Fribourg, January 25, 2015

Dear Editor,

The constructive comments of the two anonymous reviewers and M. Pelto were very helpful to revise the manuscript. We have addressed all points and respond to them individually below. The most important changes are the following:

- The title of the paper now better reflects the contents of the manuscript ("Unlocking annual firn layer water equivalents from GPR data on an alpine glacier").
- The modelling sections were revised in order to streamline the description of the firn densification and refreezing schemes.
- We added an analysis on the potential effect of residual irreducible liquid water in the firn.
- We demonstrate that, if no firn cores are available, measured mass balance data or winter precipitation sums could serve for an independent verification of the layer chronology.

We hope that our revisions contribute to an improved manuscript. Please find attached the revised manuscript and a latexdiff-pdf to depict all changes to the original text.

Kind regards,

Leo Sold, on behalf of the authors.

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Remarks

`Reviewer comments in typewriter font`
Author comments in normal font
Text in the manuscript in italics
$^{\text{Superscript}}$ page- and line-numbers refer to the revised manuscript

Overall replacements

Kg m^{-3} (SI unit) is used instead of g cm^{-3}

The independency of this study from firn cores is removed

Replaced “Traveltime thickness” by “IRH traveltimes”

Removed “layer bulk density” to avoid confusion with the entire vertical mean density

Replaced “GPR profiles intersect” by “repeat GPR measurements are available”

Changes to the model

One equation was corrected

Added velocity estimation from a mixing formula (Looyenga 1965)

Changed to monthly mean offset between surface- and air-temperature

Separate run with the false IRH included (potential misinterpretation)

Comparison with measured mass balance and winter precipitation sums

Changes not requested

P4433, L18: Removed reference *Damm 2004*.

P4436, L12 [P6, L19]: Added reference *Sold et al., 2013*.

P4436, L22 [P7, L23]: Changed to "*The scheme consists of a spatial interpolation of traces to a 0.3m spacing to correct for variations in the helicopter's velocity…"*

P4436, L26: Removed "*was found to*".

P4441, L6 [P12, L5]: Changed *"within its individual history"* to *"since its deposition"*.

P4441, L22: Removed the change rate from the statement: "*The model sensitivity to those variables is controlled by the factor f (Eq. 4)."*

P4444, L15 [P14, L22]: Changed to *"clear weather"*.

P4444, L26: Changed "*the entire accumulation area*" to "*all analysed profile sections*".

P4445, L16 [P14, L5]: Changed *"four layers*" to "*analysed layers*".

P4446, L3 [P17, L1]: Changed "*four*" layers to "*several*" layers.

P4447, L14-19 were removed from the manuscript because they do not provide further detail on the used calibration scheme.

P4447, L23 – P4448, L1 [P20, L5ff] revised: "*Comparison with the densities and layer water equivalents derived from the firn cores revealed a moderate overestimation of the local densities for the 2010 and 2009 accumulation layers resulting in difference of 9% for the water equivalents (Fig. 8). This also holds when hypothetical GPR traveltimes are calculated from the measured densities to run the model. Because the density estimate for the uppermost firn layer (2011) and, thus, the initial model density is adequate, this indicates an overestimation of the compaction rate*."

P4453, L24: Removed reference *Huss et al,. 2010.*

Added to Acknowledgements: "*We gratefully acknowledge the valuable comments and suggestions by the two anonymous reviewers."*

P4460 [P32] Changed caption Fig. 5: *"(a) Average water equivalents of annual layers derived by GPR and by extrapolated glaciological field measurements at locations where all four summer layers could be extracted from the GPR signal. Error bars show the uncertainty from the initial density* $rho_f(0,t_d)$*. (b) Mean layer densities, the related uncertainty and data range for the same locations."*

Referee #1

This manuscript (MS) reports of snow surveys by GPR from a helicopter effectuated on a glacier in Switzerland over two subsequent years, and the analysis of the obtained data to unlock the information contained in layered material.

The main contribution of this study is the methodology to exploit the sequence of reflectors recorded by the GPR with regard to a chronology of annual accumulation. The method accounts for the compaction of firn due to gravitational settling and refreezing of meltwater. Using the simulated density enables calculating the propagation velocity of EM waves through the substrate and hence establishing a depth-traveltime relationship. IRHs are then attributed to summer surfaces to derive a multi-year accumulation history.

However, regarding this analysis, I have a major concern. The authors use detailed records from several firn cores to evaluate their results to find that the fundamental assumption of IRH = summer surface is not valid. IRHs occur at planes of sharp contrast of the di-electrical properties of the material, which can be caused by density/ permittivity contrasts but also by contrasts in electrical conductivity as caused for instance by dust layers. Therefore, the interpretation IRH = summer surface is ambiguous. Using the firn core records, the authors are able to avoid erroneous identification and their derived accumulation rates are therefore credible. However, in the conclusions, they state that the "approach is independent from external information such as firn cores", which is a too strong statement since the credibility of the results critically depends on the firn core record, needed to resolve potential ambiguity. It is therefore questionable whether the proposed method is reliably applicable to other glaciers where such firn core data is not available.

The statement was removed from the conclusions.

P4446, L22 – P4447, L12 [P17, L20 – P18, L20] was rewritten and a discussion on the validation of the layer chronology by means of measured mass balance and winter precipitation sums was added: "*Like it is the case for all approaches that rely on annual layer counting, a misinterpretation of an IRH affects not only the estimated water equivalent of the respective accumulation layer. Because the chronology of all following layers is shifted, an independent evaluation of the annual character of IRH is essential. We assessed potential alternatives to the in-situ dating through firn cores by comparing the mean GPR-derived accumulation layer water-equivalents to mass balance measurements and winter precipitation sums. Despite the small number of data points when comparing annual mean values (n=5) and the resulting low statistical significance of the results, Pearson product-moment correlation was chosen to depict a potential linear* *relation between the datasets. When the correct chronology from the firn cores is used to derive accumulation from IRH traveltimes, correlation with extrapolated mass balance measurements is r=0.57, but insignificant (p=0.32). If the ice lens within the 2009 accumulation layer was misinterpreted as a former summer surface, the water equivalents for the layers of 2009 and 2008 are strongly reduced and the dating of all following layers is shifted by one year (Fig. 7a). This results in a reduced correlation with the extrapolated mass balance of r=0.41 (p=0.50). Because mass balance measurements are not available at locations covered by analysed GPR profile sections this comparison relies on the extrapolation scheme used. We suggest that this explains the large overall deviation between the two datasets (Fig. 5) and the insignificance of the presented correlations. A similar comparison was performed with annual precipitation sums for the months October to April at the Zermatt weather station. To avoid the effect of variations in spatial extents of analysed layers, only sections covering all layers of 2007--2011 were used. With the correct dating from cores, correlation of winter precipitation sums with GPR-derived water-equivalents was r=0.87 (p=0.06) (Fig.7b). In contrast, it reduces to r=0.10 (p=0.87) when the chronology is disturbed by the extra layer in 2009. Both approaches cannot provide a validation as robust as through firn cores, particularly if multiple layers are missing or misinterpreted. However, in the given case, the peak in measured accumulation and winter precipitation sum in 2009 is only reproduced with the correct chronology. We suggest that such a comparison can aid an extraction of accumulation rates from GPR data when no firn cores are available*."

Added new Fig. 7 to compare GPR-derived layer water equivalents to measured mass balance and winter precipitation sums: "*Comparison of GPR-derived mean annual layer water equivalents with (a) extrapolated mass balance measurements and (b) winter precipitation sums (October -- April) at the weather station of Zermatt (1638m a.s.l.). With the correct layer chronology obtained from firn cores (red dots) the high accumulation and winter precipitation in 2009 are reproduced. A misinterpretation of an IRH within the 2009 accumulation layer disturbs the chronology and affects all following layers (black circles).*"

P4449, L19 [P21, L28] changed accordingly from "*modelled accumulation rates based on meteorological information*" to "*winter precipitation sums*".

Furthermore, the firn compaction model seems to be affected by a mistake becoming apparent in eq 2, where the mass-balance rate is multiplied by the density of ice (and subsequently in eq 4). The reason for doing so is not clear. In the original formulation by Herron and Langway (1980) the mass-balance rate is in water equivalents, whereas Reeh (2008) used the mass balance in ice equivalents and introduced the ratio rho_i/rho_w to convert to water equivalents. Huss (2013) used the same model but made a similar mistake by multiplying the w.e. mass balance with the density ratio. Ultimately, this mistake will be accounted for by the calibrated value of f such that the final results most likely are not affected. Here, the calibrated value of f is much larger than the original value used by Herron and Langway (1980) and Reeh(2008), a fact that is not mentioned in the MS, but definitely needs to be discussed! Nevertheless, this presentation of the model (which is the backbone of the entire study) is highly confusing and needs to be clarified. Also, the units of the involved empirical parameters have to be specified.

We corrected Eq. 2 in the MS and in the model.

We now provide the necessary units in section 3.2.

P4447, L13 [P19, L12] added: "*The firn densification model is calibrated with the observed changes in IRH traveltime from spring 2012 to 2013 at 12 locations and for 35 firn layers. Therefore, a different amount of liquid water at the date of the measurements could lead to an over- or underestimation of the compaction rate. This could, to some degree, account for the compaction rate scaling* $f=2614 m^{-0.5} yr^{-0.5}$ *being higher than previously published values. When the model was originally set up, Herron & Langway (1980) obtained* $f=575\ m^{-0.5} yr^{-0.5}$ *for densities above* $550 kg\ m^{-3}$*, but using ice cores in cold firn on Greenland and Antartica. Huss (2013) calibrated the same model with a set of 19 firn cores from temperate and polythermal mountain glaciers and ice caps in the European Alps, Western and Arctic Canada, Central Asia, Patagonia, and Svalbard. The larger value of* $f=1380\ m^{-0.5} yr^{-0.5}$ *is in line with the different climatic conditions and different firn compaction regimes compared to the original formulation.*"

Changed next sentence accordingly: "*Aside from the potential liquid water content, the scheme used to calibrate the model is affected by horizontal ice motion.*"

Rewrote P4438, L25 – P4440, L9 [P10, L5 – P11, L5]: "*We follow Reeh (2008) by substituting the long-term mean mass balance in Eq. 2 with the mean water equivalent of the i-1 overlying firn layers to obtain an individual proportionality factor* c_i *for each firn layer as*

$$c_i = k \cdot \left(\sum_{j=0}^{i-1} \omega_j \cdot t_i^{-1} \right)^{0.5} .$$

This allows estimating the density $rho_{f,i}$ *of a firn layer by solving Eq. 1 over* t_i*, the time since layer deposition, if the initial density* $rho_f(0,t_d)$\$ *and the water equivalents of overlying firn layers are given. Then, the difference in IRH two-way traveltime* tau_i *can be converted to the firn layer water equivalent* $omega_i$ *by*

$$\omega_i = 0.5 \cdot \tau_i \cdot v(\rho_{f,i}) \cdot \rho_{f,i},$$

with the radio wave velocity $v(rho_{f,\ i}\})$ *estimated from the density using the empirical relation by Frolov and Macheret (1999).*

When the density of the uppermost layer is known, Eq. 5 provides its water equivalent and Eqs. 4 and 1 can be used to estimate the density of the second layer. The densities and water equivalents of all other layers can then be calculated similarly in a stepwise manner by using the previously obtained water equivalents of all overlying layers. In our case, the uppermost layer (i=0) is the winter snow cover. We set its density to $rho_{f,0}=400 kg\ m^{-3}$*, which is in line with observations in spring 2010--2013 (395 pm* $32 kg\ m^{-3}$ *from 14 measurements >3200m a.s.l.). According to Reeh (2008), the deposition of a layer at time* t_d *is attributed to the end of the respective melting season. Because the GPR measurements were taken in spring, we set the age of the first annual firn layer (i=1) as* $t_1=0.3yr$*. This also accounts for the associated* *compaction processes beiing stronger during the summer months due to higher temperatures and the refreezing of meltwater. For all subsequent layers we set* $t_{i+1}=t_i+1yr$.

To account for the temperate nature of Findelengletscher, temperature was set to T=0°C= 273.15K (constant). …"

The stated aim of assessing spatial distribution is worthwhile but it barely addressed in the entire MS. The authors state the glacier was surveyed along 79km profiles in a regular grid covering the area 500m but the data presented here is only from a few 100m. I doubt that the surveys produced only so few repeat points, even if the grid navigation were maximally off.

Indeed only a very small part of the recorded GPR profiles could be used for the analysis. This is (1) due to the general limitation to the firn area (>50% of the GPR profiles for the monitoring of winter accumulation are in the ablation area), (2) because reflectors cannot be tracked over longer distances (as stated in the introduction), and (3) because the approach is based on layer counting, i.e. the observer must ensure that all annual layers exist at the analysed locations. Due to the latter, the approach is limited to areas with sufficient amounts of annual accumulation and, thus, to the upper accumulation area.

P4437, L4 [P8, L4] rewrote paragraph: *"The analysis of firn layers is limited to locations where accumulation occurs. To extract an annual firn layer, at least two IRH must be present, i.e. representing two subsequent summer surfaces. Furthermore, it must be ensured that between the upper- and lowermost detected IRH all other IRH of summer surfaces are present and can be distinguished. Thus, areas with no or little accumulation as well profile sections where the interpretation was ambiguous were excluded from the dataset. The reduced set of processed GPR data consists of disjunct profile sections in the accumulation area of Findelengletscher (7.3km total length for the uppermost firn layer in May 2012). The penetration depth of the GPR signal depends on the height of the helicopter above ground and the physical properties of the subsurface. Therefore, the IRH of deeper, i.e. older, layers appear in shorter sections, leading to differences in the spatial extent of extracted layers. We found reflections down to about 20m below the snow surface and a maximum of eight IRH. They were digitised manually in the processing software due to noise and lateral variability in layer thickness which impede a reliable automatic tracking of IRH."*

P4445, L1 [P15, L8] added: *"As described above, the firn densification model was applied to all GPR traces individually where multiple IRH were found that correspond to subsequent previous summer surfaces. Thus, the analysis is limited to areas where sufficient annual accumulation allows distinguishing the corresponding IRH. Furthermore, a continuous tracking of IRH is impeded due to crevasses, ice dynamics, irregular accumulation such as avalanche deposits, changes in the distance of the helicopter to the snow surface, or lateral variations in layer properties that determine the strength of IRH. The total length of analysed IRH was, 7.3km, 6.8km, 5.9km, 2.8km, 1.3km, and 0.1km for the accumulation layers of 2011 to 2006, respectively."*

P4432, L11 [P2, L11] (Abstract) changed to "*Along GPR profile sections from across the accumulation area we obtain the water equivalent of several annual firn layers. Because deeper IRH could be tracked over shorter distance, the total length of analysed profile sections varies* *from 7.3km for the uppermost accumulation layer (2011) to 0.1km for the deepest, i.e. oldest, layer (2006).*"

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The other aim indicated in the title is to analyze recent accumulation rates, which is not at all covered here. So the title is misleading. In addition, since the analysis is based on a reduced dataset, the helicopter-borne aspect of the data is not relevant for the MS; the limited dataset presented here could have easily been achieved by ground-based GPR.
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The title of the paper was changed to better match the manuscript ("*Unlocking annual firn layer water equivalents from GPR data on an alpine glacier*"). We agree that the helicopter-borne data acquisition is not fundamental for the presented analysis. However, we believe that even the reduced dataset could not have been obtained by ground-based GPR in the high alpine terrain of the study site.

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I recommend reformulating the title to better reflect the content of the MS which also should be revised to appear more streamlined. In its current form the overall objectives appear splattered and need to be more focused. Do the authors want to address recent accumulation? Spatial distribution of snow from high-degree coverage by helicopter borne GPR or is it to unlock the layer information? From the MS the latter stands out as the primary objective and this needs to be clearly defined in the MS and reflected in the title.
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Added (P4434 L18 [P4, L19]): "*In order to obtain the density and water equivalent of firn layers, meltwater that percolates from the surface into the firn must be taken into account. Aside from its effect on the propagation velocity (Schmid et al., 2014), it changes the density and water equivalent of firn layers when it refreezes.*"

Rewritten last paragraph of the introduction (P4434, L28 [P5, L1]): "*In this study we obtain IRH traveltimes from GPR data measured in May 2012 by 400MHz helicopter-borne GPR on Findelengletscher, a temperate alpine valley glacier in Switzerland. The analysis is limited, however, to the upper part of the glacier where sufficient accumulation allows distinguishing multiple IRH. Due to IRH discontinuities and variations in the GPR signal penetration depth, the analysed subset consists of disjoint profile sections. The chronology of the IRH is directly retrieved from two shallow firn cores. Comparison with density and impurity profiles shows that not all IRH represent former summer surfaces. The measured traveltimes of annual IRH serve as input to a simple transient model for the density of firn layers and the refreezing of meltwater. The model is calibrated with an observed change in the IRH traveltimes at multiple locations. They are obtained from a repeat survey conducted in April 2013. The model is run for all analysed GPR measurement locations separately and provides estimates for the density, water equivalent and meltwater refreezing in annual firn layers. Thus, on the basis of the layer chronology from firn cores, we estimate annual accumulation rates for Findelengletscher over a multi-year period from airborne GPR measurements.*"

In my view, although based on an interesting idea, the MS does not live up to the expectation raised in the introduction. The MS needs major revisions to a) focus on a clearly defined objective and b) not to oversell their findings but honestly discuss the associated shortcomings and c) to improve readability and precision of the text by an extensive proof reading (English native speaker?). Further examples supporting this point are found in the list of detailed comments below.

Detailed comments:

1. P4432, Abstract, L13: the SI units for density should be used, not only here but throughout the MS

Changed throughout the MS.

2. L13/14: "ACCORDING TO MODEL RESULTS, refreezing accounts..",

P2, L15 Changed as suggested

3. L16: "in the same order AS.."

Sentence removed from the abstract.

4. P4433, L11: "the low ELECTRICAL conductivity.." to avoid confusion with thermal conductivity

P3, L10 Changed as suggested

5. P4434, L14: "...to convert the GPR traveltime to depth...an estimate..of the propagation velocity is required. This velocity depends on density of the material, the latter also needs to be estimated or measured. This procedure introduces..."

P4, L15 Changed to "*Furthermore, an estimate of the propagation velocity is required to convert the GPR traveltime to depth. Because the velocity depends on the density of the material, the latter needs to be measured or estimated (Plewes and Hubbard, 2001). Thus, density introduces an uncertainty, as it also does for conventionnal accumulation measurements that are based on the determination of layer thickness.*"

6. P4435, L1: "the bulk density of firn layers" is very clumsy wording and confuses the reader. What has been estimated here, the bulk density of the entire firn volume/ column or the density of layers? From my understanding, the latter applies here and the term “bulk” should be avoided when referring to the vertical profile. This wording appears several times throughout the MS.

Removed “*bulk*” throughout the manuscript.

7. L2: “...where GPR intersect in subsequent years” a bit unclear, do you mean “where repeat surveys from subsequent years exist”? Anyhow, it is surprising how little repeat points have been produced (12) given the stated density of the GPR profiling in grids of 500m spacing. Obviously, the data have been filtered according to some criteria which need to be clearly stated. The statement made in the last paragraph of sec 1 is one of my major problems here: you need the information of the firn core to unambiguously associate IRHs with summer surfaces but then you claim that your method is only based on GPR and the firn densification model.

“…GPR intersect…” was changed to “*repeat measurements exist*” throughout the manuscript.

A discussion on the small number of calibration points and the reduced dataset was added to the revised manuscript (see general comments).

Following the general comments, we extended the discussion of the verification of the layer dating and the necessity of firn cores P4446, L22, supported by a new Fig. 7.

8. L11/12: “accumulation characteristics are strongly determined by the synoptic weather patterns” this is trivial and can be omitted

Removed statement as suggested.

9. P4436, L1: “...were taken AT Findelengletscher..”

[P6, L6] Changed as suggested.

10. 1rst par: here you state that both surveys were conducted along a regular grid of 500m spacing, covering the entire glacier. This must produce more than just 12 cross-over points? if the dataset was reduced, the filter criteria need to be stated. The stated coverage and density of the surveys are interesting but since >90% of the data are neither presented nor analyzed, this information appears obsolete.

See general comments and comment (7). Also note that a large part of the dataset actually covers the ablation area and obviously cannot provide annual accumulation layers. This is now clarified in the manuscript.

11. L5: "With a flying speed...measurements were taken from 5-10 m above the surface at time intervals of 0.02 s corresponding to a trace spacing of approximately 0.2 m."

P6, L10 Changed to "*With a flying speed of approx. 10ms^{-1}, measurements were taken from 5-20m above the surface at time intervals of 0.02s, corresponding to a trace spacing of approximately 0.2m.*"

12. L5/6: "...the position obtained from a differential global positioning system (DGPS), a time window..."

P6, L12 Changed as suggested.

13. P4437, L20: "An estimate for..."

P8, L27 Changed as suggested.

14. L26: "...the approach to MODEL firn compaction..."

P9, L6 Changed to "*We used the approach by Reeh (2008) to model firn layer compaction. It is based on the…*"

15. P4438: L5: state the unit of the parameter c is it consistent in eq 1 and eq2?

P9, L12 Added "*dimensionless*". Because Eq. 2 was corrected according to the general comments the units of parameter c are now consistent in Eqs. 1 and 2.

16. L10: What are the units of k and f?

We now provide the units of temperature, mass balance, activation energy, gas constant, and f on P9 - 10.

17. Eqs 2 and 3 are for rho_f>=550 kg m-3, what happens with rho_f < 550 ??

This was described in P4439, L11. The sentence is moved to P4438, L8 [P9, L15] and slightly modified: "*Here, we neglected the lower stage (rho_f < 550kg m^{-3}), because the model will be calibrated and measured autumn snow densities were not considerably lower (see below).*"

P4439, L14 removed redundant sentence.

18. Eq2 is not identical to the similar equation used by Reeh, 2008. The b used by Reeh is in m ice equivalent and the ratio rho_i/rho_w is used to convert it to water equivalent. I assume your mass balance values are in w.e. and do not need conversion, anyhow just using a factor rho_i instead of the ratio would be wrong by a factor 1000!

Corrected (see general comments).

19. L12: "...is an empirically.." (check spelling)

Corrected.

20. L 21: "the traveltime-thickness" is very awkward, merging two fundamentally different quantities into one expression. This needs to be fixed also at the many other instances in the MS.

Changed to "*IRH traveltimes*" throughout the manuscript.

21. P4439: L 6: "water equivalent was then derived from..."

Chapter 3.2 (Modelling firn density) was revised to clarify the modelling approach, following the general comments.

22. L14: c_(i+1) cannot be the compaction rate, alternatively the variable has changed meaning since its usage in Eq 1. Please clarify.

Changed to "*proportionality factor*" in P4439, L9, L14 [P10, L10], removed "*change rate*" in P4442, L7, removed "*c*" in P4447, L15.

23. Eq4: same comment as for eq2, what is the role of multiplying mass balance with rho_i?

Corrected (see above).

24. P4440, most of the material in the paragraph before 3.3 seems to be discussion material.

Section 3.2 was revised and does not contain these statements anymore.

25. L13 ff: details of the “conservative uncertainty estimate” should be specified.

P11, L11 Changed to “*We obtained a conservative uncertainty estimate of pm 61kg m^{-3} from the mean standard deviations of (1) multiple density measurements within the same snowpits, i.e. the measurement error (pm 21kg m^{-3}), (2) within single years, i.e. the spatial variability (pm 31kg m^{-3}) and (3) at locations with annual repeat measurements, i.e. the temporal variability (pm 49kg m^{-3}).*”

26. P4441, L5: “negative temperatures” change to “subfreezing temperature”

Changed as suggested.

27. L11/12: “the amount of refrozen meltwater” it is unclear how this amount was derived or estimated. Please explain.

P12, L15 Added explanation: “*For each year and each layer, the amount of refrozen meltwater was calculated from the specific heat capacity of snow and the latent heat of fusion and was added to the layer water equivalent. The given layer thickness then allowed updating its modelled density*.”

28. P4442: L1: “At locations where GPR repeat measurements are available...”

Changed as suggested throughout the manuscript.

29. L7: “the optimal scaling factor”, optimal in which sense? Also the entire sentence is unclear and needs rewording.

P13, L12 Changed sentence to “*The model was calibrated with a scaling factor of f=2614 (Eq. 2) that was found by minimising the root-mean-square deviation of the modelled and measured IRH traveltimes of 35 layers at 12 locations (Fig. 1)*.”

30. L 15: “the outer part” of the core?

P6, L26 Changed as suggested.

31. P4443: L1 ff: if the cores cover the period from summer 2008 – 2012, how can the dust layer deposited in May 2008 be found?

[P7, L15] Here, "*summer 2008*" referred to the lowermost pronounced high-density layer. Changed to "*winter 2007 / 08*".

32. Sec 4: the results are presented in a different order than the associated methods have been described. The structure of the MS would benefit from keeping the same sequence.

In the methods section the firn core analysis was moved to the beginning in order to follow the same order as the results section.

33. P4444: L10-21: this is discussion material

The chapters were changed as suggested by referee #2: 3. Results and discussion (formerly "Results"), 3.4 Data interpretation and error analysis (formerly "Discussion"). We believe that the structure of the manuscript benefits from keeping this discussion fragment next to the respective results.

34. P4445, L2: "the model was applied to each GPR trace individually" this must be an excessive computation, given the stated trace spacing of 0.2m and the entire profile length of 79 km. clarify!

[P15, L10] Changed to: "*As described above, the firn densification model was applied to all GPR traces individually where multiple IRH were found that correspond to subsequent previous summer surfaces. Layer water equivalents were then derived from the modelled densities, the IRH traveltimes and the density-based GPR wave velocity estimates*."

Added "*where multiple IRH were found*" in P4449, L13 [P21, L25] to make clear that the model is not applied to all individual traces.

35. L24ff: Refreezing: can you specify how much of the refreezing occurs within the annual layer and how much below that (=internal accumulation)?

As requested by Referee #2 (general comments) more detail about the refreezing was provided throughout the manuscript, including explicit amounts for individual layers.

36. L29ff: you claim that the model uncertainty is only slightly larger than that of in situ measurements. This is a strong statement but cannot be judged by the reader as one quantity is presented in relative and the other in absolute values.

P16, L27 Rewritten and toned down: "*For conventional glaciological accumulation measurements the density measurement error is approx. 4% (pm 21kg m^{-3} from repeat measurements). In contrast, the combination of GPR with a firn density model provides a considerable spatial coverage for four annual accumulation layers with a small trade-off in terms of uncertainty*."

Statement was removed from the Abstract.

37. P4446, L26: "verification" change to "evaluation".

P17, L23 Changed as suggested.

38. P4447, L10 "unstable verification" what do you mean by that?

The statement was removed from the manuscript.

39. L15: "...is not exceptionally stable..." do you refer to numerical stability or robustness of the results?

The statement was removed from the manuscript.

40. L27/28: "For the following..." I do not understand this sentence.

P20, L5 Changed to "Comparison with the densities and layer water equivalents derived from the firn cores revealed a moderate overestimation of the local densities for the 2010 and 2009 accumulation layers resulting in difference of 9% for the water equivalents (Fig. 8)."

41. P4448: L3/4: "the particular weather conditions in general": : :clumsy wording. Is it "in particular" or "in general"? cannot be both at the same time.

P20, L13 Removed "*in general*".

42. L15: how can "external refreezing" occur within a layer? What is meant by this?

Statement removed.

43. L23: unclear what "temporal breaks" refers to

[P20, L15] Changed to "… *differs from the accumulation component within the mass balance term regarding the definition of a `year'*."

44. P4449: L7/8: again. "bulk density" or "density of each layer"?

[P21, L20] Changed to "*a density estimate was derived*" (removed "*bulk*").

45. L9/10: "refreezing under temperate conditions" sounds mysterious, reword!

[P21, L21] Changed to "…*by modelling the end-of-winter temperature profile that, for temperate firn, is entirely compensated by refreezing.*"

46. L12/13: "our approach is independent from external information such as ice cores" but actually you need the firn cores to unambiguously relate IRHs to annual layers. So this statement is simply wrong!

We agree with Referee #1 that the approach is not independent from any external information (see general comments, also by Referee #2). The sentence was removed. However, as we discuss in P4446, L25 – P4447, L12 [P17, L21ff], the usage of firn cores can be avoided if the layer dating can be verified using e.g. mass balance data or winter precipitation sums. We provide such a verification in the revised manuscript.

47. Fig 1: I expected to see the grid of the GPR surveys, but it is probably not of relevance for this study and presumably therefore not shown on the map. Consider removing the corresponding part of the text.

Following the general comments we added a discussion on the reduced dataset to clarify which of the available GPR data was used.

48. The insert map does not aid locating the study region.

The inserted map was changed to show a smaller window of the Alps. Country borders and cities were added to help locating the study site.

Referee #2

The manuscript by Sold et al. submitted to the Cryosphere presents an approach to inversely relate radar signal reflections in an accumulation area of a glacier in the Swiss Alps to accumulation rates. To convert measured TWT values to SWE, they use a snow/ firn densification model together with a rather simple approach to account for meltwater redistribution. For validation and layer relation to summer surfaces, they use results from 2 firn cores drilled during the first radar campaign in 2012. While data on annual winter accumulation rates (point measurements) is available for this glacier, it is not presented in the manuscript. A comparison of these point measurements (and spatial extrapolation thereof) with results for the most recent accumulation derived from GPR data could support the main conclusion from this manuscript that radar accumulation estimates have a much better spatial representation to assess the actual accumulation rates on glaciers. However, only a very small part of the recorded radar transects is discussed and presented in this manuscript

Indeed, only a small part of the recorded GPR profiles could be used to extract firn layer water equivalents. Obviously, the approach is limited to the firn area (<50% of the total glacier area). Because reflectors cannot be tracked over longer distances, the analysed profile sections are disjoint. Furthermore, the approach is based on layer counting and, thus, the observer must ensure that all annual layers exist at the analysed locations. Due to the latter, the approach is limited to areas with sufficient amounts of annual accumulation and, thus, to the upper accumulation area.

P4437, L4 [P8, L4] rewrote paragraph (see general comments Referee #1).

For our study site several years of winter accumulation measurements are available from GPR and conventional snow probings combined with density measurements in snow pit. However, the presented approach does not involve the computation of melt rates and, thus, a comparison of winter accumulation measurements with annual accumulation rates is not meaningful. On the other hand, a comparison of firn layer water equivalents with annual measurements of accumulation is shown in Fig. 5 and is discussed in further detail in the revised manuscript (see general comments Referee #1).

In terms of language, the manuscript is well written, however, a couple paragraphs should be thoroughly revised (see below). Shorter and less nested sentences facilitate following your statements.

We avoided nested and long sentences in the revised manuscript in order to improve the readability.

The major point I come up with is that the presence of liquid water is disregarded in the manuscript even though it has a very strong impact on radar wave velocity even for very small volume fractions. I can see that this is beyond the scope of this paper but certainly needs to be discussed as you deal several times with it. I will explain my concerns more in detail: To convert TWT in depth, you use Frolov and Macheret (1999) to determine layer respective bulk propagation velocities. Here, you use only a 2 phase mixing formula empirically determined for dry snow/ firn conditions. The firn temperature however is set to be constant at 0C. Additionally, you define that a cold content transmitted from the surface into deeper parts is compensated by meltwater refreezing. Actually, to refreeze liquid water you need to have temps below 0C to compensate for the release of latent heat. For your assumption of isothermal conditions within the firn pack, you must assume liquid water being present. At the same time, you use equations for the conversion of EM wave velocity to density which are only valid for dry conditions. These 2 assumptions are contradictory and it means that you expect the firn always being at a certain state where all liquid water is already refrozen and the cold content of the overlying snowpack/ firn layers hasn’t yet reached the layer you are observing. In my opinion these assumptions have to be discussed more in detail. This point is very crucial for your assumptions since even small portions of remaining liquid water alter the wave speed significantly (e.g. Schmid et al., 2014).

We agree that the effect of liquid water needs to be discussed in the context of this study and that the current formulation is inconsistent. The major problem is that no measurements of the liquid water fraction are available for our study site. Furthermore, liquid water content is expected to vary not only vertically and laterally in the firn, but also temporarily. The latter has a potential impact on the calibration scheme of the model. However, at the two firn core locations the dry-snow assumption still yields a good agreement between IRH traveltimes and ice layer depths – but this cannot be generalized for the entire accumulation area. Instead of an explicit solution for this issue we provide a discussion and an estimate for the related uncertainty in the revised manuscript, using an adequate mixing formula to derive the GPR wave velocity.

P4447, L13 [P18, L21] added paragraph: “*To convert IRH traveltimes to depth and water equivalent we apply an empirical relation of density and the dielectric permittivity of firn (Frolov & Macharet 1999). However, this relation has been determined for dry snow conditions while the presence of liquid water has a considerable effect on the dielectric properties (Schmid et al., 2014). In our study, the analysed IRH traveltimes were derived from GPR measurements in spring (May 2012 and April 2013). Field measurements of temperature in the snow cover in the accumulation area in April 2014 reveal subfreezing conditions apart from a shallow surface layer. Thus, the presence of liquid water in upper firn can be ruled out at this time of the year. On the other hand, residual water from previous melting seasons might be present deeper in the* *firn. This has a potential impact on the evolution of the temperature profile over the winter season because latent heat is released when it refreezes. More importantly, it affects the GPR propagation velocity and, thus, the resulting layer water equivalents. The potential impact was assessed using a rather conservative hypothetical liquid water content of 5%vol. and the mixing formula for dielectric permittivity by Looyenga (1965). The related change in the resulting layer water equivalent is about -16%, comprising the direct effect on the estimated layer thickness (Eq. 5), as well as the effect on the modelled densities. However, comparison with the firn cores showed good agreement in the depths of IRH (Fig. 4) and, thus, no evidence for the presence of liquid water. On the other hand, this finding cannot be transferred to the lower parts of the accumulation area, and does not necessarily hold for all investigated years.*"

P4447, L13 [P19, L12] added: "*The firn densification model is calibrated with the observed changes in IRH traveltime from spring 2012 to 2013 at 12 locations and for 35 firn layers. Therefore, a different amount of liquid water at the date of the measurements could lead to an over- or underestimation of the compaction rate. This could, to some degree, account for the compaction rate scaling $f=2614m^{-0.5}yr^{-0.5}$ being higher than previously published values.*"

In section 3.3 you state that no melting occurs in the accumulation area during the winter season. This statement is somehow useless unless you define winter season. And for several accumulation areas at Alpine glaciers you will find massive melt freeze crusts within the snowpack in late April early May. On page 4444 L.13-18 you describe weather conditions which usually produce melt-freeze layers at the snow surface.

The statement that "…*no melting occurs in the accumulation area of Findelengletscher over the winter season*" was removed from P4440, L26. However, from the field measurements in mid- to end-April (snow pits) we know that melt events are rare during winter. Instead of applying a constant offset of -4.9K we now use mean monthly offsets (e.g., -3.07K in Oct., -6.71K in Dec., -3.54K in Apr.) in order to estimate the snow surface temperature based on the measured air temperature (see comment 16). Thus, the effect of surface melt on surface temperature is now implicitly taken into account.

We revised the beginning of section 3.3 to clarify the assumptions made to obtain the refreezing (P4440, L24 [P11, L19]): "*Due to cooling from the surface during winter, firn can periodically have temperatures below 0°C even on temperate glaciers. The relocation and refreezing of surface meltwater alters the water equivalent of firn layers and affects their density. Because of the temperate conditions, we assume that during each summer all subfreezing temperatures are compensated by the refreezing of meltwater. This is supported by the direct observations of summer mass balance, that generally indicate >1m w.e. of snow melt during the summer months. Thus, the amount of refreezing is given by the firn temperature profile that is generated by the surface cooling during winter. We calculate a one-dimensional end-of-winter firn temperature profile at each GPR measurement location using heat conduction from the surface in the period from 1 October to 1 May.*"

Removed sentence accordingly from P4441, L4.

The 3rd point dealing with liquid water I am concerned with is that you do not account for lateral flow, mass loss through melt and percolation of liquid water from surface layers into previous accumulation layers. You just present a 9% density increase to "affected" layers. The whole Section 3.4 needs to be revised and clarified, which layers are affected by when and at which date! Additionally, I would expect that mass loss is discussed. This manuscript presents a similar approach than the one from van Pelt et al., 2014 here for an Alpine glacier instead of polar/ subpolar glaciers. Please discuss differences.

We agree that lateral flow of liquid water is a relevant process. However, it cannot be assessed directly here and, in our opinion, is beyond the scope of this paper.

P4445, L26 [P16, L20] Added: "*This may be due to the different climatic condition but can also be related to processes not incorporated in the model, such as the formation of blocking layers and the storage or lateral flow above such barriers.*"

We model the refreezing of water that originates from the melting of the winter snow pack throughout the summer. Based on the temperate nature of Findelengletscher we assume that all end-of-winter sub-freezing temperatures in the snow and firn pack are compensated by refreezing during summer. This is supported by shallow firn temperature measurements in fall 2014 that indicated fully temperate conditions. The quantity of snow melt in the accumulation area during the summer months (known from direct mass balance observations) is generally >1m water equivalent per year. This amount of meltwater would be sufficient to completely heat up a 45m thick firn column (at 700kg m^{-3}) with an average temperature of -5°C to the melting point. On Findelengletscher the typical thickness of the total firn layer is about 10-20m and winter cooling penetrates to a depth of about 10m. This clearly indicates that our assumptions and our simplified approach are justified. In contrast to Arctic glaciers the limiting factor for refreezing is the firn temperature and not the amount of liquid water. In the revised manuscript we discuss these rough considerations based on direct field observations and compare our approach used for temperate firn to cold firn. Furthermore, we provide more details on the effect of refreezing on layer densities and water equivalents (see also previous comment).

Added P4445, L5 [P15, L18]: "*Conventional glaciological measurements refer to the annual surface mass balance, as they are taken from the recent accumulation layer in the end of the hydrological year. This layer experienced melting and the meltwater, which may partially refreeze deeper in the firn column, is not covered by the measurement. In contrast, water equivalents obtained from IRH traveltimes contain internal accumulation originating from surface melt in multiple seasons. As our goal is to reconstruct surface mass balance, consistent with conventional measurements, the computed quantity of refrozen meltwater was subtracted from each layer and was not re-attributed to its source layer*."

Changed / Added to P4445, L23 [P16, L15]: "*At the analysed GPR measurement locations the annual internal accumulation in the entire firn column is about 0.028m w.e. yr^{-1}, affecting several previous accumulation layers. In summer 2011 the accumulation layers of 2010, 2009, and 2008 gained 0.019m w.e., 0.007m w.e., and 0.001 m w.e., respectively. On average, 2% of the firn stratigraphy is made up by refrozen meltwater. In contrast, a higher value of 10% was measured by Miller & Pelto (1999) on a temperate glacier in Alaska. This may be due to the* *different climatic condition but can also be related to processes not incorporated in the model, such as the formation of blocking layers and the storage or lateral flow above such barriers.*"

Removed P4448, L5 – L16 accordingly.

P4432, L13 (Abstract) changed to "*According to model results, refreezing accounts for 10% of the density increase over time and depth and for 2% of the water equivalent.*"

Moved P4448, L16 – L21[P20, L18] to the end of the discussion section and revised paragraph: "*With a coupled energy-balance -- snow model the temporal evolution of accumulation layers can be tracked. Van Pelt et al. (2014) calibrated the accumulation input to such a model by matching modelled and observed IRH traveltimes. With this inverse approach they obtain the adjusted accumulation distribution along a GPR transect on a polythermal Svalbard glacier. Their model solves the surface energy balance and computes percolation, capillary storage, refreezing and runoff of liquid water to provide subsurface density, temperature, and water content. Storage and lateral flow of water on top of ice layers are not resolved. Postdepositional processes related to refreezing are taken into account. Thereby, uncertainties in the model initialisation and physics directly affect the obtained accumulation patterns (van Pelt et al. 2014). In this study, we used IRH traveltimes as input to a simple model for firn densification and meltwater refreezing. Thus, firn layer water equivalents could be derived in a forward approach. Our model involves strong assumptions on liquid water content and percolation, temperature evolution and densification of firn. By assuming that all subfreezing temperatures are compensated by meltwater refreezing we avoid modelling melt rates. This is reasonable under temperate conditions, but precludes an application to cold firn. On the other hand, a sound representation of physical processes depends on extensive input data such as air temperature, pressure, humidity, precipitation and radiation (Mitterer et al., 2011). Finally, both approaches share the largest source of uncertainty which is the misinterpretation of IRH as annual layers and a careful validation with reference data remains essential.*"

Some other major points that must be addressed:

A) the structure of the presented manuscript is not appropriate. There is no Result- Section. Eg Section 4.1 involves a large discussion part of the results of the chemical analysis of the firn core. I recommend changing the whole Section 4 to Results and Discussion and name 4.3 Data interpretation and error analysis instead of Discussion.

The sections were changed accordingly.

B) Neither you do present a number on the ice velocities of this glacier nor any reference dealing with this ("slow" is not appropriate here). However, you compare exactly ("intersections of radar transects") the same locations at the surface of 2 consecutive years. This is only possible when the ice velocity

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is 0m p.a. You need to discuss this, since your work is based on
an Alpine glacier with a significant topography (Fig. 1).
```

We agree that this is a critical point and, actually, mean IRH traveltimes within a 25m radius were used in order to reduce the effect of ice flow – but also of the positioning imprecision and GPR footprint size variations.

Added at P4442, L2 [P13, L5]: "*To reduce the effects of ice flow, a potential imprecision of the positioning and differences in the GPR footprint size, the model was applied using the mean IRH traveltimes within a distance of 25m from the common location*."

We now provide information on measured ice velocities at the two accumulation measurement locations on P4447, L13 [P19, L24]: "*Aside from the potential liquid water content, the scheme used to calibrate the model is affected by horizontal ice motion. At the two accumulation measurement sites (Fig. 1), flow velocities are about 35m* yr^{-1} *(northeastern site) and 1 m* yr^{-1} *(southwestern site). For the upper accumulation area, no direct observations of flow speed are available. However, due to a smaller ice thickness, velocities are expected to be considerably lower and to remain within the 25m radius that was used to evaluate the mean IRH traveltimes*."

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C) Concerning the topography, for steep reliefs, your radar data
processing scheme is not adequate. See http://www.sandmeier-
geo.de/Reflex/refl2da.htm for parts where you do make
significant errors for airborne radar data analysis if you lack
a proper topography migration/ correction. It is impossible for
the reader to identify in Fig. 1 with 100m contour lines whether
such a correction is necessary or not. A minor point concerning
the processing routine but nevertheless essential for the
presentation of good radar data is a proper surface correction.
In Fig 2 bouncing surface signals are recognizable while zooming
in. This can easily be corrected in ReflexW! Applying such a
static correction enables further processing to remove noise and
enhance continuous reflectors (running average filters etc.)
```

The terrain at the analysed GPR profile sections has a mean slope of 10deg (15deg 95% percentile, 19deg maximum, extracted from 10x10m DEM). Careful migration of the data using the reflex software was performed, however, we did not find any clear improvement of the GPR data quality by means of migration.

Added sentence on P4436, L25 [P7, L27]: "*Migration was found to not improve the data quality for the given survey design, due to the moderate surface slopes at the analysed GPR measurement locations (95% less than 15deg).*"

We provide an improved Fig. 2 with a new surface correction for several GPR traces. However, we are not entirely sure if this is what Referee #1 referred to by "bouncing surface signals".

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Minor points that should be addressed:
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1. the title indicates that this paper addresses mostly accumulation rates. Please modify to present the major part of this work which is the methodology.

The title was changed to "*Unlocking annual firn layer water equivalents from GPR data on an alpine glacier*".

2. please use SI units and indicate for whenever values have to be converted to fit models

Changed to SI units throughout the manuscript. Also stated units of parameters as suggested by Referee #1.

3. P4432 L3 this is not completely "new" - see van Pelt et al., 2014

Removed "*new*".

4. L10 IRH correspond to density max and/or liquid water occurrences. Changes in liquid water in snow can dominate any density gradients - see Schmid et al., 2014.

We agree that liquid water can generate strong IRH. However, the sentence describes our findings from the firn cores, where IRH corresponded to density maxima. The fact that GPR detects changes in dielectric permittivity such as from density, but also water content and impurities, is stated in the Introduction (P4433, L14 [P3, L14]).

5. P4433 L24-26 this sentence is hardly understandable please rephrase!

[P3, L22] Rewritten: "*Past accumulation rates are typically estimated from a set of pronounced IRH that do not correspond to annual layers. Based on a given a depth--age relation and the density, an average mass balance is obtained for the period that is covered by each pair of IRH.*"

6. P4434 L8 comment while taking melt into account for temperate glaciers. I don't think you can fully neglect residual liquid water in the firn pack. See major point above.

Discussed in the general comments and taken into account.

7. L20-27 I am missing the point here

P4, L23 Revised paragraph: "*Studies that analyse IRH in firn along GPR profiles are typically complemented by cores to provide density, layer dating, and potentially, dielectric characteristics (Pälli et al., 2002; Arcone et al., 2004; Eisen et al., 2006). However, firn cores are expensive in terms of cost and effort and provide point measurements only. Physical models can be used to estimate firn density profiles along GPR profiles. They require various input data such as temperature, precipitation, wind, and terrain to calculate the accumulation rate (Ligtenberg et al., 2011).*"

8. `P4435 L22 indicate in Fig 1 where the AWS are located or give distances in the manuscript.`

P5, L27 Changed to " *data is available from automatic weather stations at Zermatt (1638 m a.s.l. , 6km west of the glacier terminus) and Stockhorn (3421 m a.s.l., 2.5 km south of the glacier terminus).*"

9. `P4437 L11-18 again, the glacier has to be stationary for this kind of analysis, you need to comment on this!`

See general comment (B).

10. `L23 (e.g. Kovacs...)`

Added "*e.g.*"

11. `P4439 L5 you do have sufficient data to prove this is an appropriate assumption, right now it is just a number`

P10, L26 Changed to "*We set its density to $\rho_{f,0}$ = 400kg m^{-3} , which is in line with observations in spring 2010–2013 (395 pm 32kg m^{-3} from 14 measurements ≥ 3200m a.s.l.).*"

12. `L5ff this is kind of too fast here. Please present equations and detailed steps how you convert TWT to accumulation in w.e.`

Section 3.2 was revised to clarify the modelling approach and we provide an additional equation for the conversion from traveltime to water equivalent.

13. `L14 what is "considerably lower" quantify!`

P9, L16 Changed to "… *were not considerably lower (490kg m^{-3}, see below)*" on P4438, L8.

14. `P4440 L3 this is confusing I think you want to rephrase this sentence`

Section 3.2 was revised and does not contain this text fragment anymore.

15. L28ff next page; again the reader would benefit from a more detailed description and presentation of equations which you use e.g. what is the characteristic length scale, time scale etc?

The text fragment was revised (P4440, L27ff [P11, L28]) and now contains a more detailed description of the firn temperature estimation scheme: "*A vertical density profile with a resolution of 0.1 m was set up, consisting of the winter snow cover and the underlying firn layers. The winter snow cover is built up linearly between 1 October and 1 May to reach the thickness estimated from the IRH traveltime. The density was assumed to increase linearly from 100 to 400kg* m^{-3}*. For the firn section the respective modelled end-of-winter density profile was used. The thermal diffusivity of snow and firn was estimated from an empirical relationship with density (Calonne et al., 2011). The heat equation could then be solved numerically on a 1h resolution with a forward in time, central in space scheme.*"

We believe that the manuscript would not benefit from the presentation of the heat equation or its FTCS approximation.

16. P4441 L10 any citation that can support your assumption that T_ss=T_A-4.9 is always valid. I doubt this especially for melt conditions.

We now use mean monthly offsets between air and surface temperature observed at the nearby high-altitude weather station in order to take seasonal variations into account.

[P12, L10] Changed to "*In order to account for differences between the air and snow surface temperatures we applied a mean temperature offset for each month. The offset was obtained from the observed monthly mean difference in 2002--2010 at the Stockhorn weather station that was estimated from the outgoing longwave radiation. The offset is largest in December (-6.71K) and decreases to -3.54K in April.*"

17. L13ff please rephrase to enhance readability

[P12, L18] Revised: "*However, the two models for temperature and density were not fully coupled because they run on different domains. The densification model primarily steps through the layers from top to bottom, whereas the heat conduction is solved over time.*"

18. P4449 L16ff well you could present a plausibility check to prove that it is impossible that this layer does represent a former summer horizon. If you feed your model with this IRH what is the accumulation output. Is it a reasonable value and corresponds more or less with manual measurements? This could be performed almost everywhere, where an AWS can be used to relate radar derived accumulation with precip measurements. I think presenting such a plausibility check may allow you to present the statement in the following lines. Otherwise, you do need firn cores and complex data analysis to relate IRH to summer surfaces. And this is not an efficient data acquisition!

In the revised manuscript we extend the discussion of a verification of the layer dating by providing a comparison with measured mass balance with and without the false IRH included in the analysis (P4446, L22ff [P17, L21ff]), supported by a new figure. Thus, we now show how our approach could be applied if no firn cores were available (see general comments).

Short comment (Pelto)

Sold et al (2014) provide a new approach using GPR to assess accumulation distribution. The key advance in this airborne system is that it can observe multiple accumulation layers over a region assessing the retained accumulation of previous years. The system is validated using just two firn cores. The snowpits are of little value since the most recent years accumulation is not assessed. The approach is sound and the results interesting. The main issue is better illustrating the spatial distribution of accumulation and the poor validation. Better spatial validation is needed going forward, but cannot be expected of the current study.

1. 4433-5: The statement of limited accumulation zone measurements versus ablation stakes is sometimes the reverse and cannot be categorically made. For example on Storglaciaren, Sweden, Brewster Glacier, New Zealand, Columbia Glacier, Easton Glacier, Rainbow Glacier and Sholes Glacier, United States probing densities of accumulation are much higher than ablation measurement (WGMS, 2011; Pelto and Brown, 2012)

[P3, L1] Changed to: "*Ablation can be measured accurately at many locations across a glacier. For many study sites, the main drawback is a lack of accumulation measurements that typically involve the time-consuming excavation of snow pits (Østrem and Brugman, 1991). If measurements of accumulation are under-represented the spatial variability is often not resolved correctly*."

2. 4436-2: The GPR was flown in April and May and is focused on assessment of firn from previous melt seasons not the most recent accumulation season that is just ending. This point should be emphasized here.

[P6, L7] Added: "*Thus, the uppermost firn layer is covered by the recent winter accumulation layer*."

3. 4445-20: A citation that arrives at a similar finding of the percent of retained firn being from refrozen meltwater on a temperate glacier is: Miller and Pelto (1999) who found on Lemon Creek Glacier 10% refrozen meltwater. "To determine how much meltwater is retained in diagenetic ice, the walls of each test-pit have been continually surveyed. In our records from the two field seasons of 1982 and 1984, an average of 10% of the firn stratigraphy comprised this secondary ice at a density of 0.90."

Miller and Pelto (1999) find 10% of the firn comprising of refrozen meltwater in Alaska, while this is only 2% in the case of Findelengletscher. The presented value of 10% refers to the increase in firn densification due to refreezing.

[P16, L19] Added sentence and reference: "*In contrast, a higher value of 10% was measured by Miller & Pelto (1999) on a temperate glacier in Alaska. This may be due to the different climatic condition or a limitation of the model approach that e.g. does not include the formation of blocking layers*."

4. 4444-25: Wadham et al (2006) in Svalbard found a higher ratio of retained meltwater, but did note that this thick layer did represent the annual layer. The higher percent is expected in a more polar setting. The key item is that it was the annual layer where the main refrozen layer formed.

[P4, L8] Revised paragraph in the Introduction P4434, L9: "*To extract past annual accumulation rates from the GPR signal, the IRH must correspond to previous summer surfaces. In polar and sub-polar regions this is confirmed by several studies (e.g., Wadham et al., 2006; Van Pelt et al., 2014). For mid-latitude glaciers with a complex firn stratigraphy it can be difficult to establish this link (Kohler et al., 1997), although the large number of melt–refreeze cycles suggests the generation of a high-density or ice layer at the snow surface during summer. Thus, this precondition must be verified by independent layer dating information.*"

5. 4447-4 or 4449-10: Detailed mass balance can provide more than a plausibility check, it is the best means of validation on this particular glacier. Going forward a simple means of better spatial validation would be to utilize an extensive network of probing at the end of the balance year. That could be contrasted the next spring to the GPR mapping of the second annual layer down. On Storglaciaren the network allows this. On Lemon Creek Glacier we used over 300 probing measurements in 1998 and 2014 to validate our snowpits (Miller and Pelto, 1999). This could be done to validate GPR too.

On Findelengletscher we do not conduct snow probings at the end of the balance year because the determination of the last summer surface is often ambiguous while probing. Accumulation measurements are obtained from two snow pits down to a marked horizon at the sites indicated in Fig. 1. They are inter- or extrapolated using the calibrated mass balance model. This mass balance dataset is already used for a comparison (Fig. 5 and 7). However, in the revised manuscript we provide a validation of our approach using the annual mass balance data (P4446, L22ff [P17, L21ff]).

6. Figure 6: An additional figure of the distribution of accumulation from a single year is needed, to better see the details of spatial variation.

Figure 6 shows four maps of the annual layer water equivalents derived along the GPR profiles. In order to better demonstrate the spatial variability the point values were interpolated to a grid. However, we are convinced that a larger map does not provide a better visualization of the variability of accumulation because the spatial resolution of the measurements is already clearly visible and the small-scale differences are given by interpolation.

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Unlocking annual firn layer water equivalents from GPR data on an alpine glacier

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Abstract

The spatial representation of accumulation measurements is a major limitation for current glacier mass balance monitoring approaches. Here, we present a ~~new~~ method for estimating annual accumulation rates on a temperate alpine glacier based on the interpretation of internal reflection horizons (IRH) in helicopter-borne ground-penetrating radar (GPR) data. For each individual GPR measurement, the signal traveltime is combined with a simple model for firn densification and refreezing of meltwater. The model is calibrated at locations where GPR ~~profiles intersect~~ repeat measurements are available in two subsequent years and the densification can be tracked over time. Two 10.5 m long firn cores provide a reference for the density and chronology of firn layers. Thereby, IRH correspond to density maxima, but not exclusively to former summer glacier surfaces. ~~From GPR profiles~~ Along GPR profile sections from across the accumulation area ~~, we obtain spatial distributions of water equivalent for at least four~~ we obtain the water equivalent of several annual firn layers~~, reaching a mean density of 0.74~~. Because deeper IRH could be tracked over shorter distance, the total length of analysed profile sections varies from 7.3 ~~.Refreezing accounts for 9~~km for the uppermost accumulation layer (2011) to 0.1 km for the deepest, i.e. oldest, layer (2006). According to model results, refreezing accounts for 10 % of the density increase over time and depth and for 2 % of the water equivalent. The strongest limitation to our method is the dependence on layer chronology assumptions. ~~The uncertainties inherent to the modelling approach itself are in the same order of conventional point measurements in snow pits.~~ We show that GPR can be used to complement existing mass balance monitoring programs on temperate alpine glaciers, but also to retrospectively extend newly initiated time series.

1 Introduction

Mountain glaciers are known to be excellent indicators of climatic change (Haeberli and Beniston, 1998; Kaser et al., 2006; IPCC, 2013), but are also important to the hydrology and ecology of alpine regions (Beniston, 2003). In order to better understand their response and adaption, glacier changes are monitored around the globe (Barry, 2006; Zemp et al., 2009). Conventional mass balance measurements are prone to large uncertainties when compared to geodetically derived volume change. The reconciliation of the two approaches is subject of ongoing research (Huss et al., 2009; Fischer, 2011; Zemp et al., 2013). ~~Field measurements of ablation can be taken~~ Ablation can be measured accurately at many locations across a glacier. ~~The~~ For many study sites, the main drawback is ~~the~~ a lack of accumulation measurements that typically involve the time-consuming excavation of snow pits (Østrem and Brugman, 1991). ~~Thus,~~ If measurements of accumulation are underrepresented~~and~~ , the spatial variability is often not resolved correctly in modern monitoring approaches (e.g., Huss et al., 2014). To compensate for this drawback, an adequate complement to conventional accumulation measurements is necessary, which should preferably be non-destructive and efficient.

In glaciology, ground-penetrating radar (GPR) is used for a variety of purposes (Plewes and Hubbard, 2001). The low electrical conductivity of snow and ice facilitates the deep penetration of the signal, and the use of narrow-bandwidth, high-resolution systems (Ulriksen, 1982). Because the signal is reflected from boundaries with a contrast in dielectric permittivity, a change in the related material properties can be detected, such as from ice to bedrock, water content, impurities, but also changes in density are resolved (Plewes and Hubbard, 2001; Woodward and Burke, 2007). Thus, GPR applications range from ice thickness measurements ~~(Robin et al., 1969; Bauder et al., 2003; **?**)~~ (e.g. Robin et al., 1969; Bauder et al., 2003) , to the mapping of snow accumulation distribution (Machguth et al., 2006; Sold et al., 2013; Helfricht et al., 2014), to the observation of internal layers within the snow cover (e.g., Heilig et al., 2010). Thereby, airborne GPR surveys can cover large areas in short periods~~of time~~. On ice sheets, with rather homogeneous accumulation patterns, internal reflection horizons (IRH) within firn and ice can be tracked over long-ranging GPR profiles (Arcone et al., 2004; Huybrechts et al., 2009; Miège et al., 2013; Hawley et al., 2014). ~~Estimates of past~~ Past accumulation rates are typically ~~obtained from the age and density of several~~

~~pronounced but not necessarily annual IRH, which provides the~~ estimated from a set of pronounced IRH that do not correspond to annual layers. Based on a given depth–age relation and the density, an average mass balance ~~for each sequence~~is obtained for the period that is covered by each pair of IRH. Only few studies have observed and analysed the water equivalent of annually spaced IRH in radar data (e.g., Kohler et al., 1997; Hawley et al., 2006; Kruetzmann et al., 2011; Van Pelt et al., 2014), however, not on temperate mountain glaciers in mid- to low latitudes.

On temperate glaciers, or glaciers that are constrained by topography and have complex flow fields, the continuous tracking of IRH is often difficult (Karlsson et al., 2009). Therefore, studies have focused on the mapping of facies zones and other general glaciological characteristics (Pälli et al., 2003; Langley et al., 2008; Eisen et al., 2009; Dunse et al., 2009). On the other hand, GPR could not only accompany ongoing monitoring programs to complement the sparse accumulation measurements with high spatial resolution, but could also be used to retrospectively extend newly initiated time series into the past.

To extract past annual accumulation rates from the GPR signal, the IRH must correspond to previous summer surfaces. ~~On~~ In polar and sub-polar regions this is confirmed by several studies (e.g., Wadham et al., 2006; Van Pelt et al., 2014) . For mid-latitude glaciers ~~this suggests a high potential of GPR for mass balance studies due to the numerous~~ with a complex firn stratigraphy it can be difficult to establish this link (Kohler et al., 1997) , although the large number of melt–refreeze cycles ~~that can generate~~ suggests the generation of a high-density or ice layer at the snow surface during summer. ~~However~~Thus, this precondition ~~needs to~~ must be verified by independent layer dating information. ~~Additionally, to transform~~

Furthermore, an estimate of the propagation velocity is required to convert the GPR traveltime ~~signal to the depth-domain and, ultimately, to obtain the water equivalent, an estimate or measurement of the firn density is required~~ to depth. Because the velocity depends on the density of the material, the latter needs to be measured or estimated (Plewes and Hubbard, 2001). Thus, density introduces an uncertainty, as it also does for ~~all~~ conventional accumulation measurements that are based on ~~thickness determination .~~ the determination of layer thickness. In order to obtain the density and water equivalent of firn layers, meltwater that percolates from the surface into the firn must be taken into account. Aside from its effect on the propagation velocity (Schmid et al., 2014) , it changes the density and water equivalent of firn layers when it refreezes.

Studies ~~based on GPR~~ that analyse IRH in firn along GPR profiles are typically complemented by cores to provide density, layer dating, and potentially, dielectric characteristics (Pälli et al., 2002; Arcone et al., 2004; Eisen et al., 2006). However, firn cores are expensive in terms of cost and effort ~~. Furthermore, they only~~ and provide point measurements ~~and little is known about the spatial variability of density (Lundberg et al., 2006) . On the other hand, physical modelling of snow or firn density over time requires~~ only. Physical models can be used to estimate firn density profiles along GPR profiles. They require various input data such as temperature, precipitation, wind, and terrain to ~~obtain~~ calculate the accumulation rate (Ligtenberg et al., 2011)~~, whereas in mountainous terrain, the precipitation data alone can introduce a strong uncertainty (Lopes, 1996)~~ .

In this study ~~, we combine~~ we obtain IRH traveltimes from GPR data measured in May 2012 by 400 MHz helicopter-borne GPR ~~measurements~~ on Findelengletscher, a temperate alpine valley glacier in Switzerland~~, with~~ . The analysis is limited, however, to the upper part of the glacier where sufficient accumulation allows distinguishing multiple IRH. Due to IRH discontinuities and variations in the GPR signal penetration depth, the analysed subset consists of disjoint profile sections. The chronology of the IRH is directly retrieved from two shallow firn cores. Comparison with density and impurity profiles shows that not all IRH represent former summer surfaces. The measured traveltimes of annual IRH serve as input to a simple transient model for the ~~bulk~~ density of firn layers and the refreezing of meltwater. The model is calibrated ~~at locations where GPR profiles intersect in subsequent years. For each individual GPR trace, this provides the firn layer water equivalents. Comparison with densityand impurity profiles from shallow firn coresshows that not all IRH represent former summer surfaces. By taking this into account, we demonstrate that an estimate for the~~ with an observed change in the IRH traveltimes at multiple locations. They are obtained from a repeat survey conducted in April 2013. The model is run for all analysed GPR measurement locations separately and provides estimates for the density, water equivalent and meltwater refreezing in annual firn layers. Thus, on the basis of the layer chronology from firn cores, we estimate annual accumulation rates for Findelengletscher over a multi-year ~~accumulation of an alpine glacier can be obtained from repeated airborne GPR if complemented with a firn densification model~~period from airborne GPR measurements.

2 Study site and field data

Findelengletscher is a 13 km^2 temperate alpine valley glacier in the vicinity of Zermatt, Switzerland, ranging from 2600 to 3900 m a.s.l. It is situated directly below the main Alpine ridge in north-westerly exposure (Fig. 1). ~~Thus, its accumulation characteristics are strongly determined by the synoptic weather conditions and inflow from the south and south-east.~~ A monitoring program for annual mass balance was started in 2004 (Machguth, 2008) with a network of 13 ablation stakes and two snow pits for density measurements in the accumulation area (Fig. 1). Since 2009, the data record is complemented by measurements of winter mass balance using conventional snow probings and snow pits. The seasonal mass balance measurements are extrapolated to the entire glacier by constraining a distributed accumulation and temperature-index melt model operating on a daily resolution (Huss et al., 2009). The model is calibrated for each year individually using the point measurements of ablation and accumulation and takes into account spatial variations of potential solar radiation and snow accumulation. Meteorological data is available from ~~an automatic weather station~~ automatic weather stations at Zermatt (1638 m a.s.l.~~) and at~~ , 6 km west of the glacier terminus) and Stockhorn (3421 m a.s.l., 2.5 km south of the glacier terminus). A comprehensive description of the model is given in ~~Huss et al. (2009); **?**~~ Huss et al. (2009) . Since the onset of measurements, the average annual mass balance of Findelengletscher is negative which is accompanied by a retreat of the glacier snout (Glaciological Reports, 2011).

Helicopter-borne constant-offset 400 MHz GPR measurements were taken ~~for~~ at Findelengletscher on 10 May 2012 and 14 April 2013. Thus, the uppermost firn layer is covered by the recent winter accumulation layer. The surveys were conducted along regular

500 m × 500 m grid lines covering the entire glacier and had a total profile length of 79 km. With a flying speed of approx. 10 m s^{-1}, measurements were taken ~~with a time increment~~ from 5–20 m above the surface at time intervals of 0.02 s~~from 5–10~~, corresponding to a trace spacing of approximately 0.2 m~~above the surface~~. Together with the position ~~at Differential Global Positioning System~~ obtained from a differential global positioning system (DGPS)~~accuracy~~, a time window of 250 ns was recorded for each trace at a waveform sampling interval of 0.24 ns.

To obtain ground reference data, two shallow firn cores were recovered by mechanical drilling in the upper accumulation area of Findelengletscher on the same date as the GPR measurements in May 2012 (Fig. 1). The choice for the two sampling sites on a smooth ridge at 3495 and 3530 m a.s.l., respectively, was based on the availability of GPR profiles of preceding years at these locations (Sold et al., 2013) and an expected slow glacier flow. The recovered cores were about 10.5 m long and 58 mm in diameter.

3 Methods

3.1 Firn sampling, analysis and dating

The two 10.5 m firn cores recovered during the campaign in spring 2012 using the electromechanical drill FELICS small (Ginot et al., 2002) were stored in polyethylene tubes in sections of 0.5–0.7 m length at −20 °C. After a visual inspection for melt features or dust layers, the outer part of the core was removed and the sections were cut with a resolution of ca. 0.06 m using a band-saw with stainless steel blades and Teflon-covered tabletops and saw guides to derive decontaminated samples of approx. 60 mm × 17 mm × 17 mm dimension. They were melted in individual pre-cleaned 50 mL plastic tubes under inert gas (N_2) before the analysis. The density of each sample was determined gravimetrically from its measured volume. The concentration of the major soluble inorganic cations and anions including ammonium (NH_4^+) and sulfate (SO_4^{2-}) was determined by ion chromatography (Metrohm 850 Professional IC combined with a 872 Extension Module and a 858

Professional Sample Processor autosampler). Additionally, the water stable isotope ratio (δD) was measured using Wavelength-Scanned Cavity Ring Down Spectrometry (Picarro L2130-i).

Dating of the two firn cores was performed by annual layer counting, using the pronounced seasonality of ammonium concentrations and water stable isotope ratios δD, both peaking in summer (Dansgaard, 1964; Eichler et al., 2000) (Fig. 4). A distinct dust layer from the Saharan dust fall on 28 May 2008 (Hostettler and Bader, 2008) found in 10.2 m (Core 1) and 8.5 m (Core 2) depth was used to corroborate the dating. Core 1 and 2 cover the time periods of winter 2007 / 08 to spring 2012 and summer 2007 to spring 2012, respectively.

3.2 GPR data processing

A sequence of processing steps was applied to the GPR data in order to reduce noise and to improve the general visibility of reflectors. The selection of individual processing steps and their parameter settings depend on the field conditions and survey intention and, thus, no universal procedure is available (Annan, 1993; Fisher et al., 1996; Ulriksen, 1982). However, we applied a scheme that was previously used when mapping the snow accumulation distribution on Findelengletscher (Sold et al., 2013) ~~,~~ but with some adjustments to the parameter sets. The scheme consists of a spatial interpolation of traces to ~~match their average~~ a 0.3 m spacing to correct for variations in the helicopter's velocity; a frequency bandpass filter and background removal to reduce noise; and a gain function to account for signal attenuation with depth. Additionally, the profiles were flattened to a horizontal snow surface that is represented by the first and most pronounced reflector. Migration was found to not improve the data quality for the given survey design, due to the moderate surface slopes at the analysed GPR measurement locations (95 % less than 15°). The processing was performed with the software Reflexw (Sandmeier Scientific Software) and ~~was found to sufficiently improve the~~ sufficiently improved data quality without the risk of over-processing and generation of artificial reflectors (Fig. 2). ~~Additionally, the profiles were flattened to a horizontal snow surface that is represented by the first and most pronounced reflector.~~

~~The~~

The analysis of firn layers is limited to locations where accumulation occurs. To extract an annual firn layer, at least two IRH must be present, i.e. representing two subsequent summer surfaces. Furthermore, it must be ensured that between the upper- and lowermost detected IRH all other IRH of summer surfaces are present and can be distinguished. Thus, areas with no or little accumulation as well profile sections where the interpretation was ambiguous were excluded from the dataset. The reduced set of processed GPR data ~~revealed several reflectors within the firn column for disjunct parts of the measured profiles~~ consists of disjunct profile sections in the accumulation area of Findelengletscher (~~Fig. 2~~7.3 km total length for the uppermost firn layer in May 2012) (Fig. 1). The penetration depth of the GPR signal depends on the height of the helicopter above ground and the physical properties of the subsurface. ~~In the accumulation area we found IRH down to~~ Therefore, the IRH of deeper, i.e. older, layers appear in shorter sections, leading to differences in the spatial extent of extracted layers. We found reflections down to about 20 m below the snow surface and a maximum of eight IRH. They were digitised manually in the processing software due to noise and lateral variability in layer thickness which impede a reliable automatic tracking of IRH.

For the evaluation of ~~GPR data from consecutive years~~the GPR repeat measurements in May 2012 and April 2013, we aimed at locating the correspondent of each reflector at its new depth in the ~~subsequent~~ second year. A matching procedure was applied on the traveltime-domain at ~~locations where detected reflectors overlap~~ 12 locations where a sequence of IRH was found in both GPR datasets. (Fig. 1). Thereby, the uppermost IRH in the ~~last~~ second year was omitted, representing the added ~~past~~ first year's accumulation. A free scaling of $\pm 20\,\%$ of the depth of the uppermost reflector in the ~~earlier~~ first year was applied, which experiences the strongest compaction over the year. Then, the one-to-one mapping of reflectors was found with the minimum distance in the time-domain.

3.3 Modelling firn density

An assumption of estimate for the dielectric permittivity of the firn is required to obtain the radar wave velocity, converting the two-way travel time of the GPR signal from time- to depth-domain. Density strongly affects the dielectric properties of snow and firn and several empirical formulas exist to estimate the permittivity (Kovacs et al., 1993; Frolov and Macheret, 1999) (e.g. Kovacs et al., 1993; Frolov and Macheret, In addition, the density is required to ultimately determine the water equivalent of firn layers.

We used the approach to by Reeh (2008) to model firn layer compaction by Reeh (2008) . It is based on the empirical steady-state model of Herron and Langway (1980), which assumes density changes over time t to be linearly related to the pressure of overlying snow or firn:

$$\frac{\mathrm{d}\rho_\mathrm{f}}{\mathrm{d}t} = c\cdot(\rho_\mathrm{ice} - \rho_\mathrm{f}), \tag{1}$$

where ρ_f is the density of the firn fraction of an annual layer, ρ_ice is the density of ice and c is a dimensionless parameter depending on the mean annual firn temperature T $T\,[\mathrm{K}]$ and the average mass balance $\bar{b}$ $\bar{b}\,[\mathrm{m\,w.e.\,yr^{-1}}]$ that controls the overlying weight. It is split apart by $\rho_\mathrm{f} = 550\,\mathrm{kg\,m^{-3}}$ to respect different stages during the densification process (Herron and Langway, 1980). Here, we neglect the lower stage ($\rho_\mathrm{f} < 550\,\mathrm{kg\,m^{-3}}$), because the model will be calibrated and measured autumn snow densities were not considerably lower (492 $\mathrm{kg\,m^{-3}}$, see below). For $\rho_\mathrm{f} \geq 550\,\mathrm{kg\,m^{-3}}$ c is obtained as

$$c = k\cdot(\bar{b}\cdot\rho_\mathrm{ice})^{0.5} \quad \text{with} \tag{2}$$

$$k = f\cdot\exp\left(-\frac{21\,400}{R\cdot T}\,\frac{E}{R\cdot T}\right), \tag{3}$$

where R $R = 8.314\,\mathrm{J\,K^{-1}\,mol^{-1}}$ is the gas constant and f is an emprirically , $E = 21\,400\,\mathrm{J\,mol^{-1}}$ the activation energy, and $f\,[\mathrm{m^{-0.5}\,yr^{-0.5}}]$ is an empirically derived constant controlling the densification rates. This steady-state approach was used by Reeh

(2008) but with variable accumulation rates, initial densities and air temperatures. The density $\rho_{\mathrm{f}}(t,t_{\mathrm{d}})$ of an annual firn layer t years after its deposition at t_{d} is then given by solving Eq. ~~(1)~~ 1 as an initial value problem with $\rho_{\mathrm{f}}(0,t_{\mathrm{d}})$ being the layer's individual initial density. Thereby, instead of assuming steady-state conditions, an individual c is obtained for each layer from the mean annual mass balances $\overline{b_{\mathrm{prev}}}$ and mean annual temperatures of the $t-1$ preceeding years since deposition.

In the context of our study, the local annual mass balances are initially unknown and the model cannot be applied as it is. However, along the GPR profiles, the ~~traveltime-thickness~~ IRH traveltimes of firn layers and the snow cover are given. We used this information to progressively derive the unknown densities $\rho_{\mathrm{f},i}$ and water equivalents, ω_i of all $i=1,\ldots,n$ layers at the time of the GPR measurements, i.e. t_i years after each layer was deposited at t_{d}. ~~According to Reeh (2008) , t_{d} is attributed to the end of the respective melting season. Therefore, we set the age of the first annual firn layer ($i=1$) as$t_1=0.3$yr. This accounts not only for the GPR measurements taken in the following spring but also for the associated compaction processes which are stronger during the summer months due to higher temperatures and the refreezing of meltwater. For all subsequent layers we set $t_{i+1}=t_i+1$yr. Based on several years of in-situ winter accumulation measurements, we assumed a density of 0.40for the overlying snow cover. Its water equivalent ω_0 could then be extracted from the GPR traveltime~~ We follow Reeh (2008) by substituting the long-term mean mass balance in Eq. 2 with the mean water equivalent of the $i-1$ overlying firn layers to obtain an individual proportionality factor c_i for each firn layer as

$$c_i = k\cdot\left(\sum_{j=0}^{i-1}\omega_j\cdot t_i^{-1}\right)^{0.5}. \tag{4}$$

This allows estimating the density $\rho_{\mathrm{f},i}$ of a firn layer by solving Eq. 1 over t_i, the time since layer deposition, if the initial density $\rho_{\mathrm{f}}(0,t_{\mathrm{d}})$ and the water equivalents of overlying firn layers are given. Then, the difference in IRH two-way traveltime τ_i can be converted to the firn layer water equivalent ω_i by

$$\omega_i = 0.5 \cdot \tau_i \cdot v(\rho_{\mathrm{f},i}) \cdot \rho_{\mathrm{f},i}\,, \tag{5}$$

with the radio wave velocity $v(\rho_{\mathrm{f},i})$ estimated from the density using the empirical relation by Frolov and Macheret (1999). Thus, an estimate for its pressure on the lower firn layers ($i \geq 1$) was derived. For the subsequent firn layer the compaction rate c_{i+1} was then obtained by replacing the average mass balance $\bar{b}$ in

When the density of the uppermost layer is known, Eq. (2) by the mean water equivalents of all overlying layers $\omega_0, \ldots, \omega_i$. Additionally, we neglected the lower densification stage ($\rho_\mathrm{f} < 550\,\mathrm{kg\,m^{-3}}$) that was suggested by Herron and Langway (1980) , because the compaction rate will be calibrated and measured autumn snow densities were not considerably lower (see below).An individual compaction rate c_{i+1} for each firn layer was then derived from the water equivalent of the overlying layers as

$$c_{i+1} = k \cdot \left(\sum_{j=0}^{i} \omega_j \cdot t_{i+1}^{-1} \cdot \rho_{\mathrm{ice}} \right)^{0.5},$$

where the density of ice was set to $\rho_{\mathrm{ice}} = 0.918$.

The density of the next layer was then derived by solving Eq. (1) with the initial density $\rho_\mathrm{f}(0, t_\mathrm{d})$ as boundary condition. This provided the GPR wave velocity and the water equivalent ω_{i+1} of that layer. Likewise, the 5 provides its water equivalent and Eqs. 6 and 1 can be used to estimate the density of the second layer. The densities and water equivalents of all firn layers were estimated by stepping through the layers $i = 1, \ldots, n$ and using the overlying water equivalent to derive its density t_i years after deposition, i.e. its age at time of the GPR measurements. Although this approach does not take into account the internal layer densification due to its own weight, spatial variations in a layer 's density are obtained through the weight of overlying snow cover and firn layers. Furthermore, our procedure neglects the variability of the loading history, affecting the rate of compaction with depth

(Reeh, 2008) . other layers can then be calculated similarly in a stepwise manner by using the previously obtained water equivalents of all overlying layers. In our case, the uppermost layer ($i = 0$) is the winter snow cover. We set its density to $\rho_{f,0} = 400\,\mathrm{kg\,m^{-3}}$, which is in line with observations in spring 2010–2013 ($395 \pm 32\,\mathrm{kg\,m^{-3}}$ from 14 measurements ≥ 3200 m a.s.l.). According to Reeh (2008) , the deposition of a layer at time t_d is attributed to the end of the respective melting season. Because the GPR measurements were taken in spring, we set the age of the first annual firn layer ($i = 1$) as $t_1 = 0.3$ yr. This also accounts for the associated compaction processes beiing stronger during the summer months due to higher temperatures and the refreezing of meltwater. For all subsequent layers we set $t_{i+1} = t_i + 1$ yr.

The inputs to define are f controlling the compaction rate, the firn temperature T, and the initial density $\rho_f(0, t_d)$. In order to To account for the temperate nature of Findelengletscher, temperature was set to $T = 0\,°\mathrm{C} = 273.15\,\mathrm{K}$ (constant). Although k is dependent on the firn temperature (Eq. 2), any change to the constant value will be compensated by the calibration of f. On the other hand, a dynamic implementation of the heat transfer from air into the firn column would not only require a fully coupled model for refreezing, but also for melting at the surface and the percolation of meltwater. For the initial firn density we used $\rho_f(0, t_d) = 0.49 \rho_f(0, t_d) = 492\,\mathrm{kg\,m^{-3}}$ as the mean density measured within the conventional glaciological accumulation measurements at the end of the summer in 2010–2013. We obtained derived a conservative uncertainty estimate of $\pm 0.061 \pm 61$ from the standard deviation $\mathrm{kg\,m^{-3}}$ from the mean standard deviations of (1) multiple density measurements within the same snowpits(measurement error , i.e. the measurement error ($\pm 21\,\mathrm{kg\,m^{-3}}$), (2) the spatial variability within single years, i.e. the spatial variability ($\pm 31\,\mathrm{kg\,m^{-3}}$) and (3) at locations with annual repeat measurements, i.e. the temporal variability ($\pm 49\,\mathrm{kg\,m^{-3}}$). The initial density is assumed to be spatially and temporarily constant. However, as the uppermost firn layer is of age $t = 0.3$ $t_1 = 0.3$ yr, it experienced compactionand thus. Thus, this assumption does not imply a spatially homogeneous layer density, but rather defines the initial (i.e. the preceding autumn) model condition.

3.4 Refreezing of meltwater

Due to cooling from the surface during winter, firn can periodically have temperatures below 0 °C even on temperate glaciers. Thus, the refreezing of meltwater percolating into the firn column has to be taken into account by the firn densification scheme, because the The relocation and refreezing of water does not only alter surface meltwater alters the water equivalent of firn layers but also and affects their density. We numerically modelled the Because of the temperate conditions, we assume that during each summer all subfreezing temperatures are compensated by the refreezing of meltwater. This is supported by the direct observations of summer mass balance, that generally indicate > 1 m w.e. of snow melt during the summer months. Thus, the amount of refreezing is given by the firn temperature profile that is generated by the surface cooling during winter. We calculate a one-dimensional end-of-winter firn temperature profile at each GPR measurement location using heat conduction from the surface . This is a reasonable approximation as no melting occurs in the accumulation area of Findelengletscher over the winter season. The thermal diffusitivity of snow was estimated from an empirical relationship with snow density (Calonne et al., 2011) . To obtain a conservative estimate for the end-of-winter temperature profile, the respective modelled end-of-winter density profile was usedin the period from 1 October to 1 May. A vertical density profile with a resolution of 0.1 m was set up, consisting of the winter snow cover and the underlying firn layers. The winter snow cover was distributed is built up linearly between 1 October and 1 May and its to reach the thickness estimated from the IRH traveltime. The density was assumed to increase linearly from 0.1 to 0.4100 to 400 . Due to the temperate conditions, we could assume that all negative temperatures are compensated by the refreezing of meltwater. kg m^{-3}. For the firn section the respective modelled end-of-winter density profile was used. The thermal diffusivity of snow and firn was estimated from an empirical relationship with density (Calonne et al., 2011) . The heat equation could then be solved numerically on a 1 h resolution with a forward in time, central in space scheme.

We applied the model to every annual layer and all ~~years within its individual history using the air temperature record from~~ winter periods since its deposition using the daily mean air temperature at the automatic weather station at Stockhorn, corrected for elevation with a moist adiabatic lapse rate of $-0.006\,\mathrm{K\,m^{-1}}$. In order to account for differences between the air and snow surface temperatures we applied a ~~constant offset of -4.9as the observed long-term mean difference estimated from outgoing longwave radiation~~ mean temperature offset for each month. The offset was based on the observed monthly mean difference in 2002–2010 at the Stockhorn weather station ~~during the winter months. The~~ that was estimated from the outgoing longwave radiation. The offset is largest in December ($-6.7\,\mathrm{K}$) and decreases to $-3.5\,\mathrm{K}$ in April. For each year and each layer, the amount of refrozen meltwater was ~~annually~~ calculated from the specific heat capacity of snow and the latent heat of fusion and was added to the ~~density and water equivalentof the affected layers.~~ layer water equivalent. The given layer thickness then allowed updating its modelled density.

However, the two models for temperature and density were not fully coupled because ~~the~~ they run on different domains. The densification model primarily steps through the layers from top to bottom, whereas the heat conduction ~~was~~ is solved over time. Thus, each year's density profile remains static in the temperature model, whereas the layer water equivalents stay constant within the densification model but are adjusted separately. This is in line with the model itself neglecting variations in the loading history of each firn layer.

3.5 Model calibration

Aside from the refreezing, the change in density over time is controlled by the density contrast to the density of ice and the weight of overlying layers (Eq. 6). The model sensitivity to those variables is controlled by the ~~change rate c that is scaled by the~~ factor f (Eq. 3). Changes in f propagate through the entire model as they do not only affect the densities of individual layers, but also their water equivalent, their weight and, ~~thus~~hence, the modelled densities of the following layers. Because the initial density $\rho_\mathrm{f}(0,t_\mathrm{d})$ can be constrained with conventional measurements in autumn, we used the parameter f to calibrate the model to our site characteristics.

At locations ~~were GPR profiles intersected in the two consecutive years~~where repeat GPR measurements are available in 2012 and 2013, the density change of each layer was modelled over the time of one year. To reduce the effects of ice flow, a potential imprecision of the positioning and differences in the GPR footprint size, the model was applied using the mean IRH traveltimes within a distance of 25 m from the common location. In order to obtain the new overlying weight on each layer, the ~~traveltime thickness~~ IRH traveltimes of the snow cover and the new annual accumulation layer were considered. The resulting layer densities for the second year were used to estimate the respective hypothetical GPR signal traveltimes. ~~By comparing the~~ The model was calibrated with a scaling factor of $f = 2614\,\mathrm{m}^{-0.5}\,\mathrm{yr}^{-0.5}$ (Eq. 2) that was found by minimising the root-mean-square deviation of the modelled and measured ~~traveltime thicknesses~~ IRH traveltimes of 35 layers at 12 locations (Fig. 1)~~, the optimal scaling factor $f = 2900$ within the change rate formulation c (Eq. 2) was found.~~ . However, the temporal density change also depends on the density contrast that is linked to the initial density. Therefore, the optimal value of f is related to the choice of $\rho_\mathrm{f}(0, t_\mathrm{d})$ (Fig. 3).

3.6 ~~Firn sampling, analysis and dating~~

4 Results and discussion

~~The two 10.5firn cores recovered during the campaign in spring 2012 using the electromechanical drill FELICS small (Ginot et al., 2002) were stored in polyethylene tubes in sections of 0.5–0.7length at -20. After a visual inspection for melt features or dust layers, the outer part was removed and the sections were cut with a resolution of ca. 6using a band-saw with stainless steel blades and Teflon-covered tabletops and saw guides to derive decontaminated samples of approx. 60$\times$17$\times$17dimension. They were melted in individual pre-cleaned 50mL plastic tubes under inert gas (N_2) before the analysis. The density of each sample was determined gravimetrically from its measured volume. The concentration of the major soluble inorganic cations and anions including ammonium (NH_4^+) and sulfate (SO_4^{2-}) was determined by ion chromatography (Metrohm~~

850 Professional IC combined with a 872 Extension Module and a 858 Professional Sample Processor autosampler). Additionally, the water stable isotope ratio (δD) was measured using Wavelength-Scanned Cavity Ring Down Spectrometry (Picarro L2130-i).

Dating of the two firn cores was performed by annual layer counting, using the pronounced seasonality of ammonium concentrations and water stable isotope ratios δD, both peaking in summer (Dansgaard, 1964; Eichler et al., 2000) (Fig. 4). A distinct dust layer from the Saharan dust fall on 28 May 2008 (Hostettler and Bader, 2008) found in 10.2(Core 1) and 8.5(Core 2) depth was used to corroborate the dating. Core 1 and 2 cover the time periods summer 2008 to spring 2012 and summer 2007 to spring 2012, respectively.

5 Results

4.1 Local results at firn core locations

We observed a variable density profile for both firn cores that increased with depth (Fig. 4). Maximum densities corresponded to melt features of bubble free or poor bubble-free or -poor ice. They are more transparent and form when surface snow melts and the meltwater percolates into deeper layers where it fills the pores and refreezes. In many cases melt features involve enhanced concentrations of NH_4^+ and δD. Due to the temperate conditions at the drilling site, refreezing of meltwater contributes to the densification of firn and alters the water equivalents of firn layers, but also strongly influences the chemical and stable isotope composition (Ginot et al., 2010). The drilling took place in spring 2012 and thus, the snow accumulation of winter 2011/12 did not experience major melting. In contrast, the firn layers below experienced one or more cycles of melting and refreezing, leading to an enhanced smoothing of seasonal variations and potentially, a partial relocation of chemical species. Nevertheless, in agreement with studies of on the nearby polythermal Grenzgletscher (Eichler et al., 2001), NH_4^+ and δD seasonal cycles were still detectable, even under temperate conditions.

The measured density profile allowed for a direct estimation of the GPR signal velocity using the empirical relation by Frolov and Macheret (1999). On the traveltime-domain, we observed agreement between the GPR signal and pronounced changes in the density profile (Fig. 4), suggesting that the reflectors were composed of dense layers. This underlines the high potential of GPR for the detection of summer layers. However, not all density maxima and melt layers correspond to a former glacier summer surface, but can also originate from exceptional melting and refreezing in other seasons, or from percolation of melt water into deeper parts of the firn. In core 1 at a depth of 9.2 m (7.2 m in core 2) the accumulation layer of 2009 contained a pronounced ice layer of 0.12 m (0.15 m) thickness, corresponding to maximum measured densities of ~~0.86~~856 ~~(0.85~~kg m^{-3} (853 kg m^{-3}) (Fig. 4). The low δD ratio implies low temperatures during the formation of the precipitation that was incorporated into the ice layer by in-situ densification or refreezing. We suppose that this layer was formed by surface meltwater that was hindered from further percolation by a blocking layer, such as a boundary with a change in the grain structure or a thin ice layer (Pfeffer and Humphrey, 1996). This is supported by a high concentration of most of the measured ions right below the ice layer (e.g. SO_4^{2-}) that typically just extends over one or two samples. By preventing meltwater from percolating and refreezing underneath the ice layer, the chemical composition is preserved and does not experience enhanced smoothing. After a period of major snow falls, high wind-speeds and mild temperatures were registered on 20 December 2008. It was followed by ~~high radiation~~ clear weather until mid January (Etter et al., 2011). We suggest that this allowed the formation of a dense layer at the surface of a fresh snow pack, creating a hydraulic barrier for meltwater formed later in the season. Because no defined clear ice layer was built up in the following summer of 2009 (Fig. 4), meltwater of several seasons could have penetrated down to, and have been retained above the blocking layer, resulting in the thick ice layer with a considerable water equivalent within the firn layer of 2009 and a strong IRH in the GPR signal.

4.2 Spatial extraction of recent accumulation rates

The firn core profiles of density, NH_4^+ concentrations, and δD ratios suggested that, aside from the ice lens inherent to the 2009 accumulation layer, the IRH can be attributed to dense summer layers. In fact, the related reflection in the GPR signal was observed across the entire accumulation area in all analysed profile sections and was more pronounced at higher altitudes. The spatial continuity of the ice layer is further supported by its evidence in both firn cores. By disregarding the respective IRH, the water equivalents of annual accumulation layers were extracted. As described above, the firn densification model was applied to each GPR trace individually all GPR traces individually where multiple IRH were found that correspond to subsequent previous summer surfaces. Thus, the analysis is limited to areas where sufficient annual accumulation allows distinguishing the corresponding IRH. Furthermore, a continuous tracking of IRH is impeded due to crevasses, ice dynamics, irregular accumulation such as avalanche deposits, changes in the distance of the helicopter to the snow surface, or lateral variations in layer properties that determine the strength of IRH. The total length of analysed IRH was, 7.3 km, 6.8 km, 5.9 km, 2.8 km, 1.3 km, and 0.1 km for the accumulation layers of 2011 to estimate local layer densities based on the weight from overlying layers 2006, respectively.

Conventional glaciological measurements refer to the annual surface mass balance, as they are taken from the recent accumulation layer in the end of the hydrological year. This layer experienced melting and the meltwater, which may partially refreeze deeper in the firn column, is not covered by the measurement. In contrast, water equivalents obtained from IRH traveltimes contain internal accumulation originating from surface melt in multiple seasons. As our goal is to reconstruct surface mass balance, consistent with conventional measurements, the computed quantity of refrozen meltwater was subtracted from each layer and was not re-attributed to its source layer. Layer water equivalents were then derived from the IRH traveltime-thicknesses and the density-based GPR wave velocity estimate.

The water equivalents of annual firn layers derived from GPR exceeded those obtained by spatial extrapolation of conventional mass balance measurements, albeit reproducing their temporal pattern (Fig. 5a). This can be attributed to the limited number of direct observations in the mass balance monitoring programme and the extrapolation scheme applied. Layer water equivalents derived from the firn cores revealed similar discrepancies with extrapolated mass balance. These findings highlight the need for a further investigation and better representation of accumulation processes in current glacier mass balance monitoring programs.

The spatial distribution of each annual layer's water equivalent showed a considerable small- and medium-scale variability, following the general topography to some degree (Fig. 6). The large-scale pattern of areas with increased annual accumulation rates recurs in all four analysed layers. However, with increasing depth, older IRHs were more difficult to locate in the radargrams and appear in shorter profiles sections, thus hampering a direct temporal comparison of the accumulation patterns. Modelled layer densities increased with age as expected (Fig. 5b) reaching a mean value of 0.74728 kg m^{-3} four years after deposition. The cumulative effect of spatial variations in layer water equivalent, together with the fixed initial density in the densification model, results in a higher variability of the density of deeper, i.e. older, firn layers. Refreezing is a considerable contributor to firn densification on alpine glaciers. It accounted for approx. 910 % of the density increase over time and depth (Fig. 5b)and corresponds to a mean of 28. At the analysed GPR measurement locations the annual internal accumulation in the entire firn column is about 0.028 over the entire firn column in the accumulation area of Findelengletscher. m w.e. yr^{-1}, affecting several previous accumulation layers. In summer 2011 the accumulation layers of 2010, 2009, and 2008 gained 0.019 m w.e., 0.007 m w.e., and 0.001 m w.e., respectively. On average, 2 % of the firn stratigraphy is made up by refrozen meltwater. In contrast, a higher value of 10 % was measured by Miller and Pelto (1999) on a temperate glacier in Alaska. This may be due to the different climatic condition but can also be related to processes not incorporated in the model, such as the formation of blocking layers and the storage or lateral flow above such barriers.

The conservative uncertainty estimate for the initial model density that covers measurement uncertainty, spatial and temporal variability, and the related uncertainty introduced within the model calibration affects the modelled layer densities and thus, the layer water equivalents by ~~7~~ $\pm 8\,\%$ (Fig. 5a). ~~A conventional glaciological point accumulation measurement is only slightly better (± 0.021~~For conventional glaciological accumulation measurements the density measurement error is approx. 4 ~~density measurement error), but lacks any information about the spatial distribution. By combining GPR with the model for firn density a~~ % ($\pm 21\,\mathrm{kg\,m^{-3}}$ from repeat measurements). In contrast, the combination of GPR with a firn density model provides a considerable spatial coverage for ~~four~~ several annual accumulation layers ~~can be obtained~~ with a small trade-off in terms of uncertainty.

5 ~~Discussion~~

4.1 Data interpretation and error analysis

Generally, the formation of ice layers is not limited to surface processes. At boundaries with changes in the grain structure or on top of a blocking layer, e.g. a thin ice layer, meltwater can be retained (e.g., Pfeffer and Humphrey, 1996). Thus, an outstanding weather event during winter is not a necessary criterion to generate an ice lens that can potentially be misinterpreted as a former summer surface in the GPR signal. In the case of Findelengletscher, such a layer could be identified within the 2009 accumulation layer with the help of reference data from firn cores. Ultimately, the presented method of deriving past accumulation rates from GPR is based on the interpretation of GPR profiles by an observer, with the IRH relating to high-density layers (Fig. 4). Therefore, the interpretation of GPR data can be ranked similar to a visual and density-based interpretation of a firn profile.

Conventional glaciological measurements, comprising snow probings and snow pits for density measurements, are likewise prone to misinterpretations of the stratigraphy. This can be either visually in a snow pit, by hitting an internal ice layer, or by penetrating the designated summer surface during probing. In contrast to the presented approach, conventional accumulation measurements are conducted on an annual basis, cover individual years and thus, do not require interpretation of multiple layers. ~~On the other hand, a~~

Like it is the case for all approaches that rely on annual layer counting, a misinterpretation of an IRH affects not only the estimated water equivalent of the respective accumulation layer, but in fact, . Because the chronology of all following layers , by shifting the chronology of the layers. However, this source of error is inherent in all approaches that rely on annual layer counting. An independent verification is shifted, an independent evaluation of the annual character of IRH requires either is essential. We assessed potential alternatives to the in-situ measurements from firn cores or a model that can simulate the relevant small-scale processes. This comprises solving the surface energy balance , heat transfer, water percolation, and formation of internal hydraulic barriers such as ice layers (Mitterer et al., 2011) . Modelled or independently measured mass balance data could be usedfor a plausibility check (e.g., Van Pelt et al., 2014) . We showed that the weak representation of the spatial distribution of accumulation is a drawback in current mass balance extrapolation schemes (Figdating through firn cores by comparing the mean GPR-derived accumulation layer water-equivalents to mass balance measurements and winter precipitation sums. Despite the small number of data points when comparing annual mean values ($n = 5$) and the resulting low statistical significance of the results, Pearson product-moment correlation was chosen to depict a potential linear relation between the datasets. When the correct chronology from the firn cores is used to derive accumulation from IRH traveltimes, correlation with extrapolated mass balance measurements is $r = 0.57$, but insignificant ($p = 0.32$). If the ice lens within the 2009 accumulation layer was misinterpreted as a former summer surface, the water equivalents for the layers of 2009 and 2008 are strongly reduced and the dating of all following layers is shifted by one year (Fig. 7a). This results in a reduced correlation with the extrapolated mass balance of $r = 0.41$ ($p = 0.50$). Because mass balance measurements are not available at locations covered by analysed GPR profile sections this comparison relies on the extrapolation scheme used. 5a)and thus, such a comparison requires a cautious interpretationWe suggest that this explains the large overall deviation between the two datasets (Fig. 5) and the insignificance of the presented correlations. A similar comparison was performed with precipitation sums for the months October to April at the

Zermatt weather station. To avoid the effect of variations in spatial extents of analysed layers, only sections covering all layers of 2007–2011 were used. With the correct dating from cores, correlation of winter precipitation sums with GPR-derived water-equivalents was $r = 0.87$ ($p = 0.06$) (Fig. 7b). In contrast, it reduces to $r = 0.10$ ($p = 0.87$) when the chronology is disturbed by the extra layer in 2009. Both approaches cannot provide a validation as robust as through firn cores, particularly if multiple layers are missing or misinterpreted. However, in the given case, the peak in measured accumulation and winter precipitation sum in 2009 is only reproduced with the correct chronology. We suggest that such a comparison can aid an extraction of accumulation rates from GPR data when no firn cores are available.

To convert IRH traveltimes to depth and water equivalent we apply an empirical relation of density and the dielectric permittivity of firn (Frolov and Macheret, 1999) . However, this relation has been determined for dry snow conditions while the presence of liquid water has a considerable effect on the dielectric properties (Schmid et al., 2014) . In our case, the GPR-derived layer water equivalents exceed the extrapolated mass balance measurements while reproducing the temporal patternstudy, the analysed IRH traveltimes were derived from GPR measurements in spring (May 2012 and April 2013). Field measurements of temperature in the snow cover in the accumulation area in April 2014 reveal subfreezing conditions apart from a shallow surface layer. Thus, relative deviations could still be used for a first comparison. By relying only on the firn cores, we avoid an unstable verification approach and remain independent from measurements taken in years before the GPR survey andthe presence of liquid water in upper firn can be ruled out at this time of the year. On the other hand, residual water from previous melting seasons might be present deeper in the firn. This has a potential impact on the evolution of the temperature profile over the winter season because latent heat is released when it refreezes. More importantly, it affects the GPR propagation velocity and, thus, the resulting layer water equivalents. The potential impact was assessed using a rather conservative hypothetical liquid water content of 5 % vol. and the mixing formula for dielectric permittivity by Looyenga (1965) . The related change in the resulting layer water equivalent is about -16 %, comprising the direct effect on the estimated layer thickness (Eq. 5), as well as the effect on the modelled densities. However, comparison with the firn cores showed good agreement in the ~~extrapolation of sparse measurements.~~ depths of IRH (Fig. 4) and, thus, no evidence for the presence of liquid water. On the other hand, this finding cannot be transferred to the lower parts of the accumulation area, and does not necessarily hold for all investigated years.

The firn densification model ~~was~~ is calibrated with the observed ~~change in~~ changes in IRH traveltime from spring 2012 to 2013 at 12 locations and for 35 firn layers. ~~The fitting procedure is not exceptionally stable because an adjustment of the change rate c with the scale factor f (Eq. 3) affects the densities of layers, their water equivalent and thus, their pressure on the underlying firn mass (Eq. 6). On the other hand, the density change is linearly dependent on the contrast to the density of ice (Eq. 2)and the two effects counteract each other in the calibration scheme.~~ Therefore, a different amount of liquid water at the date of the measurements could lead to an over- or underestimation of the compaction rate. This could, to some degree, account for the compaction rate scaling $f = 2614\,\mathrm{m^{-0.5}\,yr^{-0.5}}$ being higher than previously published values. When the model was originally set up, Herron and Langway (1980) obtained $f = 575\,\mathrm{m^{-0.5}\,yr^{-0.5}}$ for densities above 550 $\mathrm{kg\,m^{-3}}$, but using ice cores in cold firn on Greenland and Antartica. Huss (2013) calibrated the same model with a set of 19 firn cores from temperate and polythermal mountain glaciers and ice caps in the European Alps, Western and Arctic Canada, Central Asia, Patagonia, and Svalbard. The larger value of $f = 1380\,\mathrm{m^{-0.5}\,yr^{-0.5}}$ is in line with the different climatic conditions and different firn compaction regimes compared to the original formulation.

Aside from the potential liquid water content, the scheme used to calibrate the model is affected by horizontal ice motion. At the two accumulation measurement sites (Fig. 1), flow velocities are about 35 $\mathrm{m\,yr^{-1}}$ (northeastern site) and 15 $\mathrm{m\,yr^{-1}}$ (southwestern site). For the upper accumulation area, no direct observations of flow speed are available. However, due to a smaller ice thickness, velocities are expected to be considerably lower and to remain within the 25 m radius that was used to evaluate the mean IRH traveltimes.

In order to obtain a reliable change rate in the model we did not run the calibration ~~on~~ for individual locations to account for spatial variations in the densification regime. Rather, the derived parameter set was assumed to represent the mean temporal and spatial condition for the investigated site. Comparison with the densities and layer water equivalents derived from the firn cores ~~showed that the local deviations are within the uncertainty range provided by the initial density~~ revealed a moderate overestimation of the local densities for the 2010 and 2009 accumulation layers resulting in difference of 9 % for the water equivalents (Fig. 8~~a). When~~). This also holds when hypothetical GPR traveltimes ~~of the layers~~ are calculated from the ~~density and water equivalent of the firn core, the modelrevealed an adequate density for the topmost layer . For the following layers of 2010 and older, densities were too high (Fig. 8b) , accounting for 9of their water equivalent. This indicates that for this individual location the given initial density is reasonable, but the change rateis too high~~measured densities to run the model. Because the density estimate for the uppermost firn layer (2011) and, thus, the initial model density is adequate, this indicates an overestimation of the compaction rate. We suggest that this discrepancy is due to spatial variations in the density regime, related to processes not incorporated in the model, such as the snow grain structure, the temperature-dependence of densification processes, or ~~the~~ particular weather conditions~~in general~~.

~~Throughout the entire study we refer to the water equivalent of firn layers in the sense of annual accumulation rates. We modelled refreezing melt water within the firn each year by using a daily time series of temperature data to calculate the temperature profile of the firn column that is entirely compensated by refreezing. However, this approach only takes into account the effect on bulk layer density and water equivalent but does not shift mass between layers. This is in line with conventional glaciological measurements that only cover the uppermost accumulation layer and thus, similarly miss the additional accumulation that is generated by refreezing in firn layers of previous years deeper in the firn column. As our GPR measurements were conducted in spring 2012, however, the winter accumulation of 2011/12 did not experience major melting and therefore, no external refreezing is expected to have occurred in the topmost firn layer representing the accumulation of 2011. In order to consistently quantify vertical mass fluxes in the firn throughout the year, a coupled energy-balance – snow model can be complemented with~~

~~GPR data. Van Pelt et al. (2014) calibrated the accumulation routine of such a model by matching modelled and observed IRH traveltimes. This provides the adjusted accumulation distribution, but requires numerous input data in order to solve the surface energy balance.~~

The water equivalent stored as firn between IRH also differs from the accumulation ~~part~~ component within the mass balance term regarding the ~~temporal breaks between years~~definition of a 'year'. Mass balance monitoring approaches typically use the hydrologic year, with 30 September marking the end of the ablation period ~~on~~ in the Northern Hemisphere. In contrast, the analysis of the GPR data is based on the firn stratigraphy, where the build-up of a high-density layer due to particular weather conditions provides the chronology of firn layers. Thus, a comparison or combination of such data sets requires ~~conversions~~ converting between the stratigraphic and the fixed-date mass balance (Mayo et al., 1972; Huss et al., 2009), but does not generally conflict with the mass balance concept. With a coupled energy-balance – snow model the temporal evolution of accumulation layers can be tracked. Van Pelt et al. (2014) calibrated the accumulation input to such a model by matching modelled and observed IRH traveltimes. With this inverse approach they obtain the adjusted accumulation distribution along a GPR transect on a polythermal Svalbard glacier. Their model solves the surface energy balance and computes percolation, capillary storage, refreezing and runoff of liquid water to provide subsurface density, temperature, and water content. Storage and lateral flow of water on top of ice layers are not resolved. Postdepositional processes related to refreezing are taken into account. Thereby, uncertainties in the model initialisation and physics directly affect the obtained accumulation patterns (Van Pelt et al., 2014) . In this study, we used IRH traveltimes as input to a simple model for firn densification and meltwater refreezing. Thus, firn layer water equivalents could be derived in a forward approach. Our model involves strong assumptions on liquid water content and percolation, temperature evolution and densification of firn. By assuming that all subfreezing temperatures are compensated by meltwater refreezing we avoid modelling melt rates. This is reasonable under temperate conditions, but precludes an application to cold firn. On the other hand, a sound representation of physical processes depends on extensive input data such as air temperature, pressure, humidity, precipitation and radiation (Mitterer et al., 2011) . Finally, both approaches share the largest source of uncertainty which is the misinterpretation of IRH as annual layers and a careful validation with reference data remains essential.

5 Conclusions

We established a new approach to derive past accumulation rates on temperate alpine valley glaciers from repeated GPR surveys. Our method is based on the interpretation of IRH as previous summer surfaces. By linking the measured GPR traveltime of each layer to a simple model for firn densification, an estimate of the bulk density a density estimate was derived for each layer. Thereby, we take into account the refreezing of meltwater by modelling the end-of-winter temperature profile that, for temperate firn, is entirely compensated by refreezingunder temperate conditions. The model was calibrated by comparing the modelled and measured change in traveltime thickness IRH traveltimes of 35 layers at locations where GPR profiles intersect measurements exist in two subsequent years. Thus, our approach is independent from external information such as firn cores. It was applied to each GPR measurement location independently where multiple IRH were found to obtain the distribution of the mass of annual firn layers along the GPR profiles.

The strongest limitation to the methodology is the non-annual character of IRH for our study site as it was found from the analysis of two shallow firn cores. A potential misinterpretation of IRH affects the results for all subsequent layers by changing their ages. We suggest that, if no firn cores are available, measured mass balance data or modelled accumulation rates based on meteorological information could serve for winter precipitation sums could serve as a plausibility check. However, the formation of high-density and ice layers is linked to small-scale physical characteristics of snow and firn and is driven by particular weather conditions. Thus, a general conclusion about the validity of a dating-by-counting scheme for different study sites cannot be drawn.

We showed that GPR measurements can be used to estimate multi-year accumulation rates on a temperate valley glacier. Thereby, measurements can be conducted from helicopter, facilitating efficient data acquisition even in inaccessible areas. Because the GPR penetrates several layers of accumulation, it could be used to complement existing monitoring programs, but also for a retrospective extension of newly initiated time series.

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Figure 1. Findelengletscher with the setup of annual mass balance measurements~~, the~~ . The mean equilibrium line altitude (ELA), the firn core locations and all analysed GPR profiles measured in 2012, as well as the locations used for the model calibration are shown. The overview map shows its location within the European Alps.

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Figure 2. Processed GPR profile exemplarily showing IRH within the firn in the accumulation area of Findelengletscher. Red lines highlight potential previous summer surfaces.

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Figure 3. Optimal scaling f of the compaction rate (Eqs. 2 and 3) as a function of the initial model density $\rho_\mathrm{f}(0,t_\mathrm{d}) = 0.49$ $\rho_\mathrm{f}(0,t_\mathrm{d}) = 492\,\mathrm{kg\,m^{-3}}$, found by comparing 35 modelled and measured changes in layer two-way traveltime (TWT) thicknesses IRH traveltimes at locations where GPR profiles repeat measurements are available in 2012 and 2013 intersect. 2013. The shading shows the root-mean-square deviation (rmsd) while the line provides the optimal relation. The horizontal error bar shows the uncertainty in the initial model density. The related uncertainty in f is indicated with black markers.

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Figure 4. GPR profile at firn core 1 (Fig. 1), the measured vertical profiles of density, transformed to the traveltime-domain, with marked melt layers (orange) and dust layers (yellow), ammonium (NH_4^+) and sulfate (SO_4^{2-}) concentrations, and the water stable isotope ratio (δD). Grey bars represent summer surfaces. For comparison, density, NH_4^+ and δD are shown for firn core 2.

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Figure 5. (a) Average water equivalents of annual layers derived by GPR and by ~~conventional evaluation based on the~~ extrapolated glaciological field measurements at locations where all four summer layers could be extracted from the GPR signal. Error bars show the uncertainty from the initial density $\rho_\mathrm{f}(0,t_\mathrm{d})$. **(b)** Mean layer densities, the related uncertainty and data range for the same locations.

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Figure 6. Annual accumulation layer water equivalent (m) derived along the GPR profiles (highlighted in black) for 2008–2011. For visualisation, the water equivalent was interpolated by inverse linear distance weighting, restricted to the 400 m surrounding of all GPR data points.

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Figure 7. Layer Comparison of GPR-derived mean annual layer water equivalents with **(a)** extrapolated mass balance measurements and densities **(b)** winter precipitation sums (October – April) at firn core 1, derived from GPR, directly from the firn core, and modelled using weather station of Zermatt (1638 m a.s.l.). With the hypothetical traveltime correct layer chronology obtained from the firn core layer water equivalent cores (red dots) the high accumulation and densitywinter precipitation in 2009 are reproduced. Error bars show A misinterpretation of an IRH within the uncertainty derived from variations in 2009 accumulation layer disturbs the initial density model parameter $\rho_{\mathrm{f}}(0,t_{\mathrm{d}})$ chronology and the linked scaling for the compaction rate f affects all following layers (black circles).

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Figure 8. Layer water equivalents **(a)** and densities **(b)** at firn core 1, derived from GPR, directly from the firn core, and modelled using the hypothetical traveltime obtained from the firn core layer water equivalent and density. Error bars show the uncertainty derived from variations in the initial density $\rho_\mathrm{f}(0,t_\mathrm{d})$.