

Reply to reviewers comments on paper entitled '**Spatial and temporal distributions of surface mass balance between Concordia and Vostok stations, Antarctica from combined radar and ice core data : First results and detailed error analysis.**' by Le Meur et al.

Dear Editor,

Please find below our reply to the 2 reviewer's comments on the above cited manuscript.

Whising you good reception,

Sincerely,

Emmanuel Le Meur in the name of the authors,

Reply to reviewer 1 :

Review form reviewer 1 was very positive in the sense that only editorial comments were proposed. For parts of text that were kept, the proposed changes have been done.

Reply to reviewer 2 :

General reply

The main point raised by the reviewer is a lengthy paper with too many details that makes the reading tedious and obscures the message to deliver.

We acknowledge that it is partly true. One explanation resides in many different subjects tackled (core chemistry, radar interpretation, error analysis...) implying different contributions from as many authors aiming at seeing their work fully described. This is particularly true for the inclusion of results from the S0 core. We also agree on the fact that the error analysis as initially proposed was unclear and also contained minor conceptual errors.

We tried our best to answer these remarks by reducing the text and figures and by partly rewriting portions of text (see details below). Parts of text and figures have also been moved to the appendices so that less important issues do not obscure the reading. However, reducing the paper to 5 000 words or so is in our view too drastic given the wealth of data and the fact that, amongst papers dealing with radar results, this draft is, to our knowledge, the first one presenting a rigorous and comprehensive (at least now) treatment of the budget error for radar-derived accumulation rates. In its 2-column version, the new paper (without appendices) is 4 pages less (for a total of 15 pages) and more importantly has been rewritten for a more fluent reading.

Reducing the figures to the extent suggested by Reviewer2 for the sake of brevity is not reasonable given their information content which we believe is necessary for the comprehensiveness of the paper. Here follows a summary of how we dealt with figures :

- Removing Fig. 3 is unrealistic since the dating process against an ice core is a key process in the proper derivation of accumulation rates. However, because they are of less importance, plots of the S0, S1, S2 cores have been moved to Appendix C where they serve for estimating cross errors for the IRHs dates. Age/depth relationships for these cores

are probably less reliable than that of the reference VOLSOL-1 core, but they are still reliable enough for estimating the age dispersion as is done in the appendix and which serves later for the global error budget. Accordingly, the corresponding table giving the ages dispersion has also been moved to the appendix.

- Fig. 4 has also been moved (to the Appendix B). It is necessary for explaining the representativeness of a single core for a place like DC. Here, only the result really matters and is solely given in the main text. The reader is thus invited to refer to Appendix B to apprehend the age dispersion of the VOLSOL cores leading to the dispersion figures proposed in the main text.

- Fig. 5 was kept since it is essential for the representativeness of a single core in terms of density this time (also necessary for the final error budget). Corresponding text was also partly modified but mainly kept because it often refers to the figure which therefore justifies the presence of the 2 in the main frame rather than in an appendix.

- The top of figure 6 (cores S1,S2, S2B) has been removed because of the limited interest of the represented S1,S2, S2B cores in terms of density content. However, the bottom representing the 2 Explore and DC5 density cores has been kept and merged on top of Fig.5. Given the importance of density, it seemed unreasonable not to present a density curve in the paper (as suggested by the reviewer). Reviewer 2 argue that the S0-Explore core should be disregarded in the paper. We do not believe so. We agree on the fact that the interpretation of the 10.48-m horizon is problematic in the S0-Explore core. It was therefore agreed to only consider the deepest reflectors of the Explore core to supplement the first 20 m of the S0 core so as to provide a hybrid S0-Explore age/ relationship for the S0 site (explained in the Appendix C). We believe this relation is still reliable enough to be used for estimating the age dispersion as is done in the appendix (and depicted in the companion figure in the appendix). Corresponding values are then considered in the main text. Last, density measurements along the Explore core are fully exploitable and are necessary for conducting the sensitivity test on accumulation rates to the different geographical cores from which one essential conclusion of the paper is drawn. Of course the text has been reconsidered so as to account for these changes and make the remaining main text consistent and fluent.

- Fig. 8 has been removed with its content in terms of error bars reported in fig.7

- As for the spatial and time dependent accumulation rates, they constitute the core of the results of the paper and their respective importances led us to expressly treat them in 2 separate paragraphs and hence in 2 figures, contrary to the suggestion of the reviewer consisting of merging Figs. 9 and 12. Moreover, merging the 2 figures in one would not bring any significant gain of space and would, in our view, alter the fluidity in the reading.

- Reviewer 2 also implicitly suggests to remove Figs. 10 and 11, but we feel they are worth presenting by providing extra independent data sets against which to compare our results.

Finally, the main frame of the text has been reduced by almost 4 (double column) pages and now includes 9 figures instead of the initial 12. Given the opposition between the 2 reviewers, we feel that most suggestions of reviewer 2 in order to shorten the paper are too drastic and that the paper can sufficiently gain in conciseness from an intermediate response as proposed here.

More specific comments and corresponding response from the authors :

- With regards to error bars of Fig. 8 and their interpretation :

Error bars on Fig. 8 in the initial version were representing the lower and upper bounds for accumulation rates computed when using the upper and lower density profiles of Fig. 6 when considering respectively the top and the bottom of the depicted error bars on the figure. These density error bars were those initially described in section 5.4 (“+- 20 kg/m³ for the first 7 m linearly decreasing to +-15 kg/m³ at 15 m deep...”). After reconsideration of the paper, it appeared that not only the text (and associated figure) is totally ambiguous but the reasoning is also dubious.

This is why we now propose an alternative method in which we integrate both the density measurement errors and the uncertainty arising from the representativeness of a single core into a single term derived from the dispersion in the accumulation rates computed from all the reliable density cores drilled at DC. This is now explained at the beginning of section 5.5, more specifically with the sentence : " Because they result from different projects implying different measurements protocols, the numerous cores drilled in the DC area provide a means of estimating the order of magnitude of the combined effect of these two terms ". This resulting combined error term is therefore estimated from the RSM dispersion of the different accumulation rates issued from these various cores obtained by summing the masses down to the required depths as shown in the new Fig. 4.

This combined error term (represented by the error bars of the insets of the new Fig. 5) is later compared to the changes in accumulation rates now obtained from using either the DC5 reference density profile or the S0-Explore core, in order to assess the sensitivity to regional changes in density. From the overlap of the error bars on Fig. 5 we come to the conclusion that accounting from the geographical changes in density at our disposal does not bring significant changes to the resulting computed accumulation rates as explained in the new Sect. 5.5.

The uncertainty solely arising from measurement errors along the DC5 core (+- 20 kg/m³ for the first 7 m linearly decreasing to +-15 kg/m³ at 15 m deep...) will only serve the purpose of estimating the uncertainty in the inference of the vertical velocity profile later used in the overall budget error section (Sect 5.6 and corresponding Table 3 that were consequently reconsidered). One extra reason for this choice is the rather arbitrary character of these density measurement errors (a very difficult term to assess). These (potentially questionable) error terms will anyhow have a minor impact as can be seen from the small contribution of the uncertainty in the velocity wave in the overall budget error compared to other terms (see term ΔH_v in column 10 of Table-3).

As a result, the entire Section 5 has been reconsidered, shortened by now including 6 subsections (instead of the initial 7). It did not drastically change our conclusions, notably the unnecessary consideration of the geographical changes along the radar profile (at least in the current context). However the question was worth asking and answering as rigorously as possible since it leads to the important conclusion that before considering the potential regional changes in density, an accurate error estimation due to the local density error should be considered. This new approach led to slightly different figures in the global error budget as represented in Table-3, but the final result is only slightly changed in terms of total maximum margins of error.

- Problems raised by the S0 core

As for the problematic dating of the S0 core, we agree that it is certainly less reliable than that of the reference core (VOLSOL-1). This is the reason why the TASTE-IDA cores (including the S0-Explore core) are not used for dating the IRHs (we exclusively use the reliable VOLSOL-1 core for that).

However, age/depth results for these cores result from a careful analysis protocol relying on detection of both volcanoes and radio-isotope horizons. Moreover, the ambiguous 10.48-m deep horizon of the Explore core is not accounted for in the derivation of its age/depth relationship. This latter is derived from horizons from the S0 core supplemented by only the deepest (> 20 m) ones of the Explore core. No shift at the transition is observable and the resulting quadratic fit still exhibits a r^2 greater than 0.99.

It should be noted that these extra cores are exclusively used for estimating the age dispersion along the selected IRHs in order to test their isochronicity. Corresponding text and figure were then moved to the Appendix instead of being simply removed because they are our only means of validating the radar approach. We insist on the fact that this paper is one of the first where a big effort is put on trying to validate the isochronicity of the IRHs and propose an as rigorous as possible error budget on the resulting accumulation rates.

Although we do not strictly follow the reviewer suggestion, text and figures devoted to these cores has been significantly reduced in the main frame of the paper. The text was also modified in order to make this new approach clearer as described below :

- Last paragraph of the introduction : We are not anymore talking about '4 age depth relationships later used for dating purposes '. Instead we say 'Ice core data are then presented with a focus on the depth markers obtained from chemistry analysis (volcanoes) and/or radio-isotope counting (nuclear tests) leading to the VOLSOL-1 age-depth relationship later used for dating purposes.'
- Beginning of section 3 : a small paragraph has been added in replacement of the old 'Ice core drilling ' section in which we clearly say that only the VOLSOL-1 core is used to time calibrate the IRHs and that the less reliable cores (S1 S2 and S0-expl) only serve as cross-over points for assessing estimates of the age dispersion along our IRHs.
- Beginning of section 4.2 (Methodology for dating the IRHs): The reasons for the above choice are precised and the way the hybrid S0-Explore age/depth relationship has been derived is precised with reference to the corresponding figure in Appendix C.
- End of section 4.3 : From the dispersion results of the Appendix C, the isochronous character of our IRHs is presented.
- Last, end of Appendix C : We explain why the results of these cores should be considered with caution, but on the other hand why we think these results are still exploitable for estimating the age dispersion.

-With regard to the last suggestions of Reviewer 2 consisting of adding a few more paragraphs

In a process of shortening the paper, we found it difficult to address most of the extra issues proposed by Reviewer 2. Apart from one (impact in terms of sea level), we did not feel like addressing them for the following reasons :

- 'How about a few paragraphs on what this suggests for where to drill a deep ice core ?'
- Low accumulation rates are a prerequisite for expecting long climatic exploitable records from ice cores ... but it is one necessary condition among many other ones like (i) a large ice thickness, (ii) specific temperature conditions at the base of the ice sheet partly driven by the geothermal heat

flux, (iii) rather smooth bedrock topography for preventing disruption in the stacking of basal layers, etc... Most of these issues are beyond the scope of the paper. In the introduction we mentioned the interest of low accumulation zones for the quest of old ice as a necessary condition, which we only present as one justification (among others) to study surface mass balance on the Antarctic plateau. We do not see what else could be said in the framework of a paper dedicated to a methodology for measuring surface mass balance measurements.

- 'How about comparing the 5% increase in accumulation rates to inferred temperatures ' Is it consistent with Clausius Clapeyron ?'

→ To our knowledge, there is no reliable temperature curve over the last 200 yrs on the Antarctic plateau, not even over the past 50 yrs or so. Models usually fail to reproduce temperature evolution over places where the lack of data (in terms of spatial coverage and duration) prevents data assimilation technique. It often leads to biases requiring correcting factors like in the ERA Interim model for instance. Moreover, air masses in these area are prone to intense supersaturation (Genthon et al., 2017,ACP) that precludes the existence of a physically consistent relationship to Clapeyron. As demonstrated by Genthon et al., (2015) and also partly mentioned in the text, explanations for the modern evolution of the SMB around DC is more to be found in changes in the storm track pathways.

- 'And what is the impact on global se level ?'

→ As for the suggested impact on sea level, the end of Section 6.3 has been supplemented by a couple of sentences that help to translate our average accumulation increase (as deduced from Fig. 9) into equivalent sea level contribution, should the observed increase apply over most of the Antarctic ice sheet. It also allows a comparison with results of the simulations of Krinner et al., (2006) about the possible contribution of Antarctica in a warmer climate by the end of the 21st Century as mentioned in our introduction.

-With regard to the very last suggestions of Reviewer 2 concerning adding a figure to compare with results from other sites :

→ As for the last suggestion of Reviewer 2, we indeed initially thought of a figure synthesizing results from other sites, but it appeared practically difficult to do since the available examples gives general tendencies but no real figures to put in a graph. Again the problem of different averaging periods over which the proposed trends apply makes it difficult to put corresponding results in a relevant figure. Last, the proposed examples are often tendencies as a result of a specific topographical or geographical context (position with regard to a ridge, continental character...) which can not be properly represented in a synthetic graph.

Spatial and temporal distributions of surface mass balance between Concordia and Vostok stations, Antarctica from combined radar and ice core data : First results and detailed error analysis.

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Abstract. Results from Ground Penetrating Radar (GPR) measurements and shallow ice cores carried out during a scientific traverse between Dome Concordia (DC) and Vostok stations are presented in order to infer both spatial and temporal characteristics of snow accumulation over the East Antarctic plateau. Spatially continuous accumulation rates along the traverse are computed from the identification of three equally spaced radar reflections spanning about the last 600 yr. Accurate dating of these Internal Reflection Horizons (IRHs) is obtained from a depth-age relationship derived from volcanic horizons and bomb testing ~~fallout~~ fallouts on a DC ice core and shows a very good consistency when tested against extra ice cores drilled along the radar profile. Accumulation rates are then inferred by accounting for density profiles down to each IRH. For this latter purpose, a careful error analysis showed that using a single and more accurate density profile along a DC core provided more reliable results than trying to include the potential spatial variability in density from extra (but less accurate) ice cores distributed along the profile.

The most striking feature is an accumulation pattern that remains constant through time with persistent gradients such as a marked decrease from 26 mm w.e.yr⁻¹ at DC to 20 mm w.e.yr⁻¹ at the South West end of the profile over the last 234-yr average (with a similar decrease from 25 mm w.e.yr⁻¹ to 19 mm w.e.yr⁻¹ over the last 592 yr). Insights into the time-dependency reveal a steady increase of accumulation on the East Antarctic plateau during the last 600 yr and more particularly since about 200 yr as already suggested by previous studies relying on GPR and/or time markers in ice cores. Maximum margins of error are in the range 4 mm w.e.yr⁻¹ (last 234 yr) to 2 mm w.e.yr⁻¹ (last 592 yr), a decrease with depth mainly resulting from the time-averaging when

computing accumulation rates. The gradients proposed in this study remain however significant since only the reduced non systematic component (with regard to space or time) of these error terms has to be considered when interpreting spatial or temporal trends.

1 Introduction

25 The surface mass balance (SMB) over the Antarctic ice sheet is of primary interest for many purposes. The mass budget of the Antarctic ice sheet can be seen as the difference between all mass exchange with the atmosphere over all the ice sheet surface (i.e the SMB) minus the calving of icebergs and basal melting under ice shelves at the coast. The first term is globally positive as it represents snow accumulation over most parts of the ice sheet with the exception of blue ice and wind
30 crust areas with negative SMB due to wind scouring and/or sublimation (Bintanja, 1999; Scambos et al., 2012). The second is negative despite the possibility of marine ice accretion under some parts of the shelves. Although current changes in the mass budget of Antarctic ice are believed to result mainly from recent dynamical effects leading to an enhanced flow of ice through outlet glaciers and ice streams (e.g., Rignot and Kanagaratnam, 2006), changes in surface mass balance should not be
35 disregarded since they potentially operate over large areas. Numerical predictions by Krinner et al. (2006) suggest that advection of warmer saturated air masses (hence containing more moisture) could lead to a 32 mm water equivalent per year increase for the Antarctic future SMB in the next century corresponding to a negative sea level contribution of 1.2 mm.yr^{-1} by the end of the 21st century. The SMB of the grounded Antarctic Ice sheet (AIS) is approximately 2100 Gt.yr^{-1} , with
40 a large interannual variability. Those changes can be as large as 300 Gt.yr^{-1} and represent approximately 6% of the 1989-2009 average (Van den Broeke et al., 2011). Moreover, the SMB uncertainty is estimated to be more than 10% (equivalent to nearly 0.6 mm.yr^{-1} of sea level rise), which is at least equal to the ice discharge uncertainty (Frezzotti et al., 2007; Magand et al., 2007).

Measuring the SMB over ice sheets therefore represents a challenge which addresses a wide number of scientific glaciological and environmental issues. It first allows for a direct assessment of the
45 SMB pattern and specific features with regard to time as well as spatial variability. Spatial variability of SMB operates over various scales ranging from less than a meter to several hundreds of km (see for instance a detailed description in Eisen et al. (2008)). Using SMB measurements for inferring mass budgets whether over a single drainage basin or all over the continent therefore requires some sampling and interpolation strategies. Unfortunately, these approaches remain approximate and suffer
50 from the sparsity of data especially over the Antarctic plateau. Remote sensing can be an alternative, but measured quantities are not always a reliable proxy for SMB, making ground truthing still necessary. Modeling is also a possibility but similarly requires control from field ground measurements and the more of these control points, the more accurate the results obtained. Persisting discrepan-

55 cies between spatially interpolated measured data (Arthern et al., 2006) and modelling results (e.g.,
van den Broeke et al., 2006) also tend to call for denser field measurements.

Accessing the temporal variability of SMB is also of major interest. As pointed by ~~Eisen et al. (2008)~~ [Eisen et al. \(2008\)](#) knowing
past and present conditions of SMB is necessary for predicting its behaviour under future climatic
conditions. Moreover, independent measurements of past SMB are of importance for interpreting ice
60 cores. Last but not least, SMB is one of the main factors driving ice dynamics and as such, represents
the principal boundary condition for ice sheet models. If past SMB is obviously required for model-
ing past ice sheet dynamics, it appears also necessary for assessing the current dynamical state of the
ice sheet given the fact that the corresponding characteristic time response makes the present-day ice
sheets still react to SMB changes that occurred for the past centuries or even millennia.

65 The proposed study aims to document both spatial and temporal variability of the SMB over a
so-far unexplored region of the Antarctic plateau. Corresponding field work took place during a sci-
entific traverse between the French-Italian Concordia station ($75,10^{\circ}S$, $123.33^{\circ}E$) and the Russian
Vostok station ($78,49^{\circ}S$, $106.65^{\circ}E$) during the 2011/2012 austral summer (See Fig. 1). This traverse
is one component of IPY lead project TASTE-IDEA (Trans-Antarctic Scientific Traverses Expedi-
70 tions Ice Divide of East Antarctica) and is also linked to the international SCAR project ITASE
(Mayewski et al., 2005). The measurement technique is based on the complementary approaches of
snow radar (GPR) and ice core analysis. The former provides a continuous mapping of isochronous
layers leading to a spatialization of snow accumulation over long distances. On the other hand, ice
cores yield a much more local information, but nevertheless necessary as a means of providing both
75 time markers for dating radar horizons and density vertical profiles from which snow quantities ac-
cumulated over the different IRHs can be assessed. The complementarity also comes from the fact
that local accumulation as revealed by ice cores has a limited representativeness due to the small
scale variability of some processes leading to the net accumulation (wind driven sublimation, wind
scouring, see for instance (Frezzotti et al., 2007)).

80 In the present study, data acquisition is first described with the radar data summarized under
a merged profile whose post processing allowed the identification of three equally spaced IRHs
covering the last 592 yr. ~~Ice core data are then presented with a focus on the depth markers obtained
from chemistry analysis (volcanoes) and/or radio-isotope counting (nuclear tests) leading to the 4
age-depth relationships later used for dating purposes.~~ Special attention was paid to the vertical
85 density distribution contained in the different ice cores of the project and used for computing the
cumulative mass deposited above each of the three IRHs. Then follows a detailed error budget on
the final computed accumulation rates which accounts for the three main sources of error stemming
from the uncertainties in (i) density profiles, (ii) age and (iii) depth of the IRHs. Finally, spatial and
temporal variations of the accumulation rates along the measured profile are presented, discussed
90 and compared (when possible) with results from previous studies.

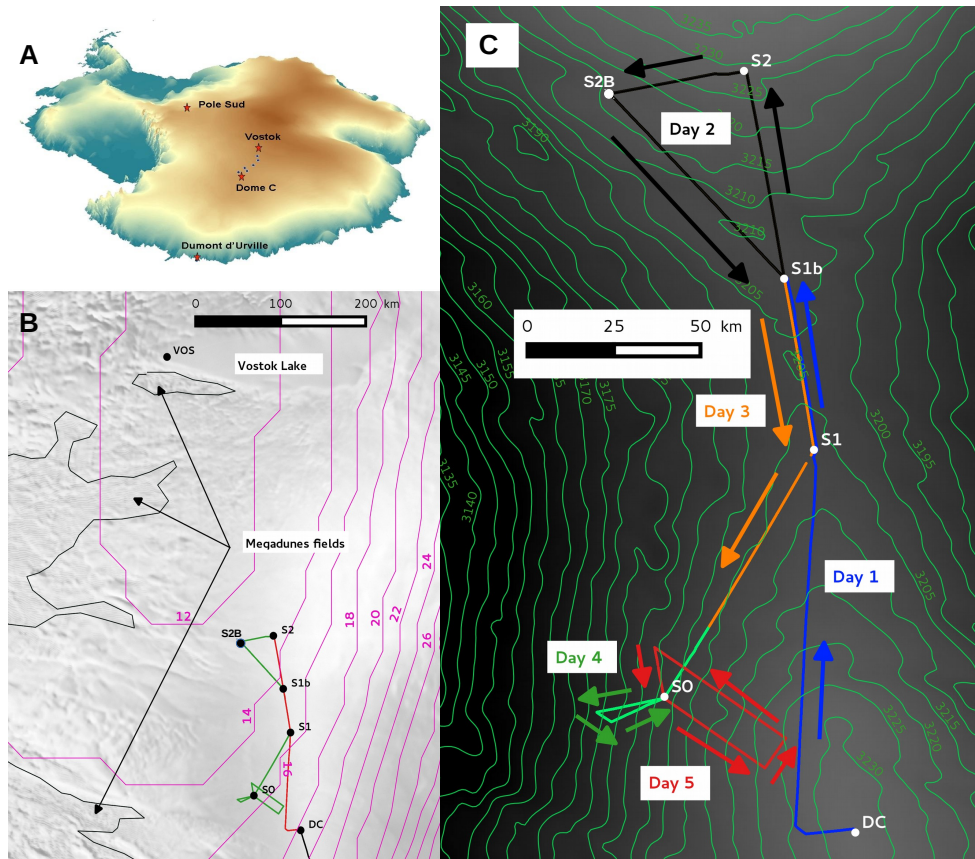


Figure 1. Map of the route followed by the 2011/12 TASTE-IDEA traverse over the east Antarctic plateau between the Dome Concordia (DC) and Vostok stations. (A) locations of departure and destination base stations on the plateau. (B) the portion of the traverse along which radar profiles have been acquired. (C) zoom detailing the five days of GPR profiling as well as the drilling sites of DC plus the locations of the firm cores retrieved during the traverse (S1, S2, S2B, S0) and used for dating the isochrones and deriving density profiles (see [Sections Sects. 3 and 4](#)). The pink contours in (B) represent iso-values of the precipitation rate as computed by the ERA 40 model of the European Center for Medium-Range Weather Forecasts (Simmons et al., 2007). Although the observed spatial and temporal variability is correctly reproduced, the precipitation is systematically underestimated (Genthon et al., 2015) and results require a systematic multiplying factor of about 1.5 to become realistic (Libois et al., 2014). Processes like sublimation and snow redistribution are omitted in the physics of the model and also explain the discrepancy with accumulation rate data.

2 Ground Penetrating Radar (GPR) data

2.1 Technical background and functional principle of GPR

The principle of GPR consists of measuring the two-way travel times of parts of an electromagnetic pulse emitted toward the ground that are reflected on discontinuities within the observed medium.

95 When pulses are emitted at points along a profile, lateral continuity of the physico-chemical transitions within the medium yields wiggles of similar travel time (hence depth) along the resulting radar trace. Once put side by side, these wiggles express under the form of horizons also called IRHs (Internal Reflection Horizons) visible on the recorded radargram. In this respect, GPR is analogous to seismic reflection but with an electromagnetic wave instead of an acoustic wave.

100 Discontinuities responsible for these partial reflections result in changes in the complex dielectric constant ϵ^* of the medium. For the snow pack, essentially two main factors can be responsible for these changes as explained in (~~Eisen et al., 2008~~) Eisen et al. (2008) and references therein. The first concerns the real part, namely the permittivity, which varies with density whereas the second acts on the imaginary part which is sensitive to the conductivity of the medium. As a result, radar horizons
105 within the first few hundreds meter of firn and ice are essentially due to changes in density and acidity from volcanic deposits.

The huge advantage of the IRHs comes from their isochronous nature, although this has not been rigorously (physically) demonstrated, only heuristically by connecting ice core chemistry analysis of different drill sites (e.g., Eisen et al., 2004; Frezzotti et al., 2005)) or by comparing accumulation
110 rates obtained ~~form from~~ both IRH depths and stake lines (Vaughan et al., 2004). This ~~isochronity~~ isochronicity is however understandable as it results from processes operating at the surface at the same time, such as acidic atmospheric deposits or density changes from the metamorphism of snow (at least the one initiated by surface interaction with the atmosphere like radiation crusts, wind re-distribution). However, the physical processes leading to these IRHs still remain poorly known. For
115 instance, as pointed by Eisen et al. (2008), annual layers are still visible with radar wavelengths much larger than the annual thickness (a typical 100 – MHz wave in the cold dry snow of the plateau has a wavelength of 2 m much larger than the 10 cm annual snow thickness at DC for instance) which contradicts the theory unless constructive interferences are considered as suggested by Palli et al. (2002) for instance.

120 Assuming ~~isochronity~~ isochronicity, the spatial variations of snow accumulation can be obtained from the varying depth of the IRHs. It thus implies transforming the two-way travel times of the reflected waves into actual depths. This is only possible if the wave velocity within the medium is known all the way from the surface down to the specific IRH and the time radargram is properly migrated (see ~~Section-Sect.~~ 2.3). Inferring accumulation rates then requires the association of an age
125 to the IRHs from independent means such as correct recognition of fallouts from identified volcanic and/or bomb testing events along firn/ice cores for instance (see ~~Section-Sect.~~ 4).

2.2 GPR set up

For the present project, GPR data were acquired with a MALÅ[®] ProEx GPR equipment fitted with a 100 MHz 'Rough Terrain Antenna (RTA)' towed behind one of the tractors used during the traverse
130 with a constant separation of 2.2 m between the emitter and receiver parts. The apparatus, operating

frequency and set up are very similar to those used on a similar traverse between base stations of Dumont d'Urville and DC during the 2008/2009 austral summer (Verfaillie et al., 2012). The triggering was set to 1 s meaning a radar trace every 4 m or so given an average speed of 14 km.h⁻¹ for the convoy. The time window was set to 1 μ s (allowing for an investigation depth of some 100 m) and was sampled at 1.1 MHz leading to roughly 1100 samples per trace. During acquisition a first improvement of the signal-to-noise ratio was obtained by an up to 64-fold stacking (which, given the time window of 1 μ s, remained compatible with acquisitions made every second). Moreover, the system was connected to a GPS receiver mounted on the vehicle and recording the geographic position of every single trace along the profiles.

140 2.3 Resulting GPR radargrams

Profiles outlined in Fig 1 represent five days of measurements between 13/01/2012 and 17/01/2012 and led to an almost continuous record of 630 km. The corresponding post-processed and concatenated radargram is shown in Fig 2. The post processing sequence consisted of time zero corrections, a zero-phase low-cut filter (devow) to remove direct continuous currents, and an 'Energy decay' gain to compensate for the volumetric spreading signal attenuation. Band pass filtering reduced to a low-pass filter under the form of a spatial averaging over 50 traces which, given the huge number of traces (164 000 altogether), appeared more efficient than traditional Finite Impulse Response (FIR) filters. Time to depth conversion was obtained by migrating the radargrams with the help of a vertical velocity profile for the radar wave. By investigating a similar region with similar firm properties, we followed the approach of Verfaillie et al. (2012) which consisted of only considering the effect of the firm density on the electromagnetic wave velocity as a result of a dry and clean snow over the Antarctic plateau. From the empirical relation of (~~Kovacs et al., 1995~~) [Kovacs et al. \(1995\)](#) relating permittivity and density, the wave velocity c is obtained according to :

$$c = \frac{c_v}{1. + 0.845 \times \rho} \quad (1)$$

155 with c_v the wave velocity in vacuum and ρ the firm density (relative to water density). The density profile comes from a recent core drilled at DC (Leduc-Leballeur et al., 2015) where high resolution measurements allowed for a detailed profile (see [Section Sect. 5.2](#)). The true restitution of dipping reflectors theoretically requires a topographic migration, but this latter appears only necessary where the topographic variations are of the same order as the reflector depths. Given the extreme flatness of the investigated area of less than 2 m.km⁻¹ (topography of the upper surface and hence that of the IRHs) no such correction has been applied here. Last, ice sheet dynamics potentially changing the IRHs geometry has to be accounted for, except in the upper part of the ice/firm column, especially over areas of slow motion such as over the Antarctic plateau as in the present case (Eisen et al., 2008).

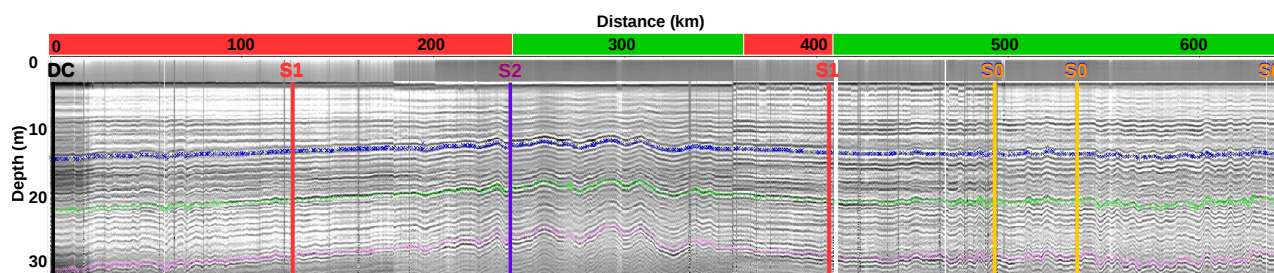


Figure 2. Continuous post-processed radargram corresponding to the merged profiles as outlined in Fig. 1. The numerous observable IRHs result from as many reflections within the snow pack and are each characterized by a laterally varying depth and a specific age. The coloured (blue, green and pink) aligned dots emphasize the three most evident and continuous IRHs that are used in the present study. The radargram as depicted here (restricted to the first 35 m of firn) has undergone a time migration (see [Section Sect. 2.3](#)) meaning that the vertical axis represents true depths instead of two-way travel times. The apparently shifted vertical scale results from the time-zero correction. The horizontal axis is the cumulated distance along the profile as given by the GPS data. The white vertical stripe is due to a breakdown of the GPR leading to a gap of less than 2 km in the data. Also represented are the crossing points with the ice/firn cores DC, S1, S2 and S0 where the intersecting depths with the three selected IRHs have been inferred for checking their isochronicity (see [Section Sect. 4](#)). The red and green upper banner refers to the position with respect to the topographic divide and correspond to the color convention of the bottom right of Fig. 1 (red for 'divide' and green for 'off divide' locations).

165 3 ~~Shallow cores~~Ice core data

3.1 ~~Ice core drilling~~

~~Four cores were~~The 102-m deep VOLSOL-1 ice core (VOLSOL program (Gautier et al., 2016))
is here used to time calibrate the IRHs observed with ground-penetrating radar;~~one intermediate~~
~~ice core (VOLSOL-1, 102-m deep) collected at DC during the 2010-11 Antarctic summer season~~
170 ~~(VOLSOL program (Gautier et al., 2016)) and~~. Owing to less reliable time-depth relationships, the
the three shallow ice cores (S0, S1 and S2, around 20-m deep each) retrieved along the TASTE-IDEA
traverse ~~. The ice cores were collected using two different electromechanical drilling systems (10-cm~~
~~diameter for VOLSOL program and 5.8-cm diameter for TASTE-IDEA). The recovered core pieces~~
~~were sealed in polyethylene bags in the field and stored in clean isothermal boxes before treatment.~~
175 ~~The VOLSOL-1 ice core was treated at DC using the laboratory facilities for chemical studies~~
~~whereas the TASTE-IDEA shallow firn cores were transported in frozen state to the cold-room~~
~~facilities of the Laboratory of Glaciology (IGE) in Grenoble, France, for radiochemical and chemical~~
~~studies. At DC, the ice core was cut in cleaned conditions and samples were sealed in precleaned~~
~~tubes before ion chromatography analysis. In Grenoble, sample preparation was also performed~~
180 ~~under clean-room laboratory conditions. After stratigraphic observations and measurements of bulk~~

density, the four firn cores were divided into two half-cores. One half was dedicated to radioactivity measurements, and the other half was analysed by ion chromatography. Due to the lack of seasonal variations of any chemical or physical parameters in snow between DC and Vostok stations, year-by-year dating of the snow layers is impossible. Only specific reference horizons can be used. In our study, the chronology of IRHs was established with the aid of sulfate spikes concentrations from past volcanic events coupled with the identification of recent thermonuclear bomb testing marker levels of CE 1955 and 1965.

3.1 Sample preparation and analysis

Samples for chemical and radiochemical analysis were prepared with a time resolution of about 0.3–0.4 yr (2-cm length) and 1.5–2.0 yr (10 cm), respectively, which is necessary for the detection of volcanic eruptions and radioactive levels. The samples were prepared and analysed using stringent contamination control procedures.

For the VOLSOL-1 ice core treatment at DC, only sulfate concentrations were determined. They were measured (more than 5000 samples) on a Metrohm 850 Professional IC system coupled with a Seal XY-2 Sampler. A Thermo Scientific Dionex IonPac AS11-HS (4-mm diameter, 50-mm long) anion separation column was used. Such a short column allowed us to develop a fast (2 min per sample) isocratic method using a 7 mM NaOH solution as eluent. Measured concentrations were calibrated in the 10–1000 ng.g⁻¹ range using dilutions of a commercial 1000 µg.g⁻¹ sulfate standard solution.

For the TASTE-IDEA firn cores treated at IGE, one half core was treated to measure major and organic chemical species from the surface down to 20 m deep (more than 5000 samples for all cores). Chemical analysis were performed using two different systems, enabling cross-checking of possible contamination processes and also validate the sulfate concentrations results. Indeed, the first measurements series were done using the same device system as the one used at DC for the VOLSOL-1 ice core treatment (sulfate concentrations measurements only) and the second series (same samples) was analysed with a Dionex® ICS3000 dual ion chromatography system. This last chromatography system was setup for the analysis of cations (Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} , Mn^{2+} , Ca^{2+} , Sr^{2+}) and anions (F^- , Cl^- , MSA^- , NO_3^- , and SO_4^{2-}) down to sub-ppb level and high level accuracy (6 standards calibration, relative standard deviation < 2%). The two different chemical analysis systems found no contamination and were reliable for sulfate concentration determinations. The results of test series consequently allowed use of only the first system with short sample run analysis (1.5 min versus 22 min) to provide complete and rapid sulfate profiles as needed.

The second half of the TASTE-IDEA firn cores were processed for artificial radioactivity measurements (^{90}Sr , ^{137}Cs , and to a lesser degree ^{241}Am , daughter of ^{241}Pu) by a Berthold® B770 low-level beta counting and Canberra® very-low background BEGe gamma spectrometry device. Analysis were performed with a continuous sampling every 10 cm from the surface down to 6 m, i.e. the necessary

~~depths to detect radioactive reference horizons from 1950s to 1980s atmospheric thermonuclear bomb tests will only serve as cross-over points for assessing estimates of the age dispersion (see appendix C). Details of the sampling and measurements procedures are given in Magand (2009); Loaiza et al. (2011) and Verfaillie et al. (2012) sample preparation and analysis are presented in appendix A.~~

3.1 Identification of volcanic eruption signals and volcanic chronology

Although sulfate in Antarctic snow comes from sea-salt spray and to a lesser degree from crustal erosion (Maupetit and Delmas, 1992; Cole-Dai et al., 2000), and principally from atmospheric oxidation of biogenic dimethylsulphide (DMS) emitted by oceanic phytoplanktonic activity (Saltzman, 1995; Prospero et al., 1991), volcanic eruptions are also major sources of SO_4^{2-} during active eruptions. To identify volcanic signals in ice cores, it is then necessary to ~~calculate~~ calculate the non-sea-salt sulfate (nss SO_4^{2-}) corresponding to total sulfate minus sea-salt sulfate, and set a threshold above which spikes can be attributed to volcanic deposition. Over the East Antarctic plateau areas, part of the sulfate background that could be related to continuous emissions from non-explosive volcanic activity, seems to be minor (Patris et al., 2000; Cole-Dai et al., 2000; Castellano et al., 2004). The sea-salt sulfate contribution to total sulfate budget, evaluated using Na^+ as a specific marker (Palmer et al., 2001; Röthlisberger, 2002), is less than 10%. The Holocene crustal contribution, calculated by non-sea-salt Ca^{2+} as a continental dust marker (Röthlisberger, 2002; Castellano et al., 2004; Plummer et al., 2012), is even lower ($< 0.05\%$). Since these contributions are of the same order of measurement reproducibility, we did not correct sulfate concentrations and will not distinguish between total sulfate and non-sea-salt sulfate in the following discussion. However, particular attention was paid to develop a reliable method for distinguishing volcanic signals from non-volcanic sulfate background and an outline of the method used is described in Cole-Dai et al. (1997, 2000); Stenni (2002); Castellano et al. (2004) and Igarashi et al. (2011). The procedure employed to identify candidate signals of volcanic eruptions in the sulfate profiles of the different cores follows that of Gautier et al. (2016).

Between five and eight volcanic events were identified in each TASTE-IDEA firm cores and ten events were detected in the VOLSOL-1 ice core from the surface to 20 and 30 m, respectively, through the application of the above described procedures (see summary in Table-1). In the considered depths for shallow TASTE-IDEA cores and the VOLSOL-1 ice core, the main volcanic events in the 1601 – 2012 CE period are Pinatubo (Philippines, 1992 CE), Agung (Indonesia, 1964 CE), Krakatau (Indonesia, 1885 CE), Coseguina (Nicaragua, 1836 CE), Tambora (Indonesia, 1816 ADCE), Unknown (1809 ADCE), Jorullo-Taal (Philippines, 1758 CE), Serua (Indonesia, 1695 CE), Gomkonora (Indonesia, 1676, CE) and Huyanaputina (Peru, 1601 ADCE). The sulfate deposition of Kuwae eruption (Vanuatu, 1457 – 1458 ADCE (Salzer and Hughes, 2007; Sigl et al., 2013, 2014,

Table 1. Depths of the dating events along the mentioned cores from known volcanoes as well as thermo-nuclear bomb testing and used for producing the time-depth relationships as depicted on Fig. 3-

Event name	Date of emission	Date of deposition	DC ^(a) VOLSOL-1	S0	Explore ^(b)	S1	S2
Pinatubo	1991	1992 ±1	1.51 (0.08)	- ^(c)	-	-	1.45
'1965 Bomb Tests'	1962-64	1965 ±1	4.20 ^(d)	3.67	-	3.37	2.75
Agung	1963	1964 ±1	3.81 (0.08)	-	-	-	-
'1955 Bomb Tests'	1952-54	1955 ±1	4.60 ^(d)	4.26	-	4.00	3.36
Krakatau	1883	1885 ±2	8.81 (0.07)	-	-	-	-
Coseguina	1835	1836 ±1	11.99 (0.07)	11.34	10.48 (?) ^(e)	11.31	10.04
Tambora	1815	1816 ±1	12.91 (0.07)	12.44	-10.48 (?) ^(e)	12.37	10.98
Unknown	?	1809 ±3	13.33 (0.07)	12.72	-	12.83	11.30
Jorullo-Taal	1754	1758 ±1	15.99 (0.06)	15.02	-	-	13.72
Serua	1694	1695 ±1	19.29 (0.06)	18.14	-	18.15	16.48
Gamkonora	1673	1676 ±3	-	19.12	-	19.39	17.26
Huaynaputina	1600	1601 ±2	-	-	-	-	20.20
Unknown	?	1646 ±3	21.92 (0.06)	-	21.65	-	-
Kuwae	1457	1459 ±3	30.19 (0.05)	-	27.35/27.61 ^{(e),(f)}	-	-
Unknown	?	1259 ±3	-	-	34.94	-	-

^(a) The value in parenthesis represents the depth shift to apply as the core was extracted a year earlier than radar measurements (see Sec. 4.2); ^(b) Time markers of the S0 and Explore cores have been merged to produce an hybrid depth relationship (see Appendix C); ^(c) An hyphen indicates an undetected volcano or an unmeasured nuclear fallout ; ^(d) These two bomb test fallouts were actually measured on a nearby shallow core close to the VOLSOL-1 one in 2011/12 and served in the determination of its age/depth relationship ; ^(e) Not accounted for in the resulting age curve since it was not clear to which volcano this sulfate peak should be attributed to. ; ^(f) These two peaks respectively dated CE 1453 and 1460 have actually been measured in the Explore core and attributed to the Kuwae volcano (Mulvaney, personal communication).

2015)) could be actually dated as 1459 ADCE, i.e., 5 to 6 years later than previously assumed (Gao et al., 2006, 2008).

The temporal duration of volcanic signals in the ice has been evaluated by several studies (Cole-
255 Dai et al., 2000; Palmer et al., 2001; Castellano et al., 2004) and general temporal durations range from 1 to 3 years. In this work, the temporal duration of volcanic signals lagged between 1.2 (3 consecutive samples) and 6 years (15 consecutive samples).

3.2 Artificial radionuclides deposition over Antarctica and associated chronology

Artificial radioisotopes resulting from atmospheric thermonuclear tests carried out between 1953
260 and 1980 were deposited in Antarctica after transport in the upper atmosphere and stratosphere, creating distinct radioactive reference levels in the snow. The dates of arrival and deposition in this polar region are well known and therefore provide a means to estimate Antarctic snow accumulation rates or describe air mass circulation patterns (Pourchet et al. (2003); Magand (2009) and references

therein). The 1955 and 1965 CE radioactivity peaks provide two very convenient horizons for dating
265 snow and firn layers and thus measuring accumulation. Special techniques have been developed
over the last 40 years to detect and measure artificial and natural radionuclides present in the ice
sheets (Pourchet et al. (2003); Magand (2009) and references therein). In Antarctica, ^{90}Sr , ^{241}Pu
(deduced from ^{241}Am analysis) and ^{137}Cs radionuclides constitute the well-known debris products
of atmospheric thermonuclear tests between CE 1953 and 1980 that we could still use to identify the
270 two well-known reference layers in snow (1955 ~~AD~~-CE and 1965 ~~AD~~-CE peaks), corresponding to
the arrival and deposition of artificial radionuclides in this region. Total beta counting and gamma
spectrometry remain the most frequent radioactivity measurement device systems used to clearly
detect artificial radionuclides and unambiguously determine the 1955 CE and 1965 CE peaks depths
in the cores. The 1955 ± 1 ~~CE~~-CE and 1965 ± 1 CE peaks were both identified in each TASTE-IDEA
275 firn core and in an extra shallow core close to the VOLSOL-1 one (see Table-1).

4 IRH dating

4.1 Identification of major IRHs

Interpretation of radar data first consisted of identifying contrasting IRHs whose continuity could
be tracked all along the entire merged profile. Three equally spaced IRHs were selected within the
280 first 35 m of firn (no sufficiently clear reflectors could be used any deeper) and are emphasized
with associated colors in Fig. 2. In order to properly capture the spatial variability, picking of these
reflectors was made every km or so yielding each time a depth and the corresponding geographical
position (~~coloured dots depicted as a colored dot~~ on the figure (the resulting number of dots leading to
an almost continuous horizon)). Of interest is the phasing of these three IRHs which is characteristic
285 of a stationary accumulation spatial pattern. It comes from the fact that local extrema in accumulation
keep the same positions through time, allowing for cumulative effects with time which amplify IRH
undulations with depth (Verfaillie et al., 2012).

4.2 Methodology for dating the IRHs

Dating is achieved by detecting the depths at which the reflectors intercept (or pass very close to) an
290 ice/firn core where a depth/age relationship has been obtained (see ~~Section~~-Sect. 3). In the present
case, as can be seen from Figs 1 and 2, each of the three reflectors passes over several ice core loca-
tions and sometimes several times over the same one, thereby offering redundant dating possibilities.
~~As a consequence, one~~ Due to its reliable dating curve including time/depth markers regularly spaced
down to about 30 m the DC-VOLSOL-1 core was selected as the reference and served for proposing
295 an age *ab initio* for each of the three IRHs. ~~By providing time/depth markers down to about 30 m,
allowing for a good constraint of the quadratic fit down to the deepest reflector ($r^2 > 0.99$), the
DC-VOLSOL-1 ice core (Gautier et al., 2016) was chosen as the reference and the remaining ones~~

(S0, S1 and S2) then allowed for a check of the isochronous character of the IRHs (see Fig. 3). The choice for the DC core is also justified by the numerous available ice core dating schemes for the site which gives a good level of confidence in the proposed age/depth relationships (Parrenin et al., 2007).

Identified and dated deposits placed in an age/depth representation according to their depths within the DC-VOLSOL-1 (DC-VOL1), S0-Explore (S0-Expl), S1 and S2 ice cores along the GPR profile. Almost systematically similar dated events (black symbols) were used from one core to the other (with vertical error bars barely exceeding 2 yr) except for the longer DC-VOLSOL1 core which allowed for one extra marker down to 30 m (Kuwae volcano) and the S0-Explore Core (Huaynaputina, Kuwae (2 peaks) and unknown-1259 CE) for which extra time markers are in red. A degree-2 polynomial fit (black line, $r^2 > 0.99$) has then been used as a continuous dating curve permitting to date any intermediary depth. At the DC-VOLSOL-1 reference core, depths of 15.08 m, 22.97 m and 31.89 m respectively give ages of 233.74 yr, 390.54 yr and 591.71 yr for the three IRHs (later rounded to 234 yr, 391 yr and 592 yr). For the other cores, intercepting depths of the three IRHs are reported and corresponding ages proposed that can then be compared to the reported reference ages from DC (black dashed lines). Insets on the S0 curves are enlargements allowing for an assessment of the dispersion in the IRH depths and resulting ages when crossing the core three times (note that S1 is only crossed two times).

For all of these cores, volcanic markers obtained from sulfate spikes have been complemented by the identification of the 1955 CE and 1965 CE radioactive reference levels (see two points around 4 m deep on Fig. 3). However, the limited depths of the extra S0, S1 and S2 cores (around 20 m) make their corresponding quadratic fits questionable for depths below the second IRH. This limitation was partly remedied thanks to the companion program Explore which benefited from the logistics of the traverse and provided a deeper (110 m) ice core extracted some 70 m away from the 2 deepest IRHs. A longer record has been artificially derived from the shallow S0 core. Sulfate peaks originating from volcano deposits were analysed by continuous melting and Fast Ion Chromatography and provided extra time markers down to about 35 m (in red on the figure, Mulvaney, personal communication, see also Table 1). As a consequence, core supplemented by the nearby (70 m) 110-m deep Explore core from the S0 core has been supplemented with these deep markers to build a hybrid S0-Explore age-depth relationship as represented in Fig 3 companion Explore program. Because of an ambiguity with a sulfate peak at 10.48 m, only the extra deepest points of the Explore core have been used to supplement the S0 age/depth relationship (see Fig. 11) used for estimating the age dispersion as described in Appendix C.

Having been extracted during the VOLSOL program (2010/11 field season) the DC-VOLSOL-1 core is a year older than the S1, S2 and S0-Explore cores radar measurements. As a consequence, a depth correction has been applied to each IRH volcanic depth in the form of a downward shift

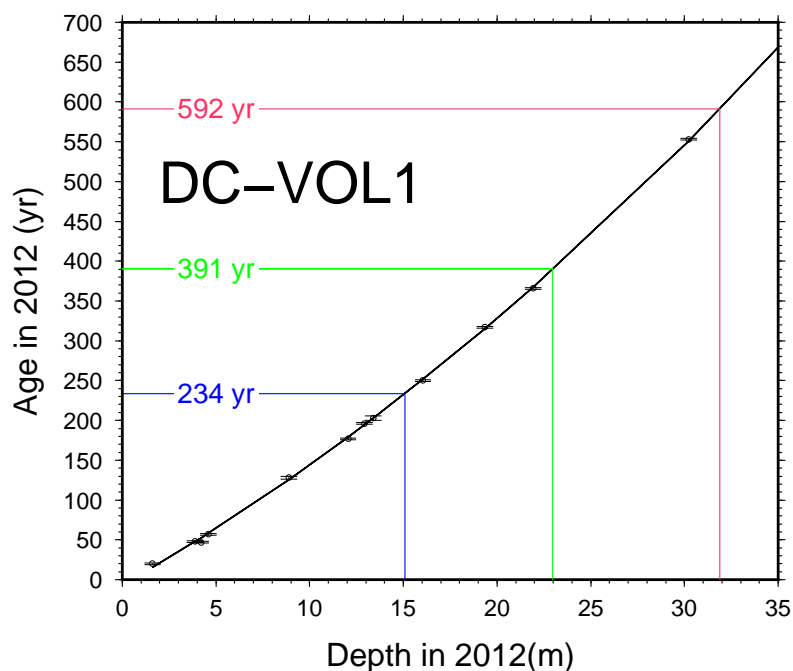


Figure 3. Identified and dated deposits placed in an age/depth representation according to their depths within the DC-VOLSOL-1 ice core. Volcanic horizons have been here completed by the integration of the two 1955 and 1965 thermonuclear horizons (depths of 4.20 m and 4.60 m) from dedicated measurements along an extra core drilled at DC in 2012 during the scientific traverse. A degree-2 polynomial fit (black line, $r^2 > 0.99$) has then been used as a continuous dating curve permitting to date any intermediary depth.

335 of 8 cm (modern snow-equivalent accumulation for DC) weighted by the density ratio between the relevant depth and the surface (i.e. 8 cm for the surface reducing to 4.53 cm for the Kuwae volcano at the depth of 31.20 m). Moreover, integration of the two extra 1955 and 1965 thermonuclear horizons along this core was possible from dedicated measurements along an extra core drilled at DC in 2012 during the scientific traverse, see Table 1).

340 4.3 Age results and the isochronous character of the IRHs

Corresponding measurement points and resulting quadratic depth/age calibrations for the four cores are depicted in Fig. 3.

As can be seen, ages for each IRH remain consistent along the entire radar profile with a limited scatter at the various crossings (either between cores or when passing several times at the same core site). For instance, the uppermost blue IRH varies by only 3% among all crossing points and has a maximum discrepancy of only 6 yr (2.5%) with the DC reference age (see detailed figures in Table 4). As for the second IRH (green), the scatter is 16 yr (4%) with a maximum deviation of 9 yr from the DC age of 391 yr. Lastly, the deepest one (pink) has a maximum deviation of 3.75%

(22 yr) with the reference age which also corresponds to its total dispersion. The only noticeable discrepancy is to be found with the deepest IRH when passing the S0 site where crossing depths lead to systematically older ages. One explanation could lie in the loss of continuity for this deepest IRH towards the end of the profile where it sometimes becomes very faint (see bottom right of Fig. 2). The other possibility could result from the hybrid depth-age relationship obtained at S0 from two different cores. Because of the short-scale variability of surface snow post-deposition processes (Eisen et al., 2008), the distance of 70 m between the two cores may explain such discrepancies as was observed by Gautier et al. (2016) who found depth shifts of the order of 20cm between five cores only separated by 1 m at the DC site. They also come to the conclusion that logging errors and analysing procedures may play a role, especially if different coring and analysing teams are involved as was the case for the S0 and Explore cores. Although it can be criticised, the construction of such an hybrid age-depth relationship makes some sense in our case since we only considered the extra Explore markers at depths where no other volcanoes were available in the initial S0 core (> 20 m). The resulting quadratic fit still yields r^2 greater than 0.99.

A sulfate peak observed in the Explore core at the depth of 10.48 m (red symbol labeled 'Tamb' on the figure) was initially attributed to Tambora (1816 AD) which markedly conflicted with the S0 Tambora depth of 12.44 m. After confirmation that such a major Volcano as Tambora could easily be missed in a low accumulation area as pointed out in (Gautier et al., 2016) where this latter is missing in two out of the five VOLSOL cores, it seemed more reasonable to attribute this peak to the Coseguina volcano (1835 AD, see red symbol 'Cose') for which the depth of 11.34 m (black symbol) has been found in the S0 core leading to the proposed quadratic fit (black curve in Fig. 3). Considering a second quadratic fit (not represented on the figure) in which Coseguina is placed at 10.48 m led to age increases of only 2 from Fig. 3, IRH depths of 15.08 m, 22.97 m and 31.89 m at the VOLSOL-1 core location respectively give ages of 233.74 yr, 390.54 yr and 1 year for respectively the upper and middle IRH and had no significant impact on the age of the lowest 591.71 yr (later rounded to 234 yr, 391 yr and 592 yr).

Depth, corresponding age and deviation with respect to the DC-VOLSOL-1 reference age for the three IRHs whenever they intersect the DC-VOL-1, S0-Expl, S1 and S2 cores DC-S0-1-S0-2-S0-3 S1-1-S1-2-S2-IRH1 depth 15.08-14.08-13.94-14.12-13.97-14.05-12.70-IRH1 age 234-234-232-235-228-229-233-IRH1 error -0%-1%-0.5%-2.5%-2.25%-0.5% IRH2 depth 22.97-21.47-21.43-21.16-21.43-21.27-19.38-IRH2 age 391-398-397-391-386-382-390-IRH2 error -1.75%-1.5%-0%-1.25%-2.25% 0.25%

IRH3 depth 31.88-29.56-29.70-29.84-29.84-29.70-26.76-IRH3 age 592-606-610-614-599-595-592-IRH3 error -2.25%-3%-3.75%-1.25%-0.5%-0%

4.4 IRH age uncertainty

The two main factors that can potentially alter the isochronous character of the picked IRHs are (i) errors in ~~the building of the~~ age-depth relationship at each coring site and (ii) errors in the depth estimates of the IRHs at these same sites deduced from the radargrams. As for the first, owing to the short-scale changes in snow deposition and erosion as expressed by the surface roughness, the archiving process can sometimes be significantly different for neighbouring cores thereby raising the problem of the correct representativeness of a single core. For several volcanoes Gautier et al. (2016) found differences in the depths of the corresponding sulfate peaks by as much as $\pm 20\text{cm}$ from one core to the other among a set of five different cores all separated by a meter. ~~Major volcanoes such as Tambora are even missing in two of the five cores.~~ As a consequence, on top of errors in the correct depth measurements of the chemical peaks, surface processes lead to an uncertainty in the core-derived age-depth relationships. ~~Figure 10~~ Fig. 10 in appendix B reports the time markers along the five cores from the study of Gautier et al. (2016). From quadratic fits along each core, five different ages are computed for our IRH depths of 15.08 m, 22.97 m and 31.89 m yielding respective RMS deviations of 6 yr, 7 yr and 7 yr with respect to our reference ages of 234 yr, 391 yr and ~~596 yr~~ 592 yr. These deviations can be considered as good estimates of the uncertainty in the correct representativeness of the single ~~cores~~ core of our study. The residency time of volcanic aerosols in the stratosphere (from 2 to 4 yr) is variable from one volcanic event to the other and therefore also contributes to some uncertainty in the depth-age relationship which makes an overall uncertainty of 8yr on the age for a given depth, a result very similar to that of Eisen et al. (2004).

As for the depth accuracy of the picked IRHs, it mainly results from the physics of radar and the chosen frequency for the electromagnetic wave. Eisen et al. (2004) gives a review of all possible resultant sources of errors and their results are applicable to our case because of the use of the same commercial radar set from MALÅ[®] Geoscience ~~Sweden~~ Sweden, with the only difference that they use 200 and 250 MHz frequencies instead of our 100 MHz. One first source of uncertainty lies in the thickness the 100 MHz-wave can resolve. Although it theoretically amounts to $\lambda/4$, one fourth of the wavelength in the firm, $\lambda/2$ is usually considered as more realistic which in our present case gives 1 m. Additionally, the pulse width also matters (length of the energetic part of the source wavelet) and was determined by Common Mid Point (CMP) analysis to be 12 ns with our system (Verfaillie et al., 2012) leading to a tracking accuracy of half this duration, which in the firm gives a shift of some 1.2 m. Since these two errors do not systematically add up, one generally considers the worse of the two. Finally, interpreting radargrams and picking reflectors is partly subjective and operator dependent which leads us to estimate the overall uncertainty on the IRH depth to be 1.5 m at the worse. Given a relatively constant slope of $20\text{ yr}\cdot\text{m}^{-1}$ of the age-depth relationships (see ~~figs 3 and 10~~ fig. 3), this depth uncertainty maps into an age uncertainty of about 30 yr. This uncertainty in the depth positioning nevertheless has a strong systematic component (in other words the error in depth positioning remains mainly the same along a given IRH) and therefore only partly alters

420 the isochronous character of the reflectors. The same can be said for depth errors resulting from a wrong assessment of the vertical velocity profile. Only lateral variations not properly accounted for would contribute, but it is well known that the plateau firm only undergoes minor lateral variations in its depth distribution of density (Muller et al., 2010) and hence velocity at the scale of a couple of hundred km.

425 As a result, one can reasonably argue that a true isochronous IRH can theoretically deviate by 10 to 15 yr. ~~When comparing to Appendix C presents the different inferred ages when reporting our IRH depths along the other cores of the project (S1,S2 and S0-Explore). From~~ the RMS dispersions of respectively 3 yr, 6 yr and 13 yr for IRHs 1 to 3 at the ~~crossing-cross-over~~ points as revealed by ~~Figure 3, Fig. 11~~ we come to the conclusion that our three IRHs ~~are actually isochronous.~~
430 ~~can be considered as isochronous.~~ We nevertheless have to keep in mind that the absolute error on the age (to be used in the budget error for mass balance computation, see ~~Section Sect.~~ 5.6) remains potentially higher than these 10 to 15 yr by integrating the biases from systematic incorrect positioning and errors from time to depth conversion in the radargrams.

~~Time markers along the five cores as studied in (Gautier et al., 2016). The reference core is~~
435 ~~VOLSOL-1 (see Section4.2) for which the quadratic fit is entirely represented in black, whereas insets represent enlargements where all quadratic fits allow for an assessment of the age dispersion around the reference at the depths of our three IRHs.~~

5 Snow accumulation along the GPR profile

5.1 Accumulation computation

440 Assuming an IRH at a given depth H , the total mass M of the unit surface (1 m by 1 m) firm column above it can be expressed as :

$$M = \int_0^H \rho(z) dz \quad (2)$$

where M can be considered as a mass flux per m^2 because of the implicit unit surface. It therefore expresses as $kg.m^{-2}$ which, given the density of water, also represents millimeter water equivalent
445 (mm w.e.). The average accumulation rate over the period since the deposition of the IRH is finally obtained by dividing by the age of the IRH leading to a final result in $mm.w.e.yr^{-1}$.

5.2 Firm density profiles for accumulation rate computations

Similarly to the depth and age, proper estimation of the density profile down to a given IRH is crucial for a good assessment of the corresponding accumulation rate. If spatial variations of accumulation
450 mainly result from differences in snow cumulative heights as revealed by undulating reflectors, one can reasonably wonder to which extent geographical changes in density may also impact. Unfor-

tunately, over the Antarctic plateau, density profiles are usually concentrated at limited sites with almost no reliable data in between. In the present case, density profiles from deep ice cores are only available at the two 'extremities' of the radar line (DC and S0). Some extra shallow cores were also drilled along the radar profile (S1, S2, S2B) but their maximum depths (about 20 m) are limiting at least for interpreting the two deepest IRHs. However, owing to the fact that over the plateau meteorological parameters controlling the densification process (e.g. air temperature, wind activity, solar radiation..) exhibit small gradients at the regional scale, a relative uniformity in firn density profiles can be first assumed over distances of the order of 100 km as can be anticipated from the small divergence between the DC and S0 density profiles (see [Section 5.4](#) [Fig. 5.3](#)). The limited variability was confirmed by Fujita et al. (2011) from pits and surface snow measurements during the JASE traverse and more specifically the resulting small impact on accumulation rates was demonstrated by Ruth et al. (2007) by-when comparing water equivalent depth profiles between Dome Fuji and EPICA DML. This led us in a first instance to only-consider-consider only deep ice cores from the DC site along which precise and high resolution density profiles have been performed (e.g., Leduc-Leballeur et al., 2015). A later sensitivity test is proposed (see [Section ??](#) [Sect. 5.4](#)) consisting of assessing changes in accumulation expected-to-expect from integrating the contribution of density profiles from different locations. These changes are then compared to the uncertainties solely arising from the choice-of-a-given-degree-of-representativeness (due to the small scale variability) and measurements errors in density when using a single density depth profile (correct representativeness, measurement errors, etc..) to be exclusively used in for computing the accumulation rate computation all along the radar line (see [Section-Sect. 5.5](#)).

5.3 Density profiles at DC

In the framework of the EPICA project (Augustin et al., 2004), along with the main core, several extra shallower drilling projects have yielded as many density profiles over at least the first 50 m for the DC area (see [Table 2](#) [and Fig. 5.3](#)). A first question as to which of these cores to use for computing accumulation rates arises, or in other words, what can be the sensitivity of the results to the choice between different nearby cores at a given site -Figure-like DC. The lower part of Fig. 5.3 shows the depth density profiles for each of the cores listed in the table along with the corresponding cumulative mass with depth (right scale in the figure). The cumulative masses have been computed either from the raw data (not represented on the figure) or from the quadratic fits (see corresponding results at the three IRH depths in the table). Despite a pronounced scatter in the individual data points around their respective fits (see [Fig. 5.3](#) and associated RMSE in the table), considering raw or fitted data does not significantly change the depth-cumulated-depth-cumulative mass with differences not exceeding 1.15% at the most (ITASE-98 at the depth of IRH1).

This illustrates a symetrie-random scatter of data points above and below the fit which leads to an almost exact compensation when summing up the cumulative mass. As a consequence, fitted density

Table 2. Density cores at DC along with the characteristics of their quadratic fits. Cumulative masses ($\text{kg}\cdot\text{m}^{-2}$) down to each of the three IRHs at respective depths of 15.08, 22.97 and 31.88 m are computed from the raw data as well as from the fitted curves.

<u>Core name</u>	<u>Depth (m)</u>	<u>r^2</u>	<u>RMSE ($\text{kg}\cdot\text{m}^{-3}$)</u>	<u>cum. raw 1 15.08 m^(a)</u>	<u>cum. fit 1 15.08 m^(a)</u>	<u>cum. raw 2 22.97 m^(a)</u>	<u>cum. fit 2 22.97 m^(a)</u>	<u>cum. raw 3 31.88 m^(a)</u>	<u>cum. fit 3 31.88 m^(a)</u>
<u>DC5^(b)</u>	<u>81.01</u>	<u>0.988</u>	<u>13.51</u>	<u>6060</u>	<u>6054</u>	<u>10087</u>	<u>10058</u>	<u>15129</u>	<u>15101</u>
<u>DC3</u>	<u>81.32</u>	<u>0.987</u>	<u>13.88</u>	<u>6050</u>	<u>6033</u>	<u>10103</u>	<u>10045</u>	<u>15154</u>	<u>15101</u>
<u>Firetracc</u>	<u>50.06</u>	<u>0.939</u>	<u>24.76</u>	<u>6352</u>	<u>6321</u>	<u>10350</u>	<u>10343</u>	<u>15361</u>	<u>15362</u>
<u>Itase-98</u>	<u>44.17</u>	<u>0.973</u>	<u>17.39</u>	<u>5963</u>	<u>5894</u>	<u>9937</u>	<u>9832</u>	<u>14884</u>	<u>14788</u>
<u>Itase-DC1</u>	<u>17.47</u>	<u>0.905</u>	<u>19.95</u>	<u>6176</u>	<u>6171</u>	<u>-^(c)</u>	<u>~</u>	<u>~</u>	<u>~</u>
<u>Itase-DC2</u>	<u>17.90</u>	<u>0.976</u>	<u>9.48</u>	<u>6218</u>	<u>6217</u>	<u>~</u>	<u>~</u>	<u>~</u>	<u>~</u>
<u>Itase-DC3</u>	<u>19.27</u>	<u>0.901</u>	<u>20.52</u>	<u>6119</u>	<u>6062</u>	<u>~</u>	<u>~</u>	<u>~</u>	<u>~</u>
<u>Itase-DC4</u>	<u>18.15</u>	<u>0.948</u>	<u>13.68</u>	<u>6250</u>	<u>6264</u>	<u>~</u>	<u>~</u>	<u>~</u>	<u>~</u>

^(a) in $\text{kg}\cdot\text{m}^{-2}$; ^(b) (Leduc-Leballeur et al., 2015) ; ^(c) depth not reached by the core

curves will hereafter be considered in the computations of accumulation rates. The second result comes from the limited dispersion in the cumulative mass from one core to the other as can be easily
 490 seen from the figure. The maximum discrepancy is to be found between the Itase-98 and Firetracc ice cores with relative differences of 7%, 5% and 4% at the depths of respective IRHs 1, 2 and 3.

~~Density profiles (left scale) as mentioned in the text and detailed in table 2. Also shown is the corresponding cumulative mass with depth (right scale). For the sake of clarity, only cores (and associated cumulative masses) exceeding 20 m are fully represented (DC5, DC3, Firetracc and
 495 Itase-98 ice cores). Insets correspond to enlargements around the depths of IRHs 1-2 and 3 where all mass curves are depicted and allow for an estimation of the dispersion in cumulative masses.~~

Of interest is the almost perfect overlap of the DC3 and DC5 curves which come from the same project and have been measured according to the same protocol by the same operator. ~~This tends~~
These results tend to show that :

- 500 (a) Most of the difference between different cores results from measurement errors
- (b) The variability of the density expressing at the scale of the typical distance between these cores (from m to km scale) is of stochastic type (Libois et al., 2014) and is therefore rapidly canceled out by the depth averaging process of cumulative mass computation leading to accumulation rates. Indeed the DC3 and DC5 cores are separated by 1.5 km but still show remarkable consistency in their quadratic fits or in their associated cumulative mass distribution with depth.
 505
- (c) Provided that systematic error measurements can be minimized, a single density profile should then be considered as representative of the local accumulation rate.

The very good similarity of the DC3 and DC5 cores attests to the quality of density measurements as confirmed by the novelty and strictness in the measurement protocols (Leduc-Leballeur et al., 510 2015). This led us to choose the DC5 as the reference for our accumulation rate computations. A sensitivity to the various density profiles along the radar line is later proposed in Sec. ??.

5.4 Density profiles along Sensitivity of the traverse route accumulation rate to geographically different density profiles

Fig. ?? now shows the density profiles from some of the cores situated along the traverse route. Apart 515 from the DC5 core (Leduc-Leballeur et al., 2015) all other cores were drilled in the framework of the project (with the S0-Expl core resulting from the Explore companion program) and corresponding density profiles measured in the following years. What the figure shows is the good similarity between the density values along the DC and S0 cores apart from slightly lower values for the latter over the first 30 m. This result is not surprising given the limited distance between the two 520 sites (66 km), although DC is located on a dome, whereas S0 is already on the eastern side of the DC-Vostok ridge (see Fig. 1) where the slope in the prevailing wind direction can have a significantly different impact on the wind-driven erosion/redeposition of snow (Frezzotti et al., 2002) and hence on the density. Going further south (S1, S2 and S2B cores) does not either change the density values significantly (at least over the first 20 m) although the comparison is less straightforward given the 525 marked dispersion in the first meters.

Density measurements along the ice/firn cores from Dome Concordia (DC5) and from the traverse route (S0-Expl, S1, S2 and S2B). For DC5 and S0-Expl, a degree-3 polynomial offered the best fit and is represented by a continuous line. The DC core used here (DC5) was drilled in 2012 and was chosen for the high resolution in density measurements (more than 1400 samples over the first 530 80 m). The S0-Expl core was drilled in the frame of a companion program (program Explore which benefited from the logistics of the traverse, and provided density measurements down to 110 m (Chappelaz, personal communication). For the sake of clarity, and having a much reduced depth of about 20 m, the S1, S2 and S2B cores are depicted in the upper insets whose imprint corresponds to the bottom dashed square. Their quadratic fits (black dashed line) as well as those of DC and S0 535 (respectively red and blue lines) are also shown.

The observed variability in density along a core as observable in Fig. ?? comes from the natural variability due to depositional processes and from measurement errors. These latter mainly result from measurement difficulties due to the weak cohesion of snow in the first meters preventing from obtaining well defined shapes that are later weighted as part of the density calculation process. As a 540 consequence, an uncertainty of $\pm 20 \text{ kg}\cdot\text{m}^{-3}$ over the first 7 m linearly decreasing to $\pm 15 \text{ kg}\cdot\text{m}^{-3}$ at 15 m deep and remaining constant further down is proposed for these density measurements (see error bars on the figure). These uncertainties are less pronounced than the ones proposed by Verfaillie et al. (2012) (10% of the density value) at least for the deepest parts of the cores, since it

545 corresponds to more recent cores over which extra-careful and high resolution density measurements were performed.

As for the natural dispersion, it is partly explained by the seasonality of deposition and changes in the local climatic conditions (Hörhold et al., 2011) and more significantly by wind-driven erosion/redeposition processes (Frezzotti et al. (2002); Libois et al. (2014)). Indeed, snow redistribution by wind is the result of a subtle interaction between the wind field and the small scale surface topography eventually leading to short-scale variations in the physical properties of the surface snow. Libois et al. (2014) showed that a stochastic scheme of the snow erosion/deposition by the wind in a multilayer detailed snowpack model could explain a significant part of the near surface variability in snow density. However Hörhold et al. (2011) show that due to competing mechanical processes, this variability rapidly decreases with depth to reach a minimum at around $600 - 650 \text{ kg.m}^{-3}$ before increasing again towards a second local maximum.

555 Despite compensation effects due to the random character of the natural variability with depth as observed in the cumulated masses (Section 5.3) measurement errors, on the other hand do not systematically cancel with depth integration (especially if systematic) and can thus become a significant contributor to the overall uncertainty due to density. Although difficult, an attempt to assess this term is proposed in the budget error Section. Before doing so, it appeared interesting to first assess the changes in accumulation pattern to be expected from the choice of different density profiles and then to compare them to the accumulation error resulting from the total uncertainty on a given density profile. Such a comparison should provide insights into the relevant strategy to adopt.

5.5 Sensitivity of the accumulation rate to different density profiles

565 ~~Figure Fig. 5~~ shows the three accumulation rates derived along each of the three IRHs along the radar line from the density profile provided by the DC-5 reference core. Since the computation uses a single density profile, ~~the IRHs and the resulting accumulation curves show very similar undulations and particularly, the persisting overall shape from one IRH to the other is maintained expressing an almost perfectly stationary pattern through time~~ no lateral changes in density are accounted for and the stationary accumulation pattern therefore expresses under shifted IRHs of the same shape. Of importance is the pronounced gradient when following the ridge going from DC towards S2 (see map on Fig. 1) with a more than 20% loss within 250km.

575 ~~As for In order to test~~ the sensitivity to the ~~the~~ use of density profiles ~~from various locations, it originating from different distant places, accumulation rates are here separately computed from both the reference DC5 density profile and the Explore one (this latter being the only reliable and deep enough density profile at our disposal).~~ The difference expresses under the form of a uniform shift along a given IRH (as can be seen from the insets) but with a decreasing sensitivity with the depth of the IRH. The difference in accumulation rates from the use of the DC and S0 (Explore) densities amounts to 1 mm w.e.yr^{-1} for the 234-yr ~~IRH-IRH1~~ (lower inset) and reduces to about half of it

580 when considering the 592-yr reflector (upper inset). The explanation is to be found in the rapidly
converging fits of the DC and S0 density curves with depth (~~Fig. ??~~top of Fig. 5.3). Indeed, the
increasing cumulative difference in mass is more than counterbalanced when dividing by the age of
the IRH in the accumulation rate computation process. Using the less reliable S1, S2 and S2B ~~does~~
~~(not represented) did~~ not lead to a significantly higher sensitivity. ~~With density fits in-between those~~
585 ~~of the DC and S0 cores (see upper insets of Fig ??) S2 and S2B accumulation rates normally lay in~~
~~between those of DC and S0. Only the S1 accumulation curve exhibits a slightly larger difference due~~
~~to a density curve systematically below those of DC and S0. It should be noted that because of their~~
~~limiting depths of some 20m the sensitivity to the S1, S2 and S2B curves cannot be assessed down~~
~~to the two lowest IRHs. The main conclusion to retain is~~ As a consequence, a maximum deviation
590 of the order of 1 mm w.e.yr⁻¹ ~~to expect is to be expected~~ from accounting for the geographical
changes in density along the profile.

5.5 Proper choice of the density core to use

Assessing the uncertainty on the accumulation rates solely arising from measurement errors in the
density profile used is not straightforward since part of these errors are random and certainly compen-
595 sate with depth, a least partially. Moreover, small-scale accumulation variability that influences the
representativeness of a single core for a given location also potentially contributes to accumulation
uncertainty, even if limited in amplitude as was shown in ~~Section Sect.~~ Sect. 5.3. Because they result
from different projects implying different measurements protocols, the numerous cores drilled in
the DC area provide a means of estimating the order of magnitude of the combined effect of these
600 two terms. In particular, the dispersion between all these cores should implicitly ~~account for~~ include
the most of the measurement errors and would only miss a systematic component (i.e an identical
error for all measurements) which in any case must remain small. Computation of the cumulative
mass down to IRH1 for these 8 cores listed in Table 2 gives an average of 6127 kg.m⁻³ with a
standard deviation of 141 kg.m⁻³. When dividing by the age of ~~the IRH~~ IRH1 (234 yr) one obtains
605 26.18 ± 0.60 kg.m⁻³yr⁻¹ or 26.18 ± 0.60 mm w.e.yr⁻¹. Similar computations down to the two
deepest IRHs (but only concerning the first four cores) respectively give 25.75 ± 0.54 mm w.e.yr⁻¹
and 25.49 ± 0.40 mm w.e.yr⁻¹ for IRH-IRHs 2 and 3. ~~This decrease in the uncertainty results from~~
~~a stabilized scattering of the density profiles with depth leading to a similarly stabilized dispersion~~
~~in the cumulative mass (Fig. 5.3) which, once divided by the age, yields smaller deviations for older~~
610 ~~IRHs.~~

~~Considering now accumulation rates along IRH1 computed from the DC5 density core (with The~~
~~resulting dispersion is then considered as representative of the total error due to the use of a local~~
~~density curve and has been represented under the form of~~ the error bars ~~on density as proposed in~~
~~Sect. 5.4) yields results represented on Fig. ??.~~ Also shown is the same accumulation profile obtained
615 ~~from the~~ in the insets of Fig. 5. The same error bars have been applied to the accumulation profiles

620 ~~from the Explore core at S0 density profile and from a combination of all available density profiles along the radar line (according to an inverse distance weighting). Keeping in mind that the resulting errors (black bars on the figure) are probably underestimating the overall uncertainty arising from the chosen density profile, and given, but they probably represent an underestimation due to a less stringent density protocol in the density measurement. From the systematic overlap and~~ the fact that similar errors have to be expected with the S0 density profile (not represented for the sake of clarity), ~~one comes~~ the Explore error bars represent lower bounds, we come to the conclusion that ~~using the DC or the S0~~ accounting for the available geographical spatial variability of density does not bring ~~any~~ significant changes in the ~~computed~~ accumulation rates. ~~If globally lower values seem to emerge from the S0 curve with IRH1, the shift rapidly reduces with depth and systematically remains within error bars which become even smaller with IRHs 2 and 3 as visible from the insets.~~ In fact, properly accounting for the geographical distribution of density would normally require integration of all available density profiles evenly distributed along the radar line according to their respective distances (~~red profiles on the figure~~). ~~Similar conclusions emerge in the sense that no significant information is gained, at least for IRH1. Despite an attempt to extend their density profiles down to IRHs 2 and 3, the reduced depth (around 20 m) of the inverse distance weighting). However, the S1, S2 and S2B cores represent a strong limitation in their actual use. Lastly, given the respective positions of DC and are of limited use because of a maximum depth of 20 m. Moreover, including the effects of density at S0 with respect to the radar line, integration of the two density profiles according to their respective inverse distance (potentially different from that at DC) according to an inverse distance weighting would not make much sense when considering the position of the S0 profile with respect to the entire radar profile (the DC-S0 gradient being perpendicular to the major axis of the radar line, see Fig 1). As a consequence, our strategy thus consists in relying on a single but reliable density profile (DC5) rather than trying to integrate the non significant geographical~~

630 ~~effects from limited or not-so-relevant extra data sets.~~

640 ~~Accumulation rates computed from (i) the DC5 density profile (black), (ii) the S0 density profile (green) and (iii) the combination (inverse distance weighting) of all available density cores along the radar line (red). Insets depicts similar representations for IRHs 2 and 3 where the S1, S2 and S2B density profiles have been artificially extended to the required depths by using the S0 fit which offers the best match (compared to DC5) as observable from the insets of Fig. ??.~~

5.6 Overall error budget for surface accumulation rates

From the expression of snow accumulation rate $\dot{A} = \frac{\bar{\rho} H}{T}$, the three error sources contributing to the overall uncertainty originate from (i) ΔH the error in the depth of the IRH, (ii) ΔT the error in its age, and finally (iii) $\Delta \bar{\rho}$ the ~~error in the depth averaged density $\bar{\rho}$ density error~~ resulting from the use of the selected density profile. ~~Each of these sources are readily obtained from proper derivation with respect to the relevant variable of the accumulation rate expression as above and All the resulting~~

650 ~~errors are readily obtained from proper derivation with respect to the relevant variable of the accumulation rate expression as above and All the resulting~~

components are summarized in Table 3. For density, assessment of the correct representativeness with a single core was already derived in Section ?? and respectively gives uncertainties of 1, 0.75 and 0.5 mm w.e.yr⁻¹ for The first error term ($\Delta \dot{A}_1$) due to density implicitly includes the uncertainty resulting from the degree of representativeness and the measurements errors of the selected core (DC5). It has already been assessed from the dispersion in accumulation rates of the numerous available density profiles at DC (see sec. 5.5) and directly expresses as an accumulation rate uncertainty (0.6, 0.54 and 0.4 mm w.e.yr⁻¹ for respectively IRHs 1, 2 and 3). As for the actual errors in the density measurement, we reconsidered the proposed depth-dependent errors of Section 5.4 whose contributions were integrated down to the depth of each of the IRHs, leading to very similar values around 18 kg.m⁻³ which once multiplied by $\frac{H}{T}$ yield a fairly similar depth-decreasing uncertainty. The global error on error due to the neglect of the geographical changes ($\Delta \dot{A}_2$), it can be estimated to be around the average along the radar line of the difference in accumulation rate when using the DC5 and the S0 core (Sect. 5.4), namely 0.98, 0.85 and 0.68 mm w.e.yr⁻¹ for respectively IRHs 1, 2 and 3. The overall error due to density is finally obtained-proposed as the RMS of these two-contribution-as-stated-in-the-5th-column-of-the-table-2 terms (see Table 3).

For the age, the two independent terms arising from (i) the relevance and associated uncertainty of the age-depth relationship of the used core ΔT_c (8 yr) and from (ii) the positioning error due to radar resolution ΔT_p (30 yr, see Sect. 4.3) give a quasi systematic RMS remaining around 30 yr which then induces total. This time error thus transforms into accumulation rate uncertainties of respectively 1.49, 1.20 and 0.97 mm w.e.yr⁻¹ 3.01, 2.06 and 1.39 mm w.e.yr⁻¹ for IRHs 1 to 3.

Finally, errors in the depth (H) of the IRHs stems from the 1.5 m radar positioning accuracy as determined in Section Sect. 4.3 plus a systematic component due to the time-depth conversion of the two-way travel time. Proper derivation of Eq. 1, with an average error of 18 kg.m⁻³ on density measurements (deduced from the estimated density measurement errors represented by the error bars of the DC5 density profile in Fig. 5.3) gives a relative error of less than 1.5% for the average wave velocity which results in errors. It leads to the resulting depth error ΔH_R as a function of the IRH depth as in-given by the Table. RMS combination of these two terms finally leads-to-the-most-pronounced-gives-an error component for the accumulation rate of respectively 2.54, 1.68 and 1.23 mm w.e.yr⁻¹ for IRHs 1, 2 and 3.

Following (Muller et al., 2010) Muller et al. (2010), the cumulative uncertainty is finally proposed as the RMS of these three main contributors ($\Delta \bar{\rho}$, ΔT and ΔH) which gives uncertainties of 4.18, 2.72 and 1.96 mm w.e.yr⁻¹ global maximum uncertainties of 4.12, 3.02 and 2.17 mm w.e.yr⁻¹ for IRHs 1, 2 and 3 respectively, later rounded to 4.2, 2.7 4, 3 and 2 mm w.e.yr⁻¹. The noticeable feature is a strong decrease with IRH depth, in contrast to (Muller et al., 2010) Muller et al. (2010) where an increasing error with depth seems to result from a rapid degradation of the signal-to-noise ratio due to the weak penetration depth and high sensitivity to water content of their high frequency (2.3 GHz) system. It should also be noticed that the proposed uncertainties here pertain to the absolute

Table 3. Different source terms in the overall error budget for accumulation rate

IRH	Depth-averaged density ($\bar{\rho}$)			IRH age (T)			IRH depth (H)				
	$\frac{H}{T} \Delta \bar{\rho}_m^{(a)}$	$\Delta \bar{\rho}_m^{(a,b)}$	$\Delta \bar{\rho}_m^{(b)}$ RMS ^(a,b)	$\Delta T_c^{(c)}$	$\Delta T_p^{(d)}$	RMS ^(c,d)	$\frac{\bar{H}}{T^2}$ RMS ⁽¹⁾	$\Delta H_v^{(e)}$	$\Delta H_s^{(f)}$	RMS ^(g,f)	$\frac{\bar{H}}{T}$ RMS
	mmw.e.yr ⁻¹	mmw.e.yr ⁻¹	mmw.e.yr ⁻¹	yr	yr	yr	mmw.e.yr ⁻¹	m	m	m	mmw.e.yr ⁻¹
1	181.10 0.60	±0.98	1.49-1.15	8	30	≈ 30	2.97-0.22 3.01	1.5	0.22	1.52	2.54 2.57
2	17-0.94 0.54	0.75-0.85	1.20-1.01	8	30	≈ 30	1.77-0.34 2.06	1.5	0.34	1.54	1.68 1.96
3	17-0.83 0.40	0.5-0.68	0.97-0.79	8	30	≈ 30	1.17-0.48 1.39	1.5	0.48	1.57	1.23 1.47

(1) Computed with averaged depths of respectively 13.87, 21.09 and 29.43 m and corresponding averaged densities of respectively 397, 498 and 553 kg.m⁻³ for IRHs 1 to 3

errors on the accumulation rates and implicitly comprise a significant systematic part that does not come into play when interpreting spatial or time-dependent gradients as in the following section.

6 Accumulation space and time distribution

6.1 Spatial distribution

A geographical representation of averaged accumulation rates (and differences between the fields) over the three periods characteristic of the selected three IRHs is represented in Fig. 6 where significant trends can be observed. The relatively good phasing between the three IRHs already noticed on the radargram is observable from the difference in the represented fields (blue scale) not exceeding 1.2 mm w.e.yr⁻¹. It is also consistent with the computed SMB of Fig. 5 and confirms a quasi stationary accumulation pattern over the past 600 yr. In particular, an overall decrease in accumulation of some 20% from DC to the South West (towards S2) similarly appears for the three IRHs. More specifically, traversing towards the South East leads to the minimum value between 19 and 20 mm w.e.yr⁻¹ (depending on the averaging period) at a place close to the S2B core site in the direction of a nearby megadune field (see Fig. 1).

It should be noted that the 2011/12 TASTE-IDEA traverse was the opportunity for the deployment of an ultrasonic range sensor (SR50, Campbell scientific) allowing for a continuous monitoring of the surface height for more than 5 yr at the S2 point. Corresponding surface heights since January 2012 are depicted on figure Fig. 7 where short term variations revealing both precipitation and/or strong snow redistribution events are clearly visible. Despite these rapid changes which eventually contribute to the meter-scale variability in surface accumulation (Libois et al., 2014), a significant trend emerges over these 5 yr of measurements. When considering surface densities between 300 kg m⁻³

710 and 330 kg m^{-3} (~~Figure ??~~Fig. 5.3), this trend maps into accumulation rates between 19.5 and 21.5 mm w.e.yr^{-1} which appear to be fully consistent with our computed accumulation rate for the S2 point over the last 234 yr as represented by the black box on Fig. 5.

Previous measurements of GPR-derived accumulation rates in the vicinity of Concordia Station were carried out in 2005 (Urbini et al., 2008). A radar profile through the station revealed an almost north-to-south gradient of $-0.02 \pm 0.01 \text{ mm w.e.yr}^{-1}.\text{km}^{-1}$ in its southern part (see Fig. 6 in Urbini et al. (2008) and Fig. 8 where corresponding data have been summarized). Despite limited areas over which they overlap, and a slightly different averaging period (the last 266 yr against our last 234-yr average) these data remain however relatively consistent with ours as can be seen from the figure. Moreover, from our data, starting from around DC and considering the upper left blue points of the figure, a difference of about 1 mm w.e.yr^{-1} can be derived over a distance of some 30 km leading to a gradient of $-0.033 \text{ mm w.e.yr}^{-1}.\text{km}^{-1}$ close to that of Urbini et al. (2008) along a similar direction. When assessing an uncertainty on our proposed gradient, only the non-systematic terms have to be considered, such as the effects of a laterally varying density which in the present case should be insignificant because of the distance of only 30 km. Errors in positioning or age along IRH1 should also remain small. Indeed, as can be seen from the limited dispersion in both ages and depths at crossing points S1 and S0 (see Table 2) the spatial variations in positioning or in the age along a given IRH are minor (maximum differences of 18 cm and 3 yr for IRH1, leading to a RMS uncertainty of ~~$0.45 \text{ mm w.e.yr}^{-1}$~~ $0.43 \text{ mm w.e.yr}^{-1}$ according to the error budget of Table 3. ~~The proposed difference therefore remains significant and It~~ leads to an uncertainty of ~~$0.015 \text{ mm w.e.yr}^{-1}.\text{km}^{-1}$~~ $0.014 \text{ mm w.e.yr}^{-1}.\text{km}^{-1}$ on the proposed gradient and makes the comparison still relevant. It should be noted that this gradient has also been observed by Genthon et al. (2015) from snow accumulation at two stake networks 50 km apart along a north south direction centred on the Concordia station. Despite a high uncertainty for the uppermost snow density which limits the derivation of absolute values of accumulation rate, the use of a uniform snow density along the 50-km long section revealed a significant gradient similar to that of Urbini et al. (2008) and of the present study. Their study also shows that despite an overall underestimation of snow accumulation, meteorological analyses from the European Center for Medium-range Weather Forecasts confirm this tendency (see the modeled precipitation field on Fig. 1). Moreover, from a careful observation of precipitation events and analysis of air mass back trajectory pathways Genthon et al. (2015) show that the core of snow fall results from relatively warm (and hence humid) air masses intrusions from the north~~which undergo a significant temperature-driven depletion in moisture when~~ When passing over the Concordia dome on their way to the south ~~.This they undergo a significant temperature-driven depletion in moisture which~~ is fully consistent with the observed gradients.

6.2 Time-dependency of accumulation

745 Because of the limited number of IRHs being analysed in this study, only a coarse characterization of the time-dependent accumulation can be proposed as is the case in (Urbini et al., 2008) ~~Urbini et al. (2008)~~ for instance. This limitation comes from the stringent requirements for a reflector to be considered as properly isochronous (showing the continuity over large distances) and assigned a relevant age (by passing through a coring site where an depth/age relationship can be independently derived).

750 ~~Focusing on a given location and considering a large number of reflectors might be tempting at first sight but this is only possible if every reflector is unambiguously connected to an ice core in order to account for the unavoidable spatial changes in the depth distribution of IRHs.~~ As for recent accumulation rates, it should be noticed that the multiple direct reflections in the air between the emitter and receiver parts of the antenna leads to a saturated signal screening potential sub-surface reflectors. The last decades of surface mass balance from GPR are therefore often missing which prevents proper comparisons with 'modern' accumulation values as derived from stakes farms for example (only operational since the late ~~nineties~~ ~~1990ies~~ for the DC area).

We therefore propose three periods over which mean accumulation rates can be derived (1411-1616, 1616-1778 and 1778-2012 CE) as can be seen from Fig. 9. Data were spatially averaged over 760 five main sectors whose respective extensions are reported on the figure with appropriate symbols. The results first confirm the stationary character in the spatial pattern of accumulation rates as was already found from inspection of Figs. 5 and 6 for example. Indeed, the trend in the time-dependent increase over the three proposed periods is remarkably similar from one sector to the other. Similarly to the above mentioned spatial patterns, only the non-systematic parts in the associated errors (with regard to time) have to be considered for interpreting these time trends. Therefore, the potential deviation in the isochronous character of the IRHs around ~~10 to 15 yr, of a similar order as the age dispersion of the IRHs at crossing points as given in section~~ ~~10 yr, as estimated in Sect.~~ 4.3 essentially comes to play. It leads to a potential margin of error ranging from ~~1.07 to 0.42 mm w.e.yr⁻¹~~ ~~1 to 0.45 mm w.e.yr⁻¹~~ for respectively IRHs 1 to 3 which would theoretically hamper the significance of the computed trends. However, the fact that these data represent averages over entire sectors and the remarkably similar evolution from one sector to the other gives some credit and suggest a regularly increasing accumulation rate for this sector of the Antarctic plateau over the last 600 yr.

Our results also compare well with those mentioned in (Urbini et al., 2008) ~~Urbini et al. (2008)~~ and references therein over the DC area (depicted in grey in the figure). More specifically, from $n_{ss}SO_4^{2-}$ volcanic spikes along the EPICA EDC96 core, an average accumulation rate of slightly less than 25 mm w.e.yr⁻¹ for the 1460 (Kuwae)-1816 (Tambora) period was proposed (Castellano et al., 2004). Then follows the 1816-1998 AD period with a 25.3 mm w.e.yr⁻¹ accumulation rate followed by a marked increase up to 28.3 mm w.e.yr⁻¹ between 1965 and 2000 deduced from nuclear test horizons along the firm cores represented by the red circles on the figure (Frezzotti et al., 2005).

780 Results from farm stakes are also proposed by Frezzotti et al. (2005) with 32 mmw.e.yr^{-1} for
the 2004-07 period and up to 39 mmw.e.yr^{-1} between 1996 and 1999, but their relevance is ques-
tionable because (i) the measuring period is extremely short with respect to a very high inter-annual
variability (ii) the derived accumulation rate requires proper knowledge of the sub-surface density
which is highly variable and difficult to accurately measure and (iii) the intrinsically strong spatial
785 variability in snow thickness at the scale of a farm stake also requires long integration periods to
gain in significance. This is confirmed by the associated standard deviation of 14 mmw.e.yr^{-1} for
the 1996-99 stake results. In any case, no comparison with radar data is possible because of corre-
sponding reflectors too close to the upper surface.

6.3 Interpretation in the frame of remote studied areas

790 Several past studies (e.g., Fujita et al., 2011; Frezzotti et al., 2004, 2005) have proposed expla-
nations for the spatial distribution of the accumulation rate on the Antarctic plateau as a func-
tion of the environment. They globally come to the same conclusion according to which surface
mass balance results from a large scale synoptic precipitation pattern and generally smaller scale
ablation/redistribution processes mainly driven by the combination of the wind and the surface
795 slope (SPWD, Slope along the Prevailing Wind Direction). From data in the Dome F-Dronning
Maud Land sector, Fujita et al. (2011) show that a significant amount of the total precipitation
deep inland comes from the synoptic scale advection of moisture-laden and warm air masses from
low latitude usually characterized by rather strong associated winds as was also demonstrated by
(~~Genthon et al., 2015~~) [Genthon et al. \(2015\)](#) for the DC area. Most of the moist is released during
800 the orographic climb towards the plateau or on the windward side of any major ridge. Conversely,
in the case of a ridge, on the leeward side, an adiabatic warming of the descending air masses re-
duces the condensation potential even more leading to the concept of 'rain shadow'. According to
the major air mass trajectory pathways as described in [figure Fig. 5](#) of Genthon et al. (2015) and
more specifically the three paths from the east accounting for 55% of the total precipitation, a varia-
805 tion in the large scale precipitation field is expected across the Vostok-DC ridge as confirmed by our
data, at least in the vicinity of DC and towards S0. As for the large scale gradient along the radar
line, a similar analysis would require a detailed picture of the circulation pattern which is beyond the
scope of this paper. Still, a continental effect as noticed by (~~Fujita et al., 2011~~) [Fujita et al. \(2011\)](#) in
the Dome Fuji Dronning Maud Land sector seems plausible and is in line with the commonly ac-
810 cepted accumulation gradient along the ridge between DC and Vostok. Finally, the lowest measured
accumulation values around the S2B point are clearly situated off divide. Although it is difficult to
assert whether they result from a corresponding low in the synoptic accumulation pattern or from
smaller scale redistribution, the less regular surface topography probably contributes to more local
erosion/deposition processes resulting in more pronounced gradients than along the main divide.

815 Again, comparing the time dependency of our results with those from other studies suffers from
the lack of correspondence between the averaged periods. [Osipov et al. \(2014\)](#) and [Fujita et al. \(2011\)](#) [Osipov et al. \(2014\)](#) and
[Fujita et al. \(2011\)](#) give a detailed overview of the time evolution of the accumulation rate over sev-
820 eral sites on the Antarctic plateau during the last millennium. More specifically, a correlation be-
tween climate and accumulation changes seems to emerge from most studies cited in ([Osipov et al., 2014](#)) [Osipov et al. \(2014\)](#) and
according to which the slightly decreased temperatures during the Little Ice Age led to a corre-
sponding decrease in accumulation rate. However, not only is the timing significantly different from
one location to the other, but some places have undergone inverse trends such as Siple or Vostok
where, for example, the CE 1261-1601 lower accumulation period (-12% compared to the CE 1260-
2010 average) was followed by a 13% increase between CE 1661 and 1815. The authors attribute
825 this positive anomaly to a high sensitivity of the large-scale circulation pattern which undergoes
shifts in the stream pathways. Strong latitudinal gradients in the accumulation rate in the Vostok
area are confirmed by Ekaykin et al. (2012) who stresses this sensitivity but also invokes possi-
bly strong snow redistribution along the Dome B-Vostok ridge due to the combination of wind
and surface slope. The time dependency of our data would have matched that of Vostok should
830 our intermediary period (CE 1616-1778) have undergone a similar anomaly. Given the sensitiv-
ity ~~to~~ of these low accumulation rate areas to the above mentioned processes, this partial mis-
match probably illustrates the stochastic aspect of the accumulation changes there and does not
constitute an inconsistency. Last, a recent positive trend in accumulation over the last decades
and more generally since the middle of the 19th century emerges from most studies on differ-
835 ent locations on the Antarctic plateau (e.g., Mosley-Thompson et al., 1993; Fujita et al., 2011;
Frezzotti et al., 2013) and especially in the DC area (see Sect. 6.1). Although they result from
measurements over short periods (for instance from the Pinatubo volcanic horizon or from recent
stake farms) and are therefore suffering larger uncertainties, they remain compatible with the re-
cent observed warming in most places in Antarctica. If such a recent trend cannot be observed
840 from our data (see Sect. 6.2), it can still be implicitly included in our last 234-yr average and con-
tribute to the associated increase in accumulation rate depicted in Fig. 9. The figure gives a rather
steady and uniform accumulation increase over our investigated area of some $0.6 \text{ mm .w.e.yr}^{-1}$ over
600 yr thus representing a yearly increase of about $10^{-3} \text{ mm .w.e.yr}^{-1}$. Assuming a similar increase
over most of the Antarctic ice sheet would correspond to a negative contribution to worldwide sea
845 level of $3.75 \cdot 10^{-5} \text{ mm .w.e.yr}^{-1}$, a contribution much smaller than the plausible $1.2 \text{ mm .w.e.yr}^{-1}$
suggested by Krinner et al. (2006) by the end of the 21st century.

7 Conclusions

Relative depths of three IRHs from a 630-km long GPR profile have been combined with time
markers as well as density profiles along ice core data to provide surface accumulation estimates

850 between the DC and Vostok stations on the Antarctic plateau. Results show a remarkably persistent accumulation pattern, whatever the investigated time period (1411-1616, 1616-1778 and 1778-2012 CE) ~~during the 600-yr total coverage~~. More specifically, over the last 600-yr, the average accumulation rate exhibits a significant NE-SW gradient from $26 \pm 2 \text{ mm w.e.yr}^{-1}$ ~~25 \pm 2 mm w.e.yr⁻¹~~ at DC to $19 \pm 2 \text{ mm w.e.yr}^{-1}$ at the other extremity of the profile ~~emerges and~~ which appears to be
855 consistent with previous radar data available over the 25 km from DC. As for the time dependency, a steady increase of about ~~5%~~ 3 – 4% is also detectable over the last 600 yr and partially matches that from similar radar data. A careful error analysis is proposed that accounts for all possible intervening terms and provides depth dependent maximum margins of error from 4 mm w.e.yr^{-1} (234-yr average) to 2 mm w.e.yr^{-1} (592-yr average). It also shows that despite the proven isochronous character
860 of the proposed IRHs, the main source of error is to be found in the uncertainty in the determination the IRH depth ~~which maps onto an age uncertainty of some~~. Not only does this 1.5 m error change the depth over which the mass is accumulated, but it also leads to a 30 yr ~~which eventually accounts for more than half in the IRH age determination and eventually contributes to the most~~ of the total uncertainty on the accumulation ~~rates~~. The error budget also shows that in our case, the uncertainty in terms of density resulting from both the representativeness and measurement errors of a
865 single core is of the same order as the changes expected from incorporating the potential geographical variability in density from extra (but less reliable) cores along the radar line. In other words, it proved better to exclusively rely on a single reliable and accurate density core at one extremity of the profile, rather than trying to incorporate doubtful spatial changes from less reliable or even non
870 exploitable intermediate density cores.

Measuring surface mass balance over Antarctica remains a challenge and amongst the different available methods, combined radar and ice core data provide a robust means of properly assessing large scale spatial patterns as well as long-term temporal changes of snow accumulation. This is fundamental for addressing the overall mass budget of the ice sheet, especially in the context of global
875 warming when increased accumulation from more moisture-laden ocean air masses compete with enhanced ice flow through outlet glaciers which casts some doubts on the future contribution of the ice sheet to future sea level. Knowing surface mass balance space and time distribution is also fundamental for interpreting and dating the ice core climatic signal. In this respect, the DC-Vostok area is of prime interest for the retrieval of long climate records by combining large ice thicknesses and low
880 accumulation rates. This area therefore becomes the focus for the quest of new coring sites where an ice archive potentially older than a million year could be exploited (project 'Beyond EPICA Oldest Ice'). Surface mass balance maps thus constitute a major input for selecting the coring site (e.g., Fischer et al., 2013). However, despite the large possibilities of the proposed method for providing large scale accumulation fields, a comprehensive and high resolution coverage of the entire Antarctic
885 ice sheet is not realistic. Surface mass balance results from a subtle interplay between the regional accumulation pattern and more local parameters such as the surface topography and the wind field.

Outputs from global circulation models associated with the local specific environment should allow for relevant surface mass balance computations. This requires deriving accurate parameterizations describing the influence of the association of surface topography and the wind field (such as the Slope along the Prevailing Wind Direction, SPWD, see for example (Frezzotti et al., 2007)). Radar data as proposed in this study are intended to be used for constraining/validating such relationships leading to a forthcoming paper.

Appendix A: Ice core sampling and analysis

The ice cores were collected using two different electromechanical drilling systems (10-cm diameter for VOLSOL program and 5.8-cm diameter for TASTE-IDEA). The recovered core pieces were sealed in polyethylene bags in the field and stored in clean isothermal boxes before treatment. The VOLSOL-1 ice core was treated at DC using the laboratory facilities for chemical studies whereas the TASTE-IDEA shallow firn cores were transported in frozen state to the cold-room facilities of the Laboratory of Glaciology (IGE) in Grenoble, France, for radiochemical and chemical studies. At DC, the ice core was cut in cleaned conditions and samples were sealed in precleaned tubes before ion chromatography analysis. In Grenoble, sample preparation was also performed under clean-room laboratory conditions. After stratigraphic observations and measurements of bulk density, the four firn cores were divided into two half cores. One half was dedicated to radioactivity measurements, and the other half was analysed by ion chromatography. Due to the lack of seasonal variations of any chemical or physical parameters in snow between DC and Vostok stations, year-by-year dating of the snow layers is impossible. Only specific reference horizons can be used. In our study, the chronology of IRHs was established with the aid of sulfate spikes concentrations from past volcanic events coupled with the identification of recent thermonuclear bomb testing marker levels of CE 1955 and 1965.

Samples for chemical and radiochemical analysis were prepared with a time resolution of about 0.3 – 0.4 yr (2-cm length) and 1.5 – 2.0 yr (10 cm), respectively, which is necessary for the detection of volcanic eruptions and radioactive levels. The samples were prepared and analysed using stringent contamination control procedures.

For the VOLSOL-1 ice core treatment at DC, only sulfate concentrations were determined. They were measured (more than 5000 samples) on a Metrohm 850 Professional IC system coupled with a Seal XY-2 Sampler. A Thermo Scientific Dionex IonPac AS11-HS (4-mm diameter, 50-mm long) anion separation column was used. Such a short column allowed us to develop a fast (2 mn per sample) isocratic method using a 7 mM NaOH solution as eluent. Measured concentrations were calibrated in the 10 – 1000 ng.g⁻¹ range using dilutions of a commercial 1000 µg.g⁻¹ sulfate standard solution.

For the TASTE-IDEA firn cores treated at IGE, one half core was treated to measure major and organic chemical species from the surface down to 20 m deep (more than 5000 samples for all cores). Chemical analysis were performed using two different systems, enabling cross-checking of possible contamination processes and also validate the sulfate concentrations results. Indeed, the first measurements series were done using the same device system as the one used at DC for the VOLSOL-1 ice core treatment (sulfate concentrations measurements only) and the second series (same samples) was analysed with a Dionex® ICS3000 dual ion chromatography system. This last chromatography system was setup for the analysis of cations (Li^+ , Na^+ , NH_4^+ , K^+ , Mg^{2+} , Mn^{2+} , Ca^{2+} , Sr^{2+}) and anions (F^- , Cl^- , MSA^- , NO_3^- , and SO_4^{2-}) down to sub-ppb level and high level accuracy (6 standards calibration, relative standard deviation $< 2\%$). The two different chemical analysis systems found no contamination and were reliable for sulfate concentration determinations. The results of test series consequently allowed use of only the first system with short sample run analysis (1.5 mn versus 22 mn) to provide complete and rapid sulfate profiles as needed.

The second half of the TASTE-IDEA firn cores were processed for artificial radioactivity measurements (^{90}Sr , ^{137}Cs , and to a lesser degree ^{241}Am , daughter of ^{241}Pu) by a Berthold® B770 low-level beta counting and Canberra® very-low background BEGe gamma spectrometry device. Analysis were performed with a continuous sampling every 10 cm from the surface down to 6 m, i.e. the necessary depths to detect radioactive reference horizons from 1950s to 1980s atmospheric thermonuclear bomb tests. Details of the sampling and measurements procedures are given in Magand (2009), Loaiza et al. (2011) and Verfaillie et al. (2012).

Appendix B: Ice core Representativeness

The age-depth relationships of the 5 studied cores in Gautier et al. (2016) are represented in the following figure from which the age differences at our 3 IRH depths can be inferred.

Appendix C: Age dispersion along the radar line

The consistency as well as the dispersion for the ages of each of our 3 IRHs have been assessed by inferring the IRH depths when passing at the various core locations along the radar line. These depths were reported in the corresponding age/depth relationships for the DC-VOLSOL1, S1, S2 and the hybrid S0-Explore cores (see Fig. 11).

As can be seen, ages for each IRH remain consistent along the entire radar profile with a limited scatter at the various crossings (either between cores or when passing several times at the same core site). For instance, the uppermost blue IRH varies by only 3% among all crossing points and has a maximum discrepancy of only 6 yr (2.5%) with the DC reference age (see detailed figures in Table 4).

As for the second IRH (green), the scatter is 16 yr (4%) with a maximum deviation of 9 yr from the DC age of 391 yr. Lastly, the deepest one (pink) has a maximum deviation of 3.75% (22 yr) with the reference age which also corresponds to its total dispersion. The only noticeable discrepancy is to be found with the deepest IRH when passing the S0 site where crossing depths lead to systematically older ages. One explanation could lie in the loss of continuity for this deepest IRH towards the end of the profile where it sometimes becomes very faint (see bottom right of Fig. 2). The other possibility could result from the hybrid depth-age relationship obtained at S0 from two different cores. Because of the short-scale variability of surface snow post-deposition processes (Eisen et al., 2008), the distance of 70 m between the two cores may explain such discrepancies as was observed by Gautier et al. (2016) who found depth shifts of the order of 20cm between five cores only separated by 1 m at the DC site. They also come to the conclusion that logging errors and analysing procedures may play a role, especially if different coring and analysing teams are involved as was the case for the S0 and Explore cores. Although it can be criticised, the construction of such an hybrid age-depth relationship makes some sense in our case since we only considered the extra Explore markers at depths where no other volcanoes were available in the initial S0 core (> 20 m). The resulting quadratic fit still yields r^2 greater than 0.99.

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Table 4. Depth, corresponding age and deviation with respect to the DC -VOLSOL-1 reference age for the three IRHs whenever they intersect the DC-VOL-1, S0-Expl, S1 and S2 cores

	DC	S0-1	S0-2	S0-3	S1-1	S1-2	S2
IRH1 depth	15.08	14.08	13.94	14.12	13.97	14.05	12.70
IRH1 age	234	234	232	235	228	229	233
IRH1 error	-	0%	1%	0.5%	2.5%	2.25%	0.5%
IRH2 depth	22.97	21.47	21.43	21.16	21.43	21.27	19.38
IRH2 age	391	398	397	391	386	382	390
IRH2 error	-	1.75%	1.5%	0%	1.25%	2.25%	0.25%
IRH3 depth	31.88	29.56	29.70	29.84	29.84	29.70	26.76
IRH3 age	592	606	610	614	599	595	592
IRH3 error	-	2.25%	3%	3.75%	1.25%	0.5%	0%

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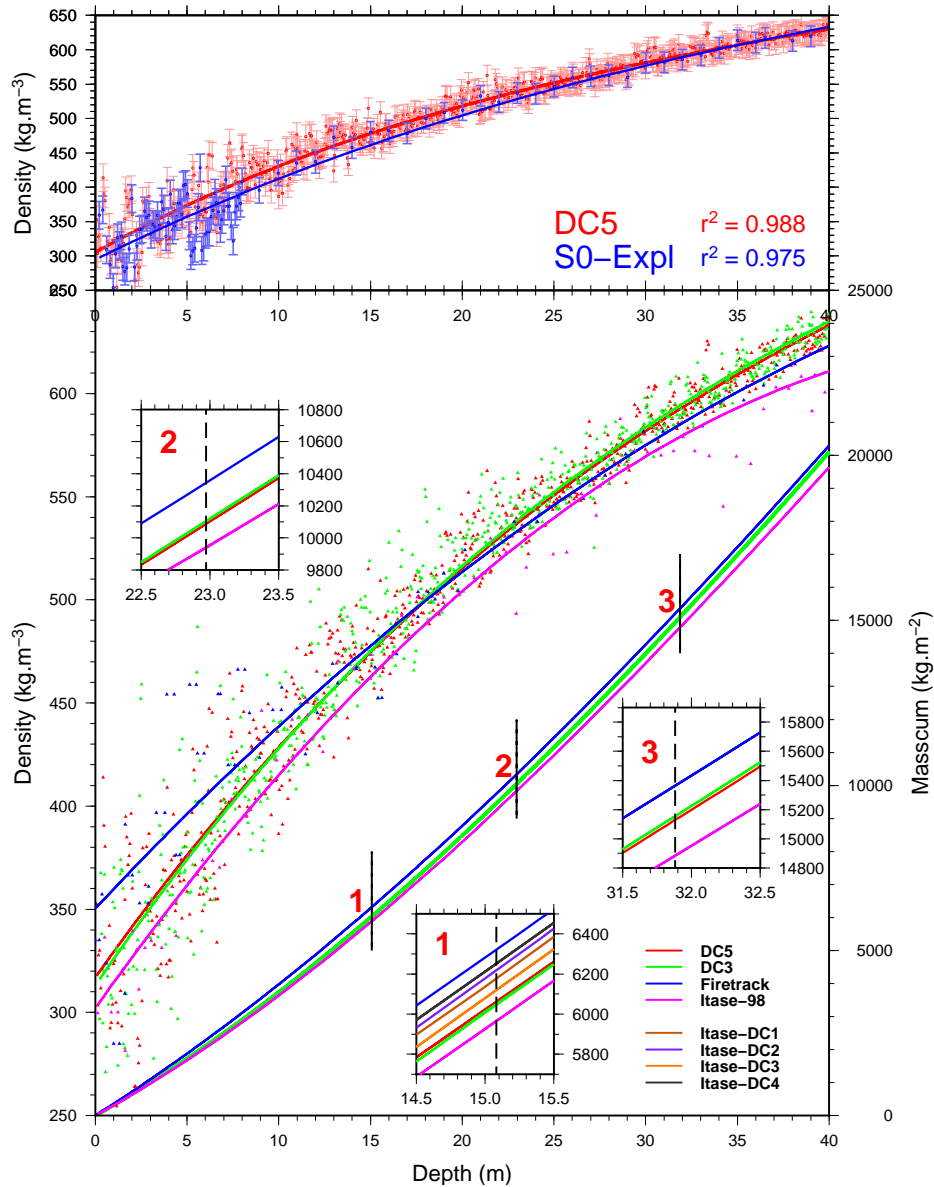
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DC3 81.32 0.987 13.88 6050 6033 10103 10045 15154 15101

Firetrack 50.06 0.939 24.76 63526321 10350 10343 15361 15362 Itase-98 44.17 0.973 17.39 5963 5894 9937 9832 14884 14788

Itase-DC1 17.47 0.905 19.95 6176 6171 ^(c) Itase-DC2 17.90 0.9769 48 6218 6217 Itase-DC3

19.27 0.901 20.526119 6062 Itase-DC4 18.15 0.948 13.68 62506264 and S0 (Explore) density profiles with estimated measurement error bars that only served for the computation of the uncertainty in the wave velocity profile (See Table 3).

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Figure 4. Density cores at DC along profiles (left scale) as mentioned in the text and detailed in table 2. Also

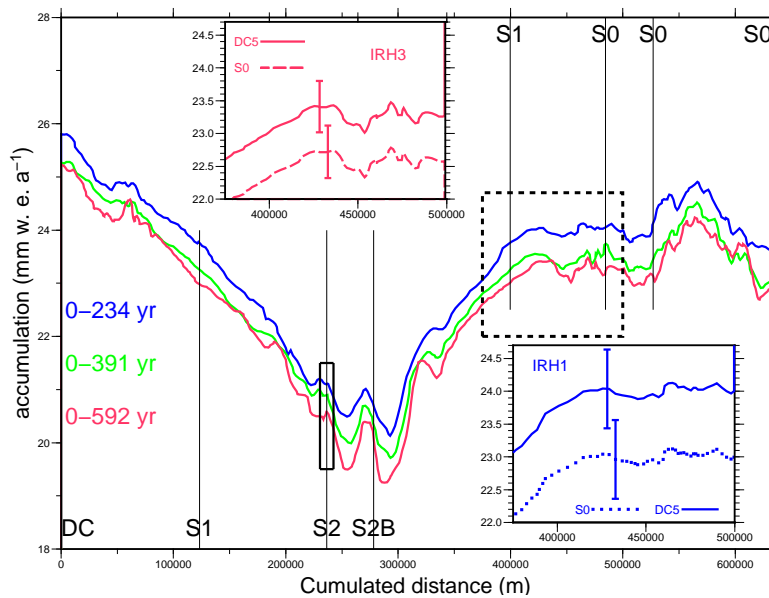


Figure 5. Computed accumulation rates since the deposition of the three IRHs according to the polynomial fit of the DC-5 density profile. The lower inset represents an enlargement over the dotted square and shows the sensitivity of the accumulation rate at the uppermost IRH to the use of the DC-5, S0, S1, S2 and S2B S0 (Explore) cores whereas the upper one does the same but for the lowermost IRH. Error bars represent the estimated uncertainty resulting from the density combined error measurements and with small scale spatial variations. These error bars (see Sect. 5.5) are only depicted once since they are uniform all along the DC-5 and S0 cores profile. Ranges for the accumulation rate at S2 inferred from the SR50 sensor (see Sect. 6.1) are represented by the blue error bar black box along the S2 vertical line.

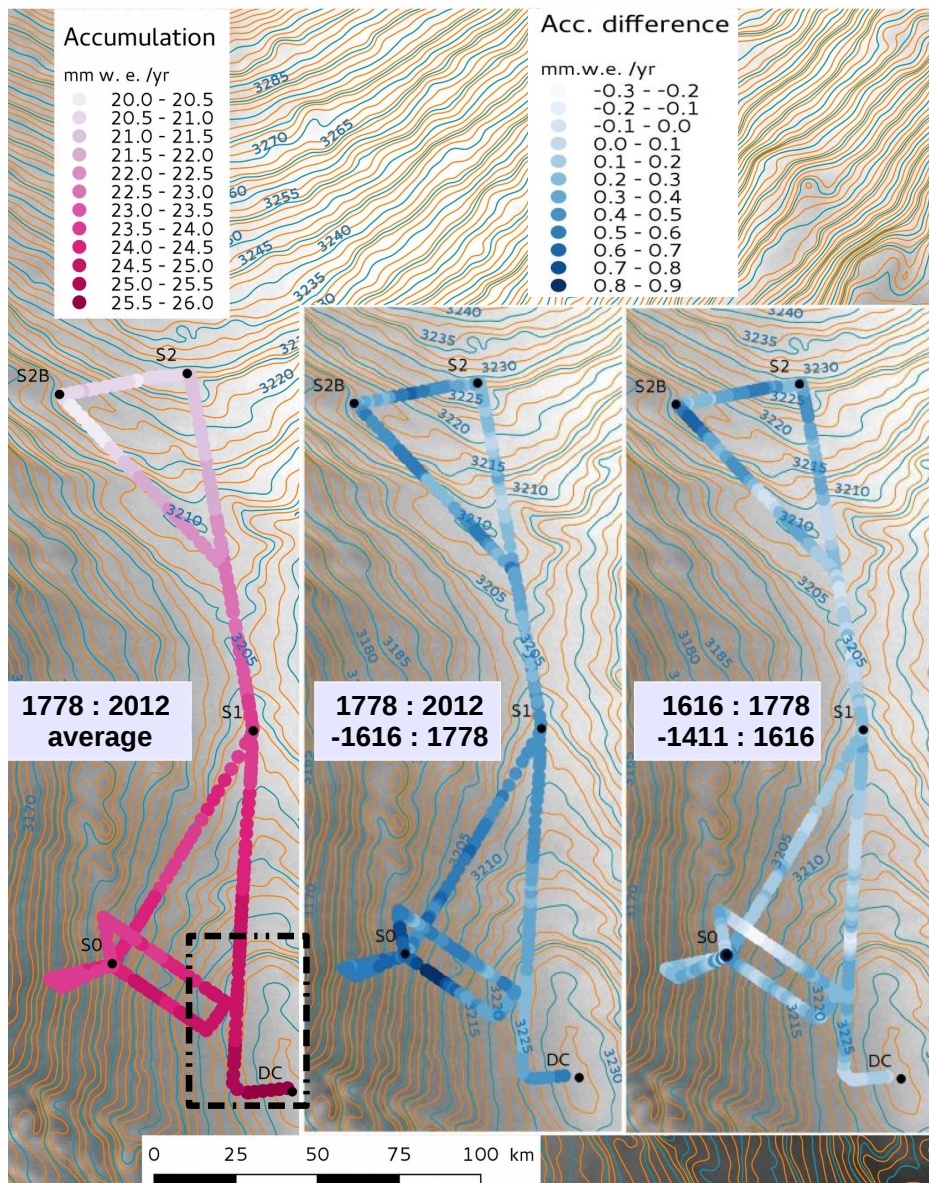


Figure 6. Geographical (polar stereographic, $71^{\circ}S$) distribution of net accumulation rates according to the ages of the three IRHs. The left panel is the average over the last 234 yr (CE 1778-2012) whereas the middle one represent this latter field minus the CE 1616-1778 average. Last, the right panel stands for the difference between the CE 1616-1778 and the CE 1411-1616 periods. Globally positive values in these differences confirm a steady overall increase through time as revealed by Fig. 9. Background is a Radarsat image of the prospected area revealing some topographic features emphasized by the contour line of the surface DEM (Bamber et al., 2009).

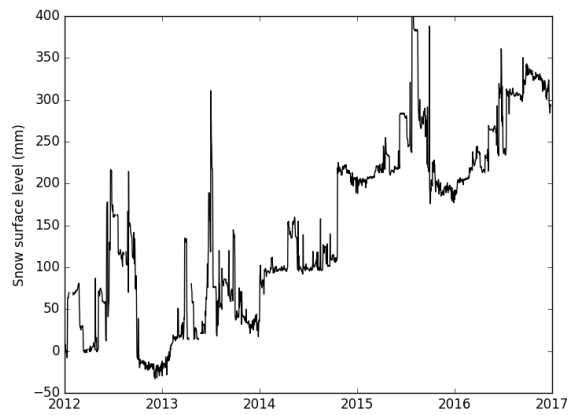


Figure 7. Snow surface level in mm above the reference level of the 1st of January 2012 obtained from acoustic distance measurements. Presented daily mean values were calculated from measurements recorded every 30 minutes and corrected for air temperature.

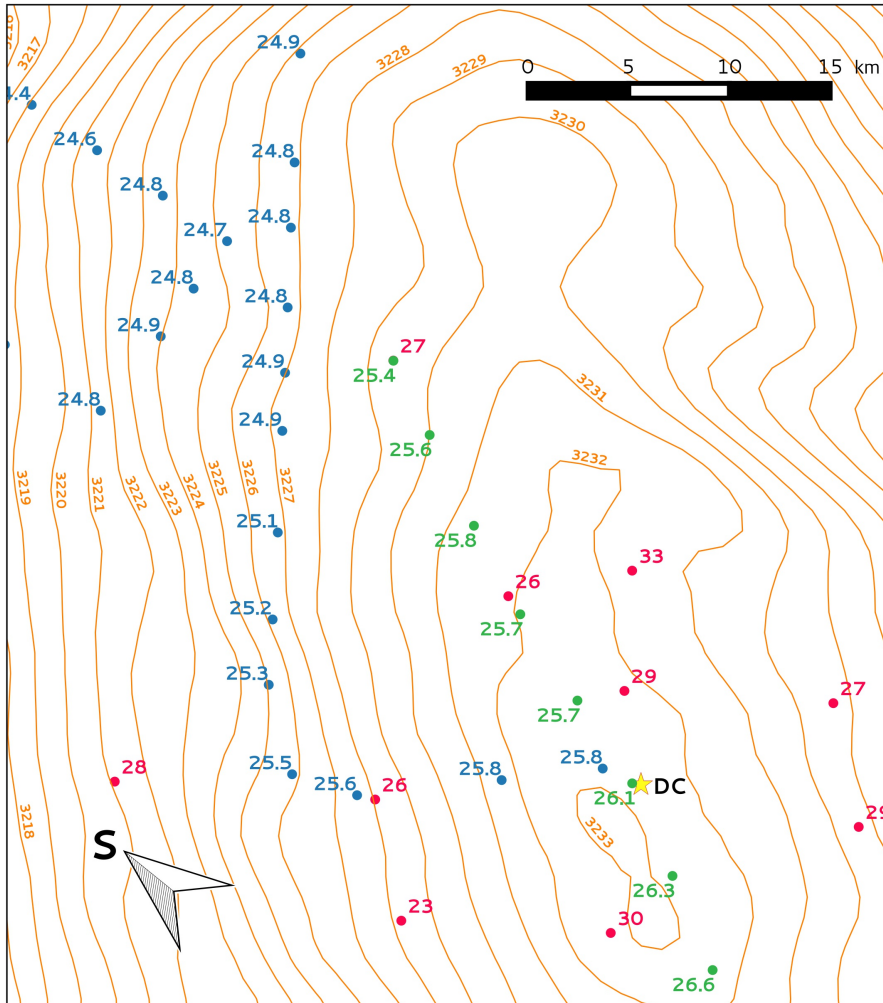


Figure 8. Comparison of our accumulation rates with those in (Urbini et al., 2008) Urbini et al. (2008) in the vicinity of Concordia Station over the area featured by the dashed inset of Fig. 6. Blue dots represent the rates as represented in Fig. 6 for the last 234 yr whereas the green ones are those from the radar transect of (Urbini et al., 2008) Urbini et al. (2008) after being equally sampled (5 km) and averaged over five measuring points. Also shown by red dots are accumulation rates inferred from an analysis of firn cores based on tritium/ β markers for the 1965-2000 period (Urbini et al., 2008, an references therein) and for which an uncertainty of 10% has been derived. Contours are altitude a.s.l. as given by (Bamber et al., 2009) Bamber et al. (2009). The Concordia Station is featured with a yellow star.

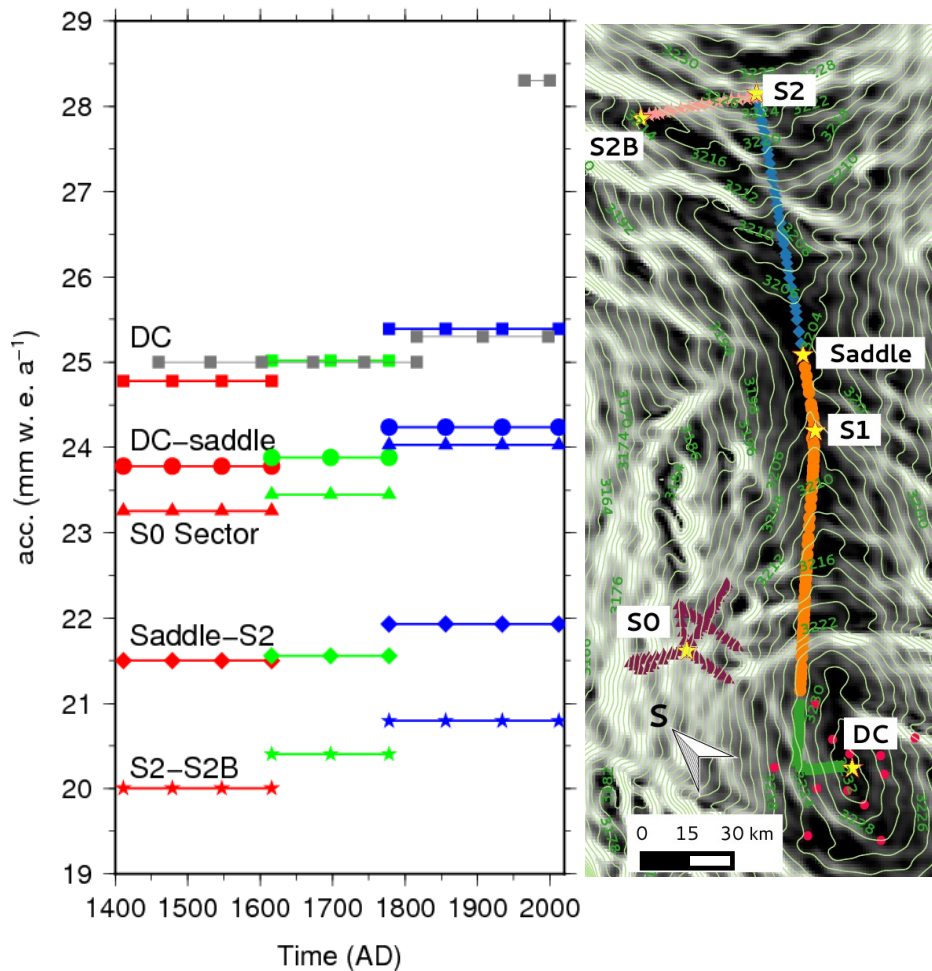


Figure 9. Time-dependent evolution of the accumulation rates spatially averaged over five sectors along the radar profile. The first sector corresponds to the DC vicinity (green squares on the map) within the firm core network as in (Urbini et al., 2008) Urbini et al. (2008) and featured by the red spots on Fig. 8. The second sector more or less follows the ridge from the end of the DC sector down to a topographic saddle (orange circles). The third (blue diamonds) continues along the ridge and climbs up to the S2 point. The fourth (purple stars) follows the perpendicular S2-S2B transect whereas the fifth (brown triangles) comprises the vicinity of the S0 point. The time frames for the time-averaging (left of the figure) correspond to the age difference from each of the three IRHs to the next above or to the surface, namely 1415-1616, 1616-1778 and 1778-2012 CE. Also presented with grey symbols are the accumulation rates as reported by Frezzotti et al. (2005) and (Urbini et al., 2008) Urbini et al. (2008) over the DC area (see text). Surface topography with 2-m contours is that of (Bamber et al., 2009) Bamber et al. (2009).

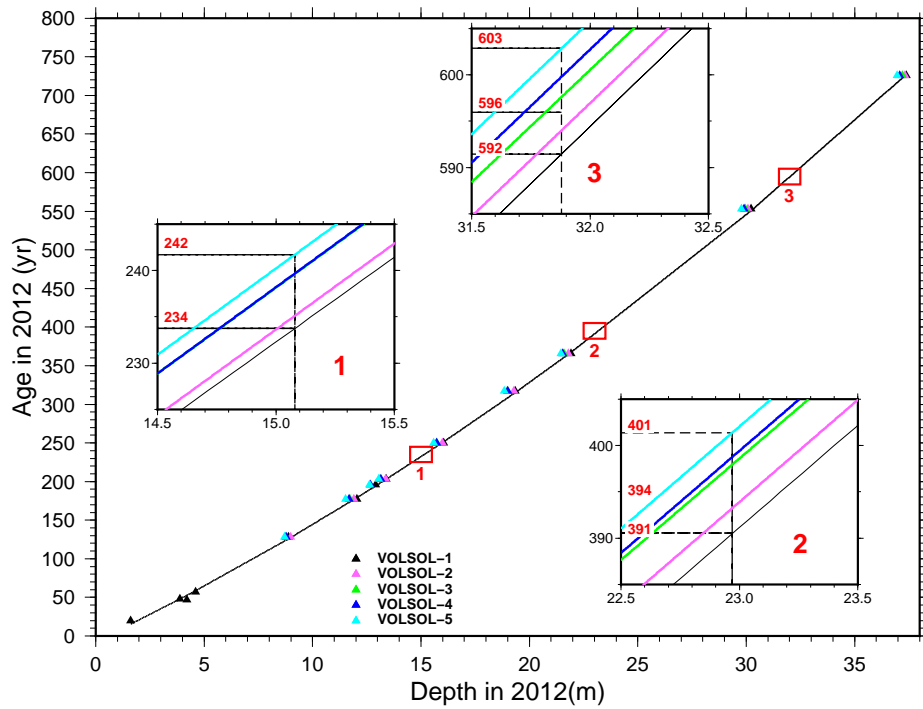


Figure 10. Time markers along the five cores as studied in Gautier et al. (2016). The reference core is VOLSOL-1 (see Section 4.2) for which the quadratic fit is entirely represented in black, whereas insets represent enlargements where all quadratic fits allow for an assessment of the age dispersion around the reference at the depths of our three IRHs.

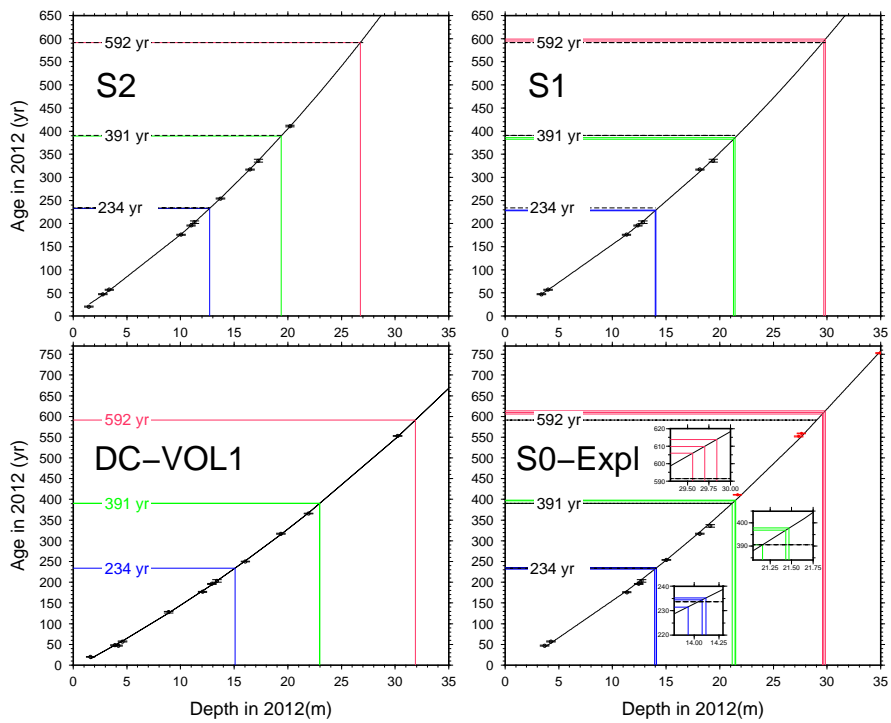


Figure 11. Same as Fig. 3 but now including the TASTE IDEA cores S1, S2 and the hybrid S0-Explore core. For this latter, extra points issued from the Explore core at larger depths are represented in red.