcGIS interpolation tool *topo to raster*, which is based on the ANUDEM algorithm (e.g., Hutchinson, 2008; Hutchinson et al., 2011), to the hand drawn and digitized contour lines and the set of reanalyzed point values. The latter method results in mass balance rasters with a 1x1 m resolution which were subsequently spatially integrated to obtain the mean specific mass balance (~~Equations 3and 4~~Eq. (3) and (4)).

3.3.2 Automatic extrapolations

In contrast to the contour line based analyses, automatic extrapolation methods avoid subjective influences, are fast and relatively simple to apply but are subject to restrictions in realistically reproducing the spatial distribution of surface mass balance. We apply three fully automatic extrapolation procedures: (i) the profile method based on a linear regression of point measurements with altitude and the area-altitude distribution of the glacier (e.g., Escher-Vetter et al., 2009), (ii) the automatic extrapolation applying the *topo to raster* function and (iii) an inverse distance weighting procedure. While the contour based methods were applied making recourse of all available information for the respective year, the three automatic methods were based on a reduced but temporally consistent set of reanalyzed point measurements which in this context means that the number and position of the measurement points used in the calculations was kept (almost) constant. This was done in order to avoid noise related to changes in the measurement set up affecting the temporal mass balance signal. For winter balances the creation of a consistent set of point values was not possible due to large year-to-year differences in amount and spatial distribution of measurements.

3.4 Geodetic mass balance calculations

The geodetic mass balance of Langenferner for the period 2005 to 2013 and the sub-periods 2005 to 2011 and 2011 to 2013 was calculated based on differencing high resolution ($1\mathrm{m}$) DEMs from ALS data ~~(e.g., Abermann et al., 2010)~~ (Abermann et al., 2010) of the respective years. The total volume change ΔV was calculated by integrating the elevation change Δh at the individual pixel

k of length r of the co-registered DEMs ~~as follows (Zemp et al., 2013)~~following Zemp et al. (2013):

$$\Delta V = r^2 \cdot \sum_{k=1}^{K} \cdot \Delta h_k. \tag{7}$$

Subsequently the derived volume change ~~is~~ was converted to a geodetic mass balance over the period of record following ~~equation 8~~Eq. (8):

$$B_{geod.PoR} = \frac{\Delta M_{geod}}{\overline{S}} = \frac{\Delta V \cdot \overline{\rho}}{\frac{1}{2} \cdot (S_{t_0} + S_{t_1})}, \tag{8}$$

where $\overline{\rho}$ denotes a mean glacier density of $850 \pm 60\ \mathrm{kg\,m^{-3}}$ as proposed by Huss (2013) and $\overline{S}$ is the mean glacier area ~~at~~ between the two acquisition dates calculated as the mean of the extents at the beginning and the end (S_{t_0} and S_{t_1}) of the PoR.

3.4.1 Corrections for snow cover and survey date

The results of the geodetic surveys were corrected for differences in snow cover between the acquisition dates as follows:

$$\Delta M_{geod.corr} = \Delta M_{geod} + \left(\overline{h}_{s_{t_0}} \cdot \overline{\rho} - \overline{h}_{s_{t_0}} \cdot \overline{\rho}_{s_{t_0}}\right) - \left(\overline{h}_{s_{t_1}} \cdot \overline{\rho} - \overline{h}_{s_{t_1}} \cdot \overline{\rho}_{s_{t_1}}\right), \tag{9}$$

where $\Delta M_{geod.corr}$ denotes the geodetically derived mass change corrected for snow cover differences between the two acquisition dates t_0 and t_1, ΔM_{geod} is the uncorrected mass change, $\overline{h}_s$ denotes the mean snow depth (at dates t_0 and t_1 respectively), $\overline{\rho}$ the bulk glacier density and $\overline{\rho}_s$ the mean snow density at the acquisition dates t_0 and t_1.

In 2005, no field measurements were performed close to the ALS survey date. But field data from September 4^{th}, 2005 in combination with meteorological records of nearby AWS, as well as photographs from nearby glaciers, indicate that there was basically no snow cover at the date of the 2005 ALS campaign. Seasonal snow was hence regarded as negligible for glacier wide analyses in 2005. In 2011, in situ measurements were performed on September 30^{th}, four days prior to the ALS campaign. Despite the short time difference between direct and geodetic measurements, we applied a correction of the measured snow depths due to relatively warm weather conditions in this period. ~~Therefor~~For this purpose, the (optimized but untuned) mass balance model was initialized at all ablation stakes and a few additional locations using the measured snow depths and densities of September 30^{th} as initial condition. In 2013, extensive direct measurements were carried out simultaneously to the ALS campaign on September 23^{rd} ~~in order~~ to quantify the high amount of snow and firn in this year.

Survey date corrections were based on modeled mass change during the periods between ALS survey and direct measurements in the years 2005 and 2011, while in 2013 the correction was based on direct measurements performed on September 23^{rd} and September 30^{th}. Point values of snow and mass change were extrapolated using *topo to raster* ~~in order~~ to calculate glacier wide mean values for the individual properties. Mean specific mass changes (representing corrections for snow cover and survey date respectively) were finally added (subtracted) to (from) the geodetically derived mass change over the survey period.

3.5 Annual glacier topographies and outlines

Changes in glacier area and topography may have significant impacts on the mass balance of mountain glaciers through various feed-backs (e.g., Paul, 2010; Huss et al., 2012) and since respective data is used as input for glacier models, they constitute glaciological key information. Hence, there is a need to frequently update topographic reference data used in mass balance calculations (e.g., Zemp et al., 2013, 2015). Langenferner was subject to remarkable hypsometry changes during the study period (Fig. 4 and 6). While glacier outlines for the current study could be directly derived from ortho-photos or ALS data for all years except for 2004, 2007 and 2009, data on glacier topography is only available through the three ALS campaigns. In order to minimize the effect of outdated area and hypsometry we calculated annual glacier outlines and topographies by combining the available set of related data with the fields of reanalyzed annual surface mass balance. ~~For that~~ Doing so we consider the change in surface elevation Δh at one location (pixel) k of the glacier over the time period ~~t~~ t as the result of the following terms:

$$\Delta h_{k,t} = \Delta h_{surf_{k,t}} + \Delta h_{dyn_{k,t}} + \Delta h_{basal_{k,t}}, \tag{10}$$

where $\Delta h_{surf_{k,t}}$ denotes the surface elevation change related to surface mass balance, $\Delta h_{dyn_{k,t}}$ represents the surface change due to glacier dynamics and $\Delta h_{basal_{k,t}}$ is the surface change related basal (and internal) processes. As the latter term is assumed to be relatively small on the glacier wide scale (e.g., Cuffey and Paterson, 2010), it is neglected. The rasters of spatially extrapolated surface mass balance for each year (~~section~~ Sect. 3.3.1) and those referring to snow and date corrections (~~section~~ Sect. 3.4.1) can be summed up for the time period between the two geodetic surveys in order to calculate the term $\Delta h_{surf_{k,t}}$. Consequently, $\Delta h_{dyn_{k,t}}$ for the respective period can be calculated as follows:

$$\Delta h_{dyn_{k,t}} = \Delta h_{k,t} - \sum_{t_0}^{t_1} \Delta h_{surf_{k,t}} = (h_{k,t_1} - h_{k,t_0}) - \sum_{t_0}^{t_1} \Delta h_{surf_{k,t}}, \tag{11}$$

where h_{k,t_0} and h_{k,t_1} are the surface elevations at the pixel k given by the DEMs taken at date t_0 and t_1 respectively and $\sum_{t_0}^{t_1} \Delta h_{surf_{k,t}}$ refers to the temporally integrated elevation change due to surface mass balance. Due to the absence of data on the temporal evolution of glacier flow velocity, we assume the rate of Δh_{dyn_k} to be temporally constant during the observation period. This simplifies the calculation of the annual $\Delta h_{dyn_{k,a}}$ to:

$$\Delta h_{dyn_{k,a}} = \frac{\Delta h_{dyn_k}}{d_{PoR}}, \tag{12}$$

where d_{PoR} is the duration of the observation period in years. The result is a raster of $\Delta h_{dyn_{k,a}}$ which can be applied to all the observation years. The surface elevation of a certain year $h_{k,a}$ can finally be calculated by adding the surface elevation change due to surface mass balance in the respective year a and the annual change related to glacier dynamics to the surface elevation of the previous year $h_{k,a-1}$ (~~Equation 13)~~Eq. (13)).

$$h_{k,a} = h_{k,a-1} + \Delta h_{surf_{k,a}} + \Delta h_{dyn_{k,a}}. \tag{13}$$

The DEM taken at the end of the observation period ~~serves~~ served as a boundary condition for surface elevation at areas which become ice-free during the observation period in a way that all raster cells in those areas showing a surface height smaller than the surface of the ice free topography are set back to the value of the latter. Glacier outlines were derived by identifying ice-free pixels as having undergone no change in surface elevation.

Note that the term $\Delta h_{dyn_{k,a}}$ represents all the differences between the direct surface measurements and geodetically detected surface changes. These are not only differences which can be associated ~~which~~ with glacier dynamics, but also shortcomings in the spatial extrapolation of surface mass balance measurements and changes due to internal or basal processes. This problem does not affect the temporally-integrated topography change, but may lead to additional errors regarding annual surface topographies. Nevertheless, this simple method provides a possibility to annually update the reference area and topography used in the mass balance calculations and hence represents a useful tool for areas with large changes in surface elevation.

4 Uncertainty Assessment

In order to enhance the value of the reanalyzed mass balance record, a detailed error assessment was performed following the recommendations of Zemp et al. (2013). We categorized potential errors in the measurements and analyses into random (σ) and systematic (ϵ) errors. In the subsequent sections we discuss the origin of such errors related to the methods applied and explain how they were assessed. Thereby we primarily focus on random uncertainties, since systematic errors are difficult to quantify in the absence of an absolute reference for validation. In order to detect an eventually significant systematic bias in the reanalyzed record of annual balance, we finally perform a comparison of directly measured mass changes to those obtained by the geodetic method. The individual ~~errors~~ error sources and the respective numbers used in the uncertainty model are listed in the supplementary material of this paper.

4.1 Uncertainties of glaciological measurements

Uncertainties in glaciological mass balances may originate from various sources and can be categorized into errors in point measurements, errors related to spatial extrapolations of point measurements and errors due to inaccurate or outdated glacier extents (Zemp et al., 2013). The random error of the mean specific mass balance for an individual year ($\sigma_{glac.total.a}$) can consequently be formulated as follows:

$$\sigma_{glac.total.a} = \sqrt{\sigma^2_{glac.point.a} + \sigma^2_{glac.spatial.a} + \sigma^2_{glac.ref.a}}, \tag{14}$$

where $\sigma_{glac.point.a}$ is the error due to uncertainties on the point scale, $\sigma_{glac.spatial.a}$ represents errors related to spatial extrapolations and $\sigma_{glac.ref.a}$ accounts for uncertainties due to inaccurate glacier outlines. In this formulation $\sigma_{glac.point.a}$ is often misinterpreted since it does not represent the typical value of point scale errors but the uncertainty of glacier wide mass balances related to the propagation of point uncertainties after the extrapolation of measurements. This term does not only depend on the magnitude of point uncertainties, but also on the number and spatial distribution of point measurements. Hence, it requires thorough evaluation (Sect. 4.1.1).

4.1.1 Uncertainties related to point measurements

Random errors on the point scale mainly originate from inaccurate readings. This involves ablation and accumulation measurements equally. For ablation stakes the respective error is in the order of two or three centimeters. Limited representativeness of an ablation stake due to surface roughness is not really an error on the point scale but can introduce errors to the analysis when the data is extrapolated to larger areas. At Langenferner such surface features are typically $\leq 20\,\mathrm{cm}$ in height, although after long periods of exceptionally strong melt, surface structures were observed to reach the order of 30 to 50 cm in the lowest sections of the glacier.

For accumulation measurements the error potential is generally higher. Snow pits with measurements of snow depth and density offer the highest accuracy (~~$\approx$ 50kg $\mathrm{m^{-2}}$~~$\approx 50\,\mathrm{kg\,m^{-2}}$). But the number of snow pits is often kept low, as they are labor intensive and time-consuming. Snow probings are somewhat less accurate since they are affected by instrument tilt, by uncertainties in the spatial extrapolation of snow density and by possible difficulties in the determination of last summer's reference surface. The latter effect can lead to large errors on the point scale but is assumed to play a minor role in this study since most "outliers" could be identified due to the high number of probings in combination with snow pit information.

However, the impact of uncertainties in point measurements on glacier wide calculations depends on the amount of point measurements and their spatial distribution. To quantify this problem, we applied a bootstrap approach (e.g., Efron, 1979) in which random errors according to a defined normal distribution were applied to all available individual point measurements before calculating the glacier wide balance 5.000 times for each case using the inverse distance weighting method for extrapolation. The respective annual uncertainties are then given by the standard deviation of the 5.000 runs and range from 11 to 26 $\mathrm{kg\,m^{-2}}$ for annual balances and from 7 to 16 $\mathrm{kg\,m^{-2}}$ for winter balances.

4.1.2 Uncertainties in the extrapolation of point measurements

Similar to the ~~above problem~~propagation of point scale uncertainties, uncertainties related to the applied extrapolation method are also dependent on the number and distribution of point measurements, as well as to spatial balance patterns of the individual year or season. We assessed those uncertainties based on the analysis of the glacier wide reanalyzed mass balances obtained from the five extrapolation methods used. The annual extrapolation uncertainty in our study is finally represented by the absolute range of the bias corrected results ~~($r_{Brea_{bc}}$ in Table 1) ranging from 24~~ ranging from 23 $\mathrm{kg\,m^{-2}}$ (~~2013~~2006) to 134 $\mathrm{kg\,m^{-2}}$ (2008). Respective values for winter vary between 31 $\mathrm{kg\,m^{-2}}$ (2013) and 95 $\mathrm{kg\,m^{-2}}$ (2004). Note that for winter balances we used the range without bias correction (r_{Brea}) since the biases between the individual extrapolation methods were small and their origin could not be unequivocally explained.

4.1.3 Uncertainties due to inaccurate glacier outlines

Since for this study we make use of annual glacier outlines derived from orthophotos, ALS, or calculated as described in ~~section 3.5~~Sect. 3.5, our analyses are not systematically affected by this issue. Hence the remaining uncertainties related to this problem are given by the random uncertainties of the annual glacier areas. We estimated the related standard error to be 15

$\mathrm{kg\,m^{-2}}$. For the year 2005 we applied a more conservative estimate of 25 $\mathrm{kg\,m^{-2}}$, since the reference area for this year suffers from larger uncertainties ~~due to the fact that~~ as it was derived by manually up-dating the 2003 glacier extent with a few ~~GPS~~ GNSS points taken in 2004.

4.2 Uncertainties in geodetic mass balances

Uncertainties in the geodetic mass balance are mainly related to two problems: (i) errors in the used DEMs and (ii) uncertainties related to the conversion of the observed surface elevation changes to changes in mass. The over-all random error of the corrected geodetic mass balances can be expressed as:

$$\sigma_{geod.corr} = \sqrt{\sigma^2_{geod.total} + \sigma^2_{dc} + \sigma^2_{sc} + \sigma^2_{sd}}, \qquad (15)$$

where $\sigma_{geod.total}$ refers to the remaining uncertainties related to geodetic measurements after all applied corrections such as co-registration etc., σ_{dc} is the error related to density conversion, σ_{sc} refers to the error due to snow cover and σ_{sd} is the remaining error due to different survey dates compared to the glaciological method. Note that ~~equation 15differs from equation~~ Eq. (15) differs from Eq. (18) in Zemp et al. (2013) in two points: Firstly we split the uncertainties related to bulk glacier density and those introduced by differences in snow cover between the two survey dates. This is done because the available set of data allows for a sound quantification of snow cover. Secondly, we do not include the impacts of basal and internal processes since they neither represent an error in geodetic mass balance calculations nor could they be quantified in a sufficient matter in the frame of the current study. Nevertheless we discuss those effects in ~~section~~ Sect. 5.7.

4.2.1 Uncertainties in ALS measurements

~~In order to~~ To minimize systematic errors in the geodetic ~~analyses, a~~ analysis, the co-registration of the three ALS data sets was ~~performed including the roofs of~~ tested using the pitched roofs of six buildings belonging to three mountain huts in the vicinity of Langenferner ~~. Thereby no significant dependence of the errors to slope and aspect of the surface~~ (Zufallhütte, Rifugio Casati and Marteller Hütte). Following Joerg et al. (2012), the inclined roof surfaces enabled to check the data for a possible horizontal shift. However, no significant aspect-dependence of DEM differences could be detected ~~. The remaining uncertainty potential related to vertical errors after co-registration and due to~~ in the data sets used for this study. The vertical error due to uncertainties in the DEM and spatial auto-correlation $\sigma_{geod.total}$ for the individual survey periods ~~$\sigma_{geod.total}$ was estimated as~~ was tested by calculating the surface differences in stable reference areas outside the glacier. The surface difference in those areas is below $\pm$ 0.1 m for terrain with a slope angle below 40°. Since there are hardly any areas with slope angles of 40°or more at Langenferner, we used 0.15 ~~m. This value is based on tests over reference areas not involved in the co-registration and can be regarded as a quite solid~~ m as an upper threshold of possible vertical errors over the glacier area.

4.2.2 Uncertainties related to glacier density

In our study uncertainties related to unknown mean glacier density are reflected by the applied density range of 850 $\pm$ 60 $\mathrm{kg\,m^{-3}}$ (Huss, 2013). Based on the knowledge about the study area, such as the typical size of the accumulation area and the absence of large crevasse zones, we estimate the real near surface glacier density in the absence of seasonal snow to be in the range of 850 to 880 $\mathrm{kg\,m^{-3}}$.

4.2.3 Uncertainties due to snow cover and survey date differences

Uncertainties due to differences in snow cover at the two acquisition dates are difficult to estimate but we assume that they are quite small after we applied respective corrections (~~section~~ Sect. 3.4.1). Similar is true for uncertainties related to different acquisition dates between geodetic and glaciological surveys. Especially for the two longer periods (2005 to 2013 and 2005 to 2011), due to the drastic mass loss both errors are at least one order of magnitude smaller than the uncertainties related to the used bulk glacier density and are hence of minor importance. However, the respective errors for both problems were estimated as 100 $\mathrm{kg\,m^{-2}}$ for all (sub-) periods.

4.3 Method comparison

In order to check the reanalyzed record of annual mass balance for a significant systematic bias, we compare the results for the period 2005 to 2013 to the mass change inferred using the geodetic method. Doing so, it has to be considered that the two methods are subject to generic differences since the glaciological method only captures (near) surface mass changes, while the geodetic approach also detects volume (and mass) changes due to internal and basal processes. Consequently, we avoid using the term "validation" for the methodological cross check. Especially since we omit the explicit consideration of the above mentioned processes due to the fact that respective estimates without related measurements are speculative. However, method comparisons were performed for the period 2005 to 2013, as well as for the sub-periods 2005 to 2011 and 2011 to 2013.

After applying the corrections described in ~~section~~ Sect. 3.4.1, the reduced discrepancy δ (Zemp et al., 2013) between the two methods can be calculated as

$$\delta = \frac{\Delta PoR}{\sigma_{common.PoR}} = \frac{B_{glac.PoR} - B_{geod.PoR}}{\sqrt{\sigma^2_{glac.PoR} + \sigma^2_{geod.PoR}}}. \tag{16}$$

Agreement between the two methods can be assumed within the 95 % (90 %) confidence interval if $|\delta| < 1.96$ ($|\delta| < 1.64$). See Zemp et al. (2013) for a detailed description of this test.

5 Results and Discussion

5.1 Modeled annual point mass balance

Overall, 80 values of annual point mass balances were calculated using the presented model approach. For 33 of those cases field measurements are available which allows for independent validation of the applied approach, yielding a root mean square deviation (RMSD) of 128 $\mathrm{kg\,m^{-2}}$ and ~~an~~ a R^2 of 0.96 between modeled and measured values (Fig. 7). The magnitude of this error is similar to the uncertainty of glaciological point measurements reported in the literature (e.g., Thibert et al., 2008; Huss et al., 2009; Carturan et al., 2012), and ~~since~~ is lower than reported uncertainties of statistical approaches (e.g., Carturan et al., 2009; Thibert and Vincent, 2009). Since no significant systematic errors such as biases for single stakes or years are detectable, the 47 ~~newly-created point values of annual mass balance~~ newly created point values constitute a valuable basis for the reanalysis of the glacier wide annual balance. ~~Note that in years~~ Despite the convincing performance, the transferability of the approach is restricted by several factors. First the method is based on data from nearby AWS which are not available for every glacier. Second, the model in its current form cannot be applied to years / locations with persisting snow cover ~~the model could not be applied in its current form. Hence for~~ since it is based on observations of the emergence of last years reference surface. However, snow line observations could for instance be replaced by snow measurements taken at some time in summer. As such observations at Langenferner are missing in 2010 and 2013, the mass balance ~~of~~ at only a few ~~stakes~~ stake locations could be modeled in these years. This reduced the number of validation points but did not affect the reanalysis procedure, since measurements for these years ~~measurements at all stake locationsare available~~are available at most stake locations.

5.2 ~~Mean~~ Glacier wide specific annual mass balance

Mean specific annual mass balances and their altitudinal distribution (Fig. 6 and Tab. 2) were calculated based on the homogenized set of measured and modeled point values, applying five different extrapolation methods and using the set of newly created annual glacier outlines and topographies. The results for the two contour-line based extrapolation methods are almost identical and differ by only 0 to 5 $\mathrm{kg\,m^{-2}}$ ($\cancel{RMSD < 2}$ $RMSD \leq 3$ $\mathrm{kg\,m^{-2}}$). Consequently, we chose the results obtained by the raster-based contour line method as our reference since this method has the advantage of being less labor intensive than the traditional contour method and it results in high resolution (1x1 m) grids of surface mass balance which were also used to calculate annual glacier topographies and outlines (~~Section~~ Sect. 3.5).

The results show a persistent mass loss in all observation years. For the reference method, single year numbers vary between -1556 $\pm$ 47 $\mathrm{kg\,m^{-2}}$ in 2012 and ~~-247~~ -246 $\pm$ 31 $\mathrm{kg\,m^{-2}}$ in 2013, with a study period average of ~~-1138~~ -1137 $\pm$ ~~80~~ 79 $\mathrm{kg\,m^{-2}}$ (Fig. 8 and ~~Table~~ Tab. 1). While all applied extrapolation methods display a common signal in terms of inter-annual mass balance variability ($R^2 > 0.98$), the three automatic extrapolations yield ~~mass-balances~~ mass balances which are considerably more negative than those obtained by the contour line approaches (~~Table 2~~see Tab. S5 in the supplementary material). The respective biases are -249 $\mathrm{kg\,m^{-2}}$ for the *topo to raster*-based automatic method, ~~-188~~ -189 $\mathrm{kg\,m^{-2}}$ for the profile method and ~~-246~~ -247 $\mathrm{kg\,m^{-2}}$ for inverse distance weighting (Fig. 9). Those negative biases can be well explained by the under-representation of accumulation areas in the consistent set of point balances ~~on which both~~ (Sect. 3.3.2) on which the three automatic methods are based. This problem is not reflected in the contour line based calculations since those benefit from snow-line observations, sporadic accumulation measurements and at least a rough knowledge about the amount of accumulation and its spatial distribution. The availability of a few continuous accumulation measurements at fixed locations would strongly reduce the biases of ~~objective~~ automatic extrapolations and would enable the calculation of the glacier wide mass balance based on a reduced number of point observations and simplified extrapolations. However, this would lead to a loss of information on the spatial pattern of surface mass balance which constitutes an important component of modern and high level glacier mass balance monitoring as it is an important source of information for studies on energy balance and other glacier surface processes.

A comparison of the reanalyzed mass balance series to the original record shows that the two records strongly differ in their inter-annual variability ($R^2 = 0.84$), though the bias of the original series (-58 $\mathrm{kg\,m^{-2}}$) is relatively small (Fig. 9, Tab. 2). Differences for single years are highest for the years 2004 and 2008 when they reach 384 $\mathrm{kg\,m^{-2}}$ and ~~317~~ 319 $\mathrm{kg\,m^{-2}}$ respectively. For ~~six~~ five of the ten observation years, differences between the original record and the reanalyzed series exceed the uncertainty range of the reanalyzed reference values. These large differences can mainly be attributed to two causes: (i) the lack of measurements in the upper glacier part during the first half of the study period and the hence insufficient representation of spatial mass balance patterns in the extrapolation of point measurements, and (ii) the usage of outdated glacier extents which in our case biases the calculated glacier wide annual balances towards more negative values. The latter problem at Langenferner leads to a negative bias of typically about 20 $\mathrm{kg\,m^{-2}}$ after only one year. After only a few years without up-dating the glacier outlines this effect can reach the order of 100 $\mathrm{kg\,m^{-2}}$. This matter is particularly affecting the original mass balance of 2004. For this first observation year, the original analyses were based on glacier outlines of 1996 (Fig. 2) since newer topographic data at this time were not available. ~~The results of all applied extrapolation methods~~

Finally, the diligent consideration of snow line information in the reanalyzed series enabled a more accurate determination of important glaciological key parameters such as ELA and AAR in the individual observation years. All relevant results of the reanalysis, as well as the original ~~balance numbers and glaciological key-numbers~~ numbers for mass balance, ELA and AAR are listed in ~~Table 1.~~ Tab. 1. For annual and seasonal results of all extrapolation methods the reader is referred to the supplementary material.

5.3 ~~Mean~~ Glacier wide specific seasonal balance

In contrast to annual mass balances, no modeling was involved in the calculations of the winter mass balances. However, the same extrapolation methods as used for the calculation of annual balances were applied to derive glacier wide winter balances. Again the two contour line based approaches displayed very similar results. For winter mass balances the differences between the two methods are slightly larger than for the annual balances which can be explained by smaller spatial balance gradients and consequently a lower spatial density of contour lines. Nevertheless, the differences for single years do not exceed 12 $\mathrm{kg\,m^{-2}}$. The mean fixed date winter balance for the study period is 929 $\pm$ 52 $\mathrm{kg\,m^{-2}}$ with a maximum of 1267 $\pm$ ~~37~~ 34 $\mathrm{kg\,m^{-2}}$ in the wet accumulation period of 2009. The exceptionally dry and warm winter 2007 resulted in the lowest value of 558 $\pm$ ~~46~~ 44 $\mathrm{kg\,m^{-2}}$. Note that in this winter period, the ~~lower most~~ lowermost parts of the glacier displayed negative mass balance due to considerable ice melt in late autumn 2006. Except for the year 2011, all reanalyzed winter mass balances are less positive than the original values (bias of original record = 71 $\mathrm{kg\,m^{-2}}$). This can be explained by the fact that all applied corrections in our case generally lower the mass balance value and more positive values can only be the result of differences in the spatial extrapolation of point values or the use of different glacier extents which both have little impact ($< 50\ \mathrm{kg\,m^{-2}}$) on the winter balance at Langenferner due to generally small spatial ~~(altitudinal) gradients in winter mass balance~~ winter balance gradients at this specific glacier.

The correlation between the original and reanalyzed records of winter mass balance is larger (~~$R^2 = 0.90$~~R^2 =0.90) than for annual balances which can be explained by the fact that the same set of point measurements has been used for both series and that differences in glacier wide values can mainly be attributed to the corrections applied to the original data set (~~section~~ Sect. 3.1). Nevertheless, differences between the original and the reference record exceed the corresponding random uncertainties for six out of ten winter periods. The homogenization of original winter balance point measurements revealed that the re-calculation of point winter balances according to the fixed date system generally showed the largest impact of the applied corrections. For the year 2010, the effect of this correction reached 140 $\mathrm{kg\,m^{-2}}$ on the glacier wide scale (17 % of the winter net accumulation). Corrections for snow of the previous hydrological year were showing a smaller effect but are still in the order of up to 100 $\mathrm{kg\,m^{-2}}$ on the glacier wide scale. For 2011, when the corresponding corrections were already applied in the original series, skipping ~~the~~ this correction would change the mean specific winter balance by more than 200 $\mathrm{kg\,m^{-2}}$. The impact of ice ablation during the hydrological winter period was greatest in the years 2004 and 2006 when it reached the order of 30 and 55 $\mathrm{kg\,m^{-2}}$ respectively. On the point scale respective values reach the order of 300 $\mathrm{kg\,m^{-2}}$ in the lower most glacier part which, in this very dry and warm winter, resulted in a negative fixed date winter balance at the lower part of the glacier tongue. For glaciers with large tongues reaching low elevations or with large sun-exposed area fractions, this issue may be of even higher relevance than at Langenferner.

~~Summer balances suffer from the largest uncertainties since they are calculated as a residual from annual and winter mass balances and are hence affected by the uncertainties in both series. Absolute values~~ Values of summer mass balance range from -2488 ± ~~73~~ 71 $\mathrm{kg\,m^{-2}}$in 2012 to ~~-1463~~-1336 ± ~~47~~ 99 $\mathrm{kg\,m^{-2}}$ in ~~2013.~~ 2010. Differences between original and reanalyzed summer mass balances exceed the uncertainties of the reanalyzed series in ~~seven~~ eight out of ten observation years reaching up to ~~445~~ 446 $\mathrm{kg\,m^{-2}}$ in 2004. A comparison of the two series yields R^2 of 0.70 while between the individual reanalysis series R^2 is ≥ 0.97. Summer balances suffer from the largest uncertainties as they are calculated as a residual from annual and winter mass balances and are hence affected by the uncertainties in both series.

5.4 ~~Geodetic~~ Integration of meteorological data in mass balance ~~2005-2013The~~ observations

The aim of the present study was, amongst others, the creation of a best possible estimate of Langenferner's mass balance during the study period serving as a reference for further investigations on the glacier. But, as already stated in Sect. 3.2, the integration of meteorological data in observational records of glacier mass balance may be problematic because there is a risk of circular reasoning: observational series of glacier mass balance are often used in investigations of glacier response to climate forcing. We argue that this risk is limited since a large part of the systematic influence that meteorological data could have on our time series is cancelled out by the calibration of $\Gamma_{i,a}$ and the constraint of matching snow observations. However, this paper and the supplements provide full insight into the applied reanalysis process and all data partly or fully resulting from the integration of meteorological data are clearly flagged in the tables or in data published through the WGMS or elsewhere. This enables a case-individual user decision on whether these data are suitable for a specific purpose or not.

5.5 Geodetic mass balance

The mean surface elevation change at Langenferner during the eight-year period 2005 to 2013 amounts to -10.35 $\pm$ 0.21 m. Surface elevation changes in the lower most glacier part reach the order of -40 m while in the highest regions changes in the order of one to three meters are detectable (Fig. 4). Assuming a bulk glacier density of 850 $\pm$ 60 $\mathrm{kg\,m^{-3}}$, this corresponds to an uncorrected geodetic mass balance of -9397 $\pm$ ~~687~~691 $\mathrm{kg\,m^{-2}}$. The correction for differences in snow cover between the two acquisition dates changes the result to -9596 $\pm$ 694 $\mathrm{kg\,m^{-2}}$. Note that the values slightly differ from those (-9381 and -9702 $\mathrm{kg\,m^{-2}}$) presented by Galos et al. (2015) since the study in hand makes use of reanalyzed data sets. ~~The~~ For the two sub-periods 2005 to 2011 and 2011 to 2013 the uncorrected geodetic balances are -7439 $\pm$ 558 and -1908 $\pm$ 228 $\mathrm{kg\,m^{-2}}$ respectively. The corrected values change to -7436 $\pm$ 560 and -2084 $\pm$ 248 $\mathrm{kg\,m^{-2}}$ showing that especially the snow cover correction for the short period 2011 to 2013 leads to a large relative change (-9 %) in the result. The results of the geodetic analyses ~~(including those for the sub-periods 2005-11 and 2011-13)~~ are summarized in ~~Table 3~~ Tab. 3 including raw and corrected values, as well as numbers for the individual corrections applied.

5.6 Uncertainties in glaciological and geodetic balances

The largest source of uncertainties in the ~~reanalized~~ reanalyzed glaciological record is the spatial extrapolation of ~~of~~ point measurements. The largest spread between individual extrapolation methods is shown in the years 2008 and 2009 in which the negative off-sets of the automatic extrapolation methods are especially large. We attribute this to very strong spatial mass balance gradients in these two years given by the fact that mass balances at stake locations were quite negative, but at the same time snow of the previous winter could sustain throughout the summer in concavely shaped areas of the upper glacier part. While these patterns are reflected in the contour line based extrapolations, automatic methods did not capture this due to missing measurements in the respective areas. This shows the importance of the integration of accurate snowline observations in calculations of glacier mass balance (e.g., Østrem and Brugman, 1991; Kaser et al., 2003). For winter balances the largest extrapolation uncertainties occur in in 2004 when only 22 point measurements are available. However, this number would most probably be sufficient if the measurements were well distributed over the glacier area (Jansson1999) which was not the case in that year. For both, annual and winter mass balances, the second largest uncertainty source is given by the uncertainties ~~of~~ related to point measurements. For annual balances they are in the order of ~~25~~ 22 $\mathrm{kg\,m^{-2}}$ while for winter balances they range from 7 to 16 $\mathrm{kg\,m^{-2}}$ due to the generally higher number of measurements combined with less distinct spatial mass balance gradients. Uncertainty terms for all years and seasons are presented in the supplementary material.

Uncertainties in the corrected geodetic balances are mostly determined by the applied density range of 850 $\pm$ 60 $\mathrm{kg\,m^{-3}}$. Other error sources only account for a few percent of the total random error, except for the short period 2011 to 2013, when the remaining uncertainty of the ~~DEMs~~ DEM exceeds the uncertainty related to the density assumption.

5.7 Glaciological versus Geodetic Method

Applying ~~equation 16~~Eq. (16) to the results of our glaciological reference method yields δ-values between ~~0.54~~ 0.55 and 1 (~~Table~~ Tab. 3) indicating that there is agreement between the glaciological and the geodetic results well within the 90 % confidence interval (Zemp et al., 2013; Sold et al., 2016). Hence, a ~~further~~ calibration of the reanalyzed glaciological record is not necessary although we did not yet account for internal or basal melt.

The results of the profile method also fulfill the above criteria for all three (sub-) periods and could hence also be regarded as acceptable. The point to raster and inverse distance weighting methods fulfill the 90 % confidence criteria only for the period 2011 to 2013 but results are within the 95 % confidence bounds for the other periods (~~Table~~ Tab. 4). However, the three automatic extrapolation methods yield results which are persistently more negative than the geodetic method (Fig. 10), while from a physical perspective, the geodetic method, especially during periods of strong glacier mass loss, can generally be expected to display results more negative than the glaciological method due to the effect of internal and basal melt processes.

5.7.1 The role of basal and internal melt

Several studies have shown, that basal and internal melt can be important contributors to total glacier ablation, depending on the specific glacier and the climatic setting (e.g., Alexander et al., 2011; Oerlemans, 2013; Andreassen et al., 2016). Generally, the most important sources of energy for subsurface melt on temperate glaciers are related to the conversion of potential energy by water run-off inside and at the base of the glacier. The water may originate from precipitation and other accumulation processes or may enter the glacier from outside. In the latter case the water may be warmer than 0°C and hence can offer an additional source of thermal energy. Other contributors to basal and internal melt are the geothermal heat flux and the conversion of potential energy related to glacier dynamics (deformation and basal friction).

In order to provide a rough estimate of subsurface melt processes at Langenferner, we calculated the melt-contribution of water run-off. We applied a similar approach ~~than~~ as used by Andreassen et al. (2016), but instead of precipitation, we considered water released by melt (Thibert et al., 2008), which was approximated by the reanalyzed summer mass balance. Liquid precipitation instantly running off the glacier and water from outside the glacier were neglected since both play a minor role at Langenferner. For the period 2005 to 2013 our calculation gives a total value of 178 $\mathrm{kg\,m^{-2}}$. Melt caused by geothermal heat and glacier dynamics is estimated based on values in the literature (e.g., Thibert et al., 2008; Alexander et al., 2011; Sold et al., 2016) as 10 $\mathrm{kg\,m^{-2}\,a^{-1}}$ and 1 $\mathrm{kg\,m^{-2}\,a^{-1}}$ respectively. However, combining the estimates for ~~the~~ all the mentioned individual contributors during the eight year period 2005 to 2013 results in a total subsurface melt of 266 $\mathrm{kg\,m^{-2}}$, which explains about 37 % of the difference between the glaciological and the geodetic method during the same period.

After re-calculating the reduced discrepancy δ (~~Equation 16)~~Eq. (16)) taking the estimate for subsurface melt into account, the contour line based extrapolation methods show the best agreement with the geodetic results (~~Table~~ Tab. 4). While the results of the profile method are still acceptable on the 90 % confidence interval for the periods 2005 to 2013 and 2011 to 2013 and on the 95 % confidence interval for the period 2005 to 2011, the results of the other two automatic methods ~~are not acceptable~~

(point to raster and inverse distance weighting) neither fulfill the 90 % nor the 95 % criteria for 2005 to 2013 and 2005 to 2011 respectively.

6 Conclusions

In this paper we have presented a detailed work-flow for reanalyzing series of annual and seasonal glacier mass balances. The approach was applied to the ten-year record of Langenferner, a small glacier in the Italian Eastern Alps. Existing sets of annual and seasonal point mass balance data were homogenized based on methodological corrections and ~~on~~ were completed by pseudo observations of point mass balance obtained by a physical model. Based on the homogenized point data, glacier wide mass balances were re-examined using a variety of extrapolation methods. Finally a detailed uncertainty assessment was performed including a cross check of glaciological results to those obtained by the geodetic method.

The reanalysis revealed that common problems often neglected in mass balance analyses can significantly disturb the derived ~~interannual~~ inter-annual mass balance signal. Comparing the reanalyzed results to those of the original record yielded differences in annual mean specific mass balances of up to 384 $\mathrm{kg\,m^{-2}}$. This by far exceeds the uncertainties of the renalyzed values, which are in the range of 31 to 136 $\mathrm{kg\,m^{-2}}$. Considering that two mass balance series for the same glacier and time period are compared, the correlation of the two records is rather low ($R^2 = 0.84$). This misfit for annual balances could mainly be attributed to missing point measurements for the upper glacier part in the original data series.

In the reanalysis, this drawback was overcome by applying a process based mass balance model. After a Monte-Carlo based parameter optimization, the performance of the model was enhanced through individual precipitation tuning for every stake and year using the observed date of ice emergence as a constraint. The validation of modeled annual point balances against independent observations showed a RMSD of 128 $\mathrm{kg\,m^{-2}}$ which is comparable to the uncertainties of glaciological point measurements reported in the literature. The applied model approach can consequently be regarded as a useful tool to generate additional accurate point mass ~~balance information and to integrate auxiliary~~ balances given that meteorological data and snow line information such as time lapse photos or satellite images ~~into glacier mass balance analyses~~are available.

Uncertainties due to missing updates of rapidly changing glacier geometries represent another important source of uncertainty, especially for annual balances. In our case this problem causes errors in the order of 20 $\mathrm{kg\,m^{-2}}$ after only one year growing almost linearly within the study period. To tackle this problem we presented a method which enables the calculation of annual glacier outlines by combining geodetic information on glacier topography and measured surface mass balance.

For winter balances the correlation between original and reanalyzed record is higher ($R^2 = 0.90$) than for annual balances which can be explained by the generally sufficient amount and spatial distribution of winter mass balance measurements. Winter balances at Langenferner are also less sensitive to changes in the spatial distribution of measurements and to missing updates of glacier geometry since in most years there is no significant altitudinal gradient in winter mass balance. Differences between the original and reanalyzed series of winter mass balance mainly originate from the fixed date correction which was applied in the course of the reanalysis. Corrections for snow from the previous hydrological year are also of considerable importance while ice melt at the beginning of the hydrological year only plays a role in two years.

~~A~~ We also presented a thorough uncertainty analysis which is transferable to other sites independently from the physical model applied in this study. The analysis revealed that the typical random uncertainty of the reanalyzed mass balances is in the order of ~~80~~ 79 $\mathrm{kg\,m^{-2}}$ for annual and about 52 $\mathrm{kg\,m^{-2}}$for winter mass balances. Numbers for single years / seasons range from 31 $\mathrm{kg\,m^{-2}}$ to 136 $\mathrm{kg\,m^{-2}}$. The largest part of the uncertainties can be attributed to the extrapolation of point values to the glacier scale which apparently do not only depend on the amount and distribution of measurement points, but also on annual characteristics such as spatial balance gradients. The propagation of point scale uncertainties to the glacier scale constitutes the second largest error source in our study with typical values of 22 $\mathrm{kg\,m^{-2}}$ for annual and 10 $\mathrm{kg\,m^{-2}}$ for winter balances. Finally, the comparison of the cumulative reanalyzed glaciological mass balance over the period 2005 to 2013 to the geodetic mass balance over the same period yields agreement between the two methods indicating that there is no significant bias between the two methods and a calibration of the glaciological results is hence not required.

While the ~~bias correction~~ calibration (bias correction) of glaciological series based on geodetic measurements has become a common procedure in the reanalysis of glacier mass balance records, the current study also addresses the inter-annual mass balance variability, as well as related uncertainties~~, a problem which has yet rarely been considered~~. In order to increase the value of mass balance series and to better understand underlying processes, future studies should address this matter by the integration of multi-source data combined with sound uncertainty analyses.

7 Data availability

All mass balance data resulting from this study were submitted to the world glacier monitoring service. Reanalyzed point values for annual and winter mass balance are listed in the supplementary material of this paper. Any further data or information is available on request at the ACINN.

Author contributions. SG designed the study, conducted the gross part of the analyses and wrote the manuscript, CK processed ALS data sets and performed a series of GIS calculations, FM contributed to the study design and performed the boot-strap calculations, LN contributed to the paper design and writing, FC created most of the figures, LR provided the 2011 ALS data and information on ALS uncertainties, WG performed the Monte-Carlo model optimization, TM provided the mass balance model and related information. GK helped to refine the manuscript and is the leader of the scientific project under which the study was carried out. All authors helped to improve the manuscript.

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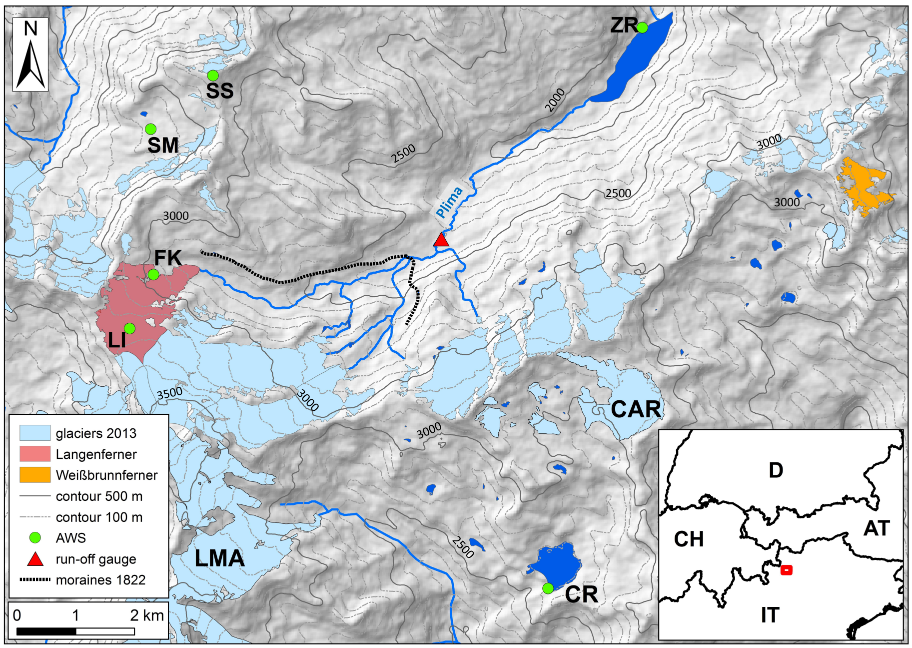

Figure 1. Overview of the study area. Langenferner is shown in red, Weißbrunnferner in orange, other glaciers in light blue (glacier outlines of 2013 derived from ALS (Galos et al., 2015)). Green dots indicate ~~AWSs~~ AWS referred to in this study: Zufritt Reservoir (ZR), Schöntaufspitze (SS), Sulden Madritsch (SM), Felsköpfl (FK), Langenferner Ice (LI) and Careser Dam Station (CR). The labels LMA and CAR refer to two other glaciers with mass balance measurements: La Mare and Careser (e.g., Carturan et al., 2012).

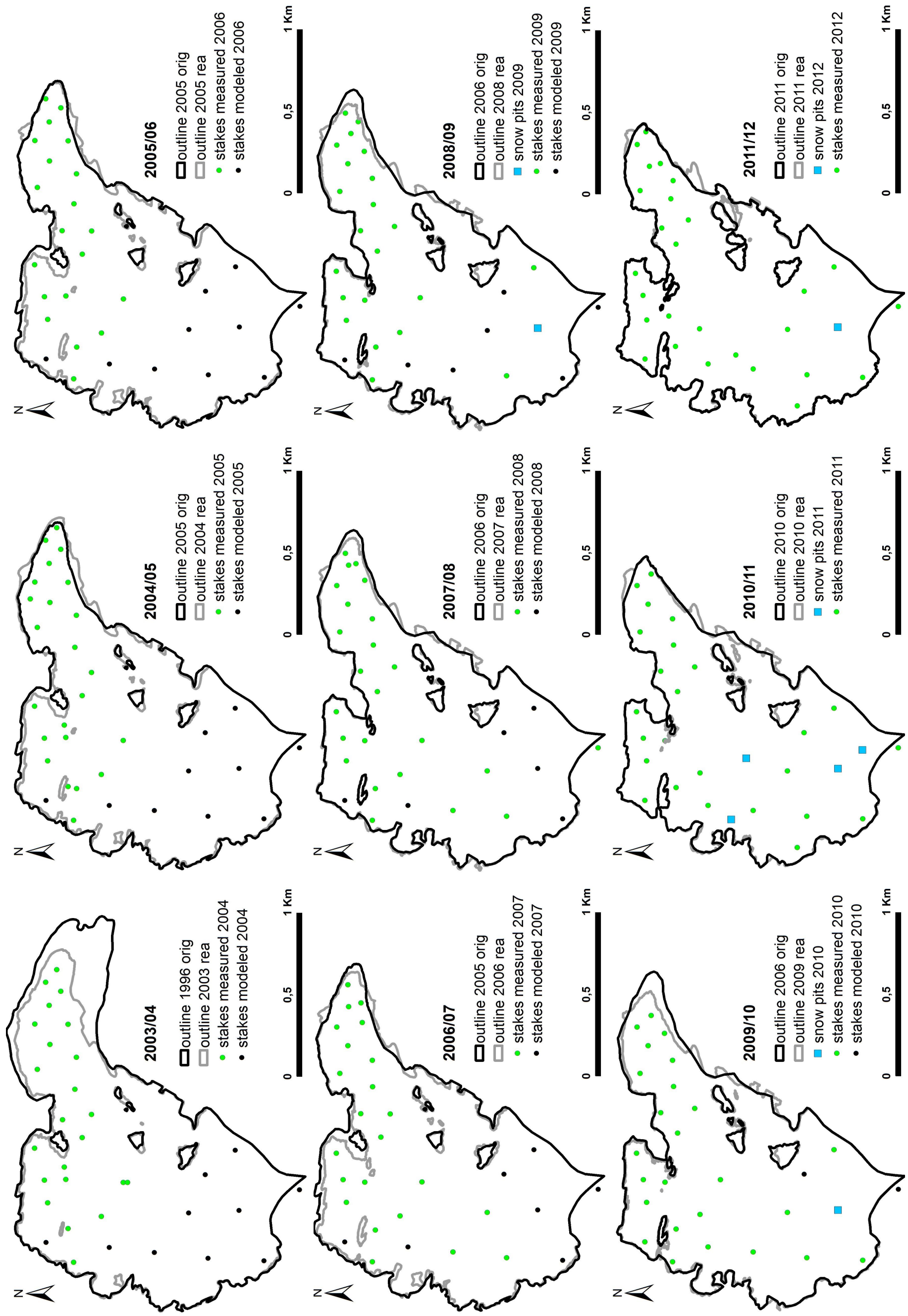

Figure 2. ~~Changes in~~ Measured and modeled point balances as used for the calculation of annual ~~data basis for mass~~ balance ~~calculations~~ at Langenferner. Black glacier outlines are those used in the original analyses while gray lines refer to the reanalyzed outlines used in this study. Green and blue symbols indicate direct measurements which were used in the original analyses and after homogenization also in this study. Black dots symbolize modeled point values generated and used in the reanalysis.

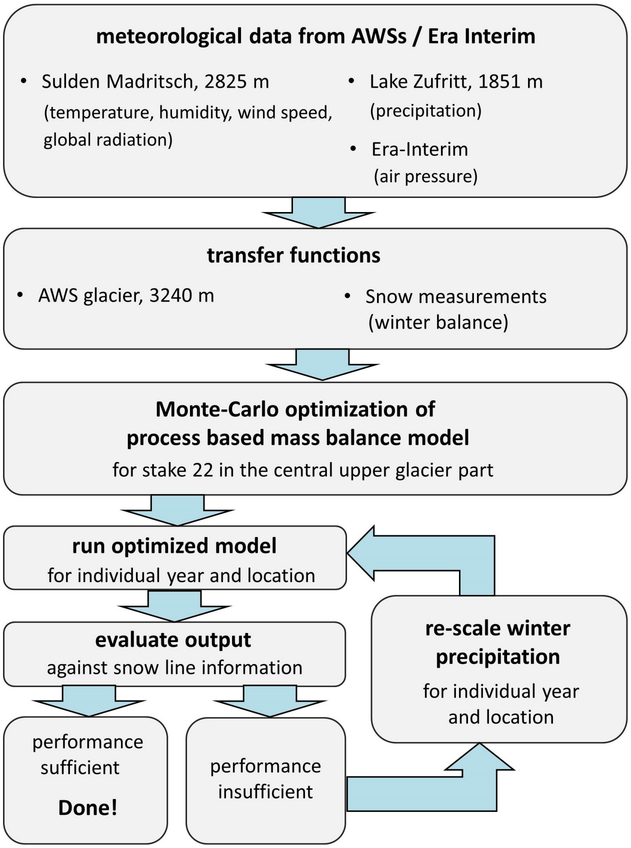

Figure 3. ~~Flow~~ Schematic flow chart ~~of~~ illustrating the applied model approach.

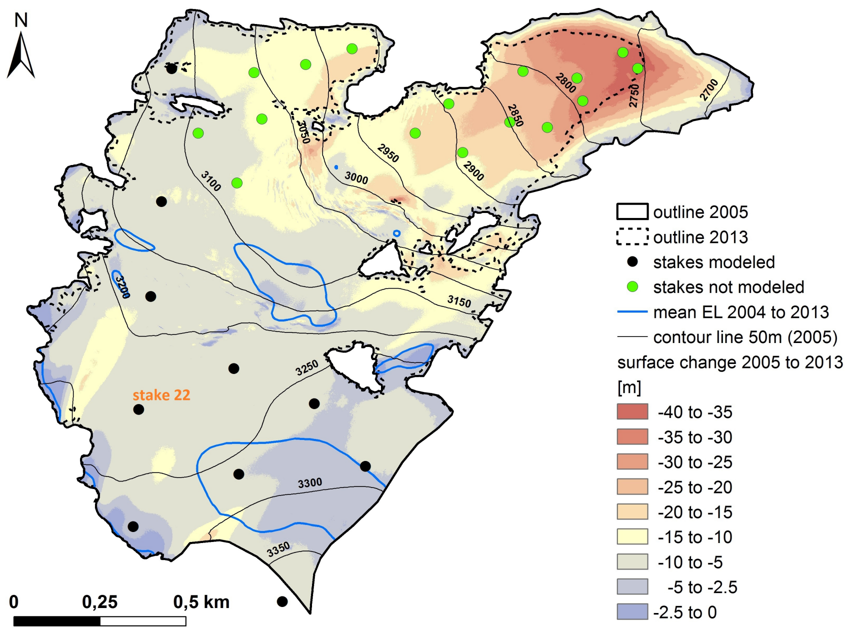

Figure 4. ~~Surface~~ ALS-derived surface elevation change ~~derived from airborne laser-scanning~~ at Langenferner for the period September 2005 to September 2013. Also shown are the ~~locations of~~ stakes used for the automatic extrapolation schemes, where black dots refer to ~~stakes~~ locations to which the mass balance model was applied. The blue line indicates the equilibrium line at the end of the hydrological years averaged over the study period.

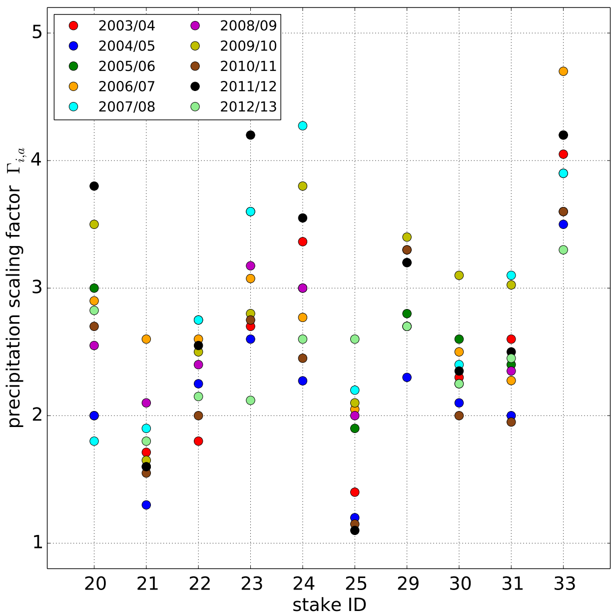

Figure 5. Precipitation scaling factors Γ for different locations $(_i)$ and years $(_a)$.

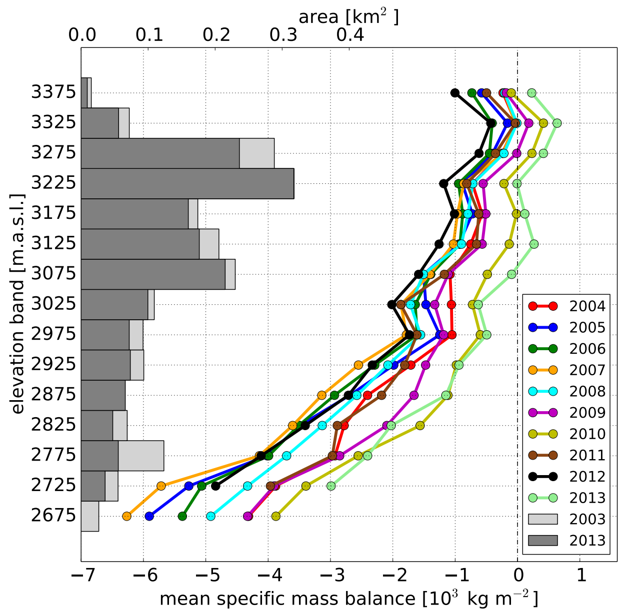

Figure 6. ~~Vertical profiles~~ Altitudinal distribution of ~~the~~ reanalyzed annual mass balances~~and the altitudinal area distribution~~ , as well as of the glacier surface area at the beginning (2003) and the end of the study period (2012).

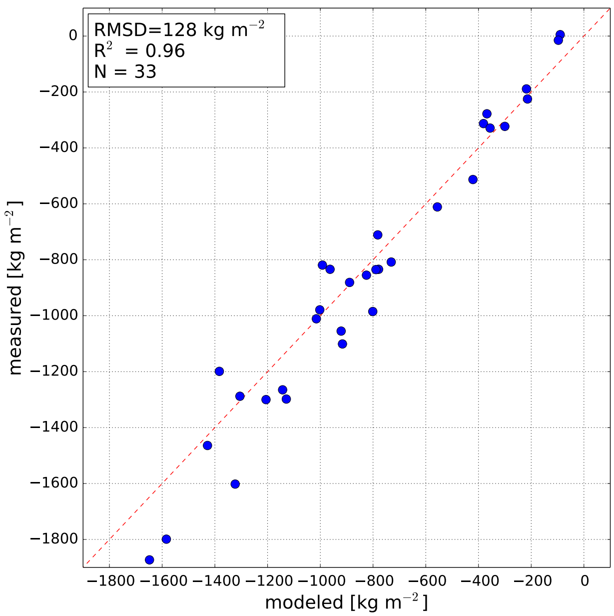

Figure 7. Scatter plot of modeled annual point mass balances against observations.

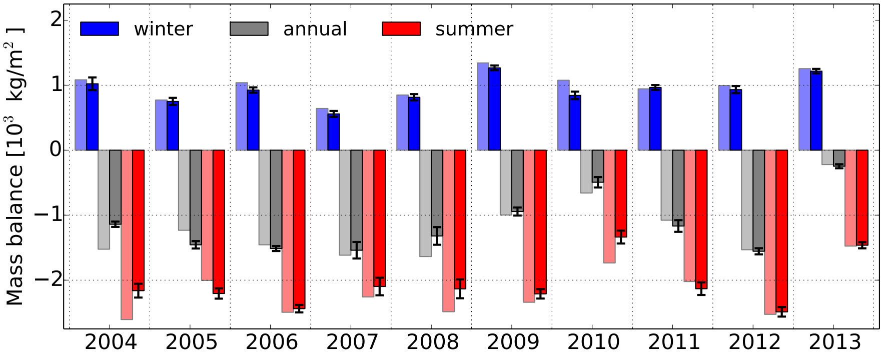

Figure 8. Original and reanalyzed seasonal mass balances at Langenferner during the study period. Error bars account for random uncertainties of the reference method as calculated in this study.

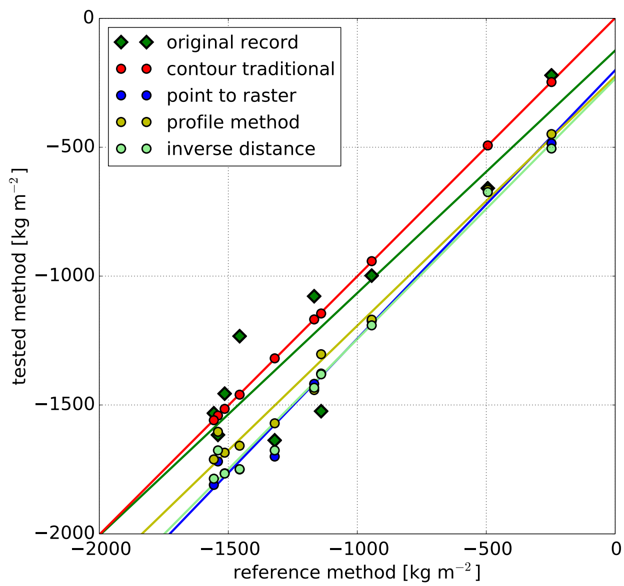

Figure 9. ~~Scatter-plot of the annual results~~ Annual mass balances as obtained ~~by~~ from the different extrapolation methods plotted against the results of the reference ~~values~~method. Basic statistics related to this plot are shown in Tab. 2.

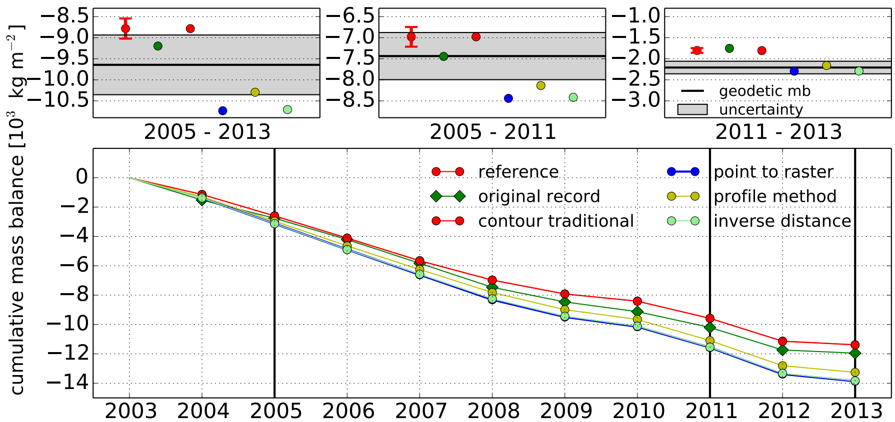

Figure 10. Comparison between geodetic and glaciological mass balances for three periods (upper three sub plots) and cumulative series of annual mass balance calculated using the ~~five~~ set of extrapolation methods described in the paper.

Table 1. Reanalized and original annual and seasonal mass balances and corresponding glaciological key numbers for Langenferner. ~~B_{ref} refers to~~ S_{rea} stands for the ~~reanalized mass balance calculated by~~ glacier area used in the ~~reference method~~reanalysis, ~~$\sigma_{glac.tot}$~~ N_{tot} is the ~~related random uncertainty~~total number of point mass balances used for glacier wide reanalysis calculations, ~~S_{rea}~~ N_{mod} is the ~~glacier area at the beginning~~ number of modeled point balances, B_{ref} is the ~~respective year~~resulting glacier wide specific balance, ~~ELA~~ $\sigma_{glac.tot}$ is the total random error, ELA_{ref} and ~~AAR~~ AAR_{ref} are the ~~corresponding equilibrium line altitude~~ reanalyzed ELA and ~~accumulation~~ AAR. S_{orig} is the glacier area ~~ratio~~used in the original series, B_{orig} ~~refers to~~ is the original ~~mass~~ glacier wide specific balance~~series. B_{clt}, B_{ptr}, B_{prm}~~ ELA_{orig} and ~~B_{ind} refer to~~ AAR_{orig} are the ~~results of the other four extrapolation methods used (contour traditional, point to raster, profile method~~ original ELA and ~~inverse distance weighting.~~ AAR and $_{orig-ref}$ ~~is~~ refers to the difference between ~~the~~ original and ~~the reference method, $r_{B_{rea}}$ the absolute range of the~~ reanalyzed record. Bold entries refer to results ~~of all five reanalysis methods and $r_{B_{rea.bc}}$ is the same range after a bias-correction of the individual series~~which are influenced by mass balance modeling.

Annual				
$Year$	S_{rea}	N_{tot}	N_{mod}	
	km^2			
2004	~~-114041~~1.938	~~>3400~~**32**	~~12~~**10**	
2005	~~-145659~~1.864	~~>3400~~**33**	~~5~~**10**	
2006	~~-151438~~1.833	~~>3400~~**30**	~~4~~**10**	
2007	~~-1540127~~1.821	~~>3400~~**30**	~~5~~**7**	
2008	~~-1320136~~1.785	~~>3400~~**32**	~~11~~**6**	
2009	~~-94462~~1.754	~~3278~~**30**	~~18~~**7**	
2010	~~-49482~~1.722	~~3249~~**28**	~~37~~**2**	
2011	~~-116790~~1.693	~~>3400~~29	~~7~~0	
2012	1.659	28	0	
2013	~~-247311~~1.620	~~3088~~100	~~50~~0	
Winter				
~~$Year$~~2004	~~B_{ref}~~1.938	~~$\sigma_{glac.tot}$~~22	~~S_{rea}~~0	~~$ELA\, AAR\, B_{orig}\, B_{clt}\, B_{ptr}\, B_{prm}\, B_{ind}$~~
2005	~~75055~~1.864	~~<2600~~87	~~1000~~	
2006	~~92542~~1.833	~~<2600~~47	~~1000~~	
2007	~~558~~1.821	~~46~~48	~~1.821~~0	
2008	~~81449~~1.785	~~<2600~~36	~~1000~~	
2009	~~126737~~1.754	~~<2600~~61	~~1000~~	
2010	~~84358~~1.722	~~<2600~~80	~~1000~~	
2011	~~96537~~1.693	~~<2600~~127	~~1000~~	
2012	~~93255~~1.659	~~<2600~~58	~~1000~~	
2013	~~121635~~1.620	~~<2600~~109	~~1000~~	
Summer				
~~$Year\, B_{ref}\, \sigma_{glac.tot}\, S_{rea}\, ELA\, AAR\, B_{orig}\, B_{clt}\, B_{ptr}\, B_{prm}\, B_{ind}\, orig-ref\, r_{B_{rea}}\, r_{B_{rea.bc}}$~~2004	~~-216210~~1.938	~~>3400~~	~~0~~	
2005	~~-220679~~1.864	~~>3400~~	~~0~~	
2006	~~-243957~~1.833	~~>3400~~	~~0~~	
2007	~~-2098135~~1.821	~~>3400~~	~~0~~	
2008	~~-2134145~~1.785	~~>3400~~	~~0~~	
2009	~~-221172~~1.754	~~>3400~~	~~0~~	
2010	~~-133799~~1.722	~~>3400~~	~~0~~	
2011	~~-213297~~1.693	~~>3400~~	~~0~~	
2012	~~-248873~~1.659	~~>3400~~	~~0~~	

Table 2. Statistical evaluation of mass balance series based on different extrapolation methods compared to the reference method. $Bias$, R^2, root mean square deviation before ($RMSD$) and after ($RMSD_{bc}$) a bias correction of the results.

Annual	B_{orig}	B_{clt}	B_{ptr}	B_{prm}	B_{ind}
$Bias$	-58	~~-1~~ -2	-249	~~-188~~ -189	~~-246~~ -247
R^2	0.84	1.00	0.99	0.98	0.98
$RMSD$	~~186~~ 187	~~2~~3	~~255~~256	~~196~~197	~~252~~253
$RMSD_{bc}$	177	2	56	56	56
Winter	B_{orig}	B_{clt}	B_{ptr}	B_{prm}	B_{ind}
$Bias$	71	2	-21	-27	-26
R^2	0.90	1.00	0.99	0.98	0.99
$RMSD$	96	5	29	41	36
$RMSD_{bc}$	65	5	19	31	25
Summer	B_{orig}	B_{clt}	B_{ptr}	B_{prm}	B_{ind}
$Bias$	~~-128~~ -129	~~-3~~ -4	~~-227~~ -228	~~-161~~ -162	~~-220~~ -221
R^2	0.70	1.00	0.98	0.97	0.97
$RMSD$	241	7	~~234~~235	175	~~229~~230
$RMSD_{bc}$	204	6	57	68	65

Table 3. Results of the geodetic analyses and the cross check between glaciological and geodetic method. ~~Where~~ PoR stands for the observation period, ΔZ is the mean surface elevation change, ΔV the volume change, B_{geod} is the uncorrected geodetic balance assuming a bulk density of 850 $\mathrm{kg\,m^{-3}}$, $corr_{sc}$ and $corr_{sd}$ refer to the corrections for snow cover and survey dates, $B_{geod.corr}$ refers to the corrected geodetic balance, $\sigma_{geod.total.PoR}$ is the total random error of $B_{geod.corr}$, $B_{glac.PoR}$ is the cumulated glaciological mass balance, $\sigma_{glac.total.PoR}$ is the corresponding random uncertainty, Δ_{rel} is the relative difference between glaciological and geodetic results and δ is the reduced discrepancy (Zemp et al., 2013).

PoR	ΔZ	ΔV	B_{geod}	$corr_{sc}$	$corr_{sd}$	$B_{geod.corr}$	$\sigma_{geod.total.PoR}$	$B_{glac.PoR}$	$\sigma_{glac.total.PoR}$	Δ_{rel}	δ
	m	$10^6\,\mathrm{m^3}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	$\mathrm{kg\,m^{-2}}$	%	-
2005-13	-10.35	-18.98	-9397	-198	-49	-9644	709	~~-8971~~ -8964	~~240~~ 241	~~7.5~~ 7.1	~~0.90~~ 0.91
2005-11	-8.34	-15.28	-7439	-38	41	-7436	560	~~-7111~~ -7105	234	~~4.4~~ 4.5	~~0.54~~ 0.55
2011-13	-2.20	-3.66	-1908	-169	-8	-2084	248	~~-1830~~ -1829	56	12.2	1.00

Table 4. Reduced discrepancies δ for all extrapolation methods used in this reanalysis and for the original mass balance record. The upper panel shows results without the consideration of basal and internal melt, while the lower panel (*) refers to δ ~~s~~ calculated accounting for subsurface melt. Bold values refer to agreement on the 90 % confidence interval.

PoR	δ_{ref}	δ_{orig}	δ_{clt}	δ_{ptr}	δ_{prm}	δ_{ind}
2005-13	**~~0.90~~0.91**	**0.32**	**0.90**	-1.74[1]	**-1.14**	-1.70[1]
2005-11	**~~0.54~~0.55**	**-0.24**	**0.54**	-1.90[1]	**-1.38**	-1.86[1]
2011-13	**1.00**	**1.19**	**~~0.99~~0.98**	**-0.95**	**-0.41**	**~~-0.92~~-0.93**
2005-13*	**~~0.54~~0.55**	**-0.04**	**0.54**	-2.10[2]	**-1.49**	-2.05[2]
2005-11*	**~~0.20~~0.21**	**-0.58**	**0.20**	-2.24[2]	-1.72[1]	-2.20[2]
2011-13*	**~~0.75~~0.76**	**0.95**	**0.74**	**-1.19**	**-0.65**	**-1.17**

[1] Agreement on the 95 % confidence interval. [2] Not acceptable on the 95 % confidence interval.