# Answers to reviewer 2

We thank the reviewer for the comments and suggestions to the manuscript. Based on the reviewer comments, we have significantly restructured and revised the paper. We will not provide a detailed summary of these structural revisions below, but hope to be allowed to submit a revised version of the paper.

In the revised version of the manuscript, we have moved the section on timescale validation by comparison to WAIS Divide to “Results”. We believe that with this structural change, it should become clearer that the RICE17 timescale is NOT synchronized to WAIS Divide, and that our matching of the two cores only forms basis for a comparison between the two timescales.

A point-to-point reply to the reviewer’s comments are provided below (in blue), along with a short description of the adjustments to the paper relating to these comments.

**The timescale is extensively compared to the WD2014 timescale which is one aspect not so clear from this manuscript: is this timescale tuned or not to WD2014?**

The timescale is not tuned to WD2014. This has been clarified in the current version of the manuscript.

**Finally, there is a discussion on the accumulation rate reconstruction and its evolution over the last 2700 years. Because of the strong uncertainties associated with the reconstruction, only the recent decrease can faithfully be discussed.**

We found an error in the calculation of uncertainty on accumulation rates in the previous version of the manuscript, which has now been corrected. With this correction the uncertainties have been significantly reduced, allowing us to discuss the observed changes in accumulation over time with much more confidence.

**The dating strategy is not clear. There is a mixing of layer counting constraints as well as use of volcanic peaks (+ nuclear bomb tests) but the uncertainty is only defined from layer counting at least on the upper part. It thus seems that the uncertainty is a bit overestimated?**

The top part of the RICE17 timescale is manually counted while using constraints from historical events (incl. volcanic peaks) observable in the RICE ice core records. These constraints reduce the uncertainty of the most recent part of the timescale (corresponding to the upper 42.5m of the core). As we account for age constraints when developing the uncertainty of the age scale, we do not consider the uncertainty in the top part to be overestimated. We have revised the text to clarify this point, and now write:

*A confidence interval was assigned to the timescale by classifying layers as certain or uncertain (Fig. 4), while accounting for age constraints from marker horizons.*

In the deeper part, for which the timescale has not been constrained, we use the statistically-produced StratiCounter results for the age uncertainty.

**Below 42.5 m, WD2014 seems to be taken as reference for the dating of the volcanic peaks as well as for adjusting the StratiCounter algorithm. Then WD2014 is used for “validation” of the timescale. By reading the methodology, it thus seems that there is something circular in the approach if WD2014 is used both for construction and validation of the timescale – could you please explain this better?**

We hope that our approach is better explained in the revised version of the manuscript.

First of all; RICE17 and WD2014 are independent timescales.

In the top part, we used historical events to constrain the RICE timescale. Below 42.5m, the timescale has not been constrained.

The only “circularity” in our approach is that we used the Pleiades tephra horizon in the RICE core to select the optimal settings for StratiCounter. This tephra horizon has previously been dated to 1251+-2 years according to WD2014, but is also found in other ice cores with similar age. It happened to be that one version of the StratiCounter output produced exactly the same age of the Pleiades tephra horizon as found in WD2014, and we decided to select those settings for the algorithm.

However, we note that our adjustments to the StratiCounter settings gave rise to very small age differences (<10 years) at the depth of this tephra layer, and that all the StratiCounter-derived timescales were in very good agreement with each other. Hence, for all practical purposes, the RICE17 and WD2014 timescales are independent of each other.

We recognize that this essential aspect was not sufficiently clear from the previous version of the manuscript, and we have made several revisions and structural changes to the text for clarification.

**The methane constraint for the RICE timescale is not clear. First, it refers heavily to a paper that is in preparation (Lee et al., 2017).**

The details of the approach used for matching the RICE and WAIS Divide ice cores using their respective high-resolution methane records will be described in the Lee et al paper, which is ready to be submitted any day now, and will soon be accessible as discussion paper in Climate of the Past Discussions. In the present manuscript, we have revised the wording of the section to improve its readability on its own.

**Second, the uncertainties associated with such tie-points are large and it is thus complicated to use them faithfully for timescale validation.**

It is true that the uncertainties associated with the individual methane match-points are relatively large. It should be noted, however, that for the RICE and WAIS Divide ice cores, these uncertainties are much smaller than for most other Antarctic ice cores (P13, L9-14).

Despite of the uncertainty on the individual match points, it is worthwhile to validate the RICE17 timescale to WD2014 based on the methane synchronization of the two cores. For instance, in Figure 6 (now: Figure 9) we observe that all methane match points below 280m are associated with older ages in WD2014 than in RICE, which corroborates the volcanic synchronization between the two ice cores.

Due to the associated uncertainties, we only use the methane match points for validation of the absolute ages of the RICE17 timescale.

**Finally, the procedure mixing Monte-Carlo technique and manual adjustment is rather unclear. I imagine that everything will be in the Lee paper but details are missing to really make use of this part which is not very robust as written here.**

After matching the two methane records using a Monte Carlo approach, we observed that the two records in this top part would fit slightly better if the match-points were slightly adjusted. These adjustments fall within the uncertainty of the gas-derived age control points. We report comparisons of the age-scale relative to the automated as well as the manually-adjusted methane match-points.

The new version reads:

*Ice cores can be stratigraphically matched using records of trapped gasses, which reflect global changes in atmospheric composition. Centennial-scale variations in methane concentrations observed in the RICE gas records are also found in similar records from WAIS Divide (WAIS Divide Project Members 2015; Mitchell et al. 2011). Matching up these records allows a comparison of the two ice-core timescales.*

*The gas records from RICE and WAIS Divide were matched using a Monte Carlo technique reported in Lee et al. (2018). The feature matching routine employed discretely-measured records of methane as well as isotopic composition of molecular oxygen ($\delta^{18}O_{atm}$). Over recent millennia, however, the $\delta^{18}O_{atm}$ concentrations are stable, and hence provided minimal matching constraints. An average spacing of 26 years between successive RICE methane samples contributes to the matching uncertainty. The matching routine identified 18 match-points over the past 2700 years, i.e. an average spacing of 150 years. Subsequent visual comparison of the methane profiles suggested minor manual refinements of the match-points (8 years on average, maximum 23 years; all within the uncertainty of the automated matching). These adjustments resulted in a slightly improved fit.*

**Some parts are very long and not useful (most of section 3.2.3.2, part of section 3.3 on l. 10 or p. 15) – I suggest to reduce these sections and better concentrates on the method and associated uncertainties.**

As suggested by the reviewer, we have significantly shortened these sections.

**Accumulation rate is certainty an input of the firn model described in p. 13 while only forcing using a site temperature history is mentioned. It is very surprising that accumulation forcing is not mentioned here since one of the aim of this paper is to provide an accumulation scenario. We are thus expecting the use (or at least validation that everything is coherent with Dage or d15N measurements) of the accumulation rate scenario in the firn model.**

It is correct that the usual form of the Herron-Langway firn densification model takes both temperature and accumulation history as an input, thereby providing lock-in-depth and delta-age as output. However, in our dynamic H-L firn model, the equations have been re-organized to account for the knowledge on past lock-in depth based on measurements of d15N-N2, after correction for the existence of a convective surface zone. Consequently, the H-L model used here is forced by the temperature history (based on water isotopes) and past firn column thickness based on measurements of d15N-N2 (P13, L2-5). Additional parameters include the surface density (fitted to the modern density profile) and density at the lock-in-depth (here estimated from the temperature). With this formulation of the H-L model, we obtain as output: 1) the age at the lock-in depth (Δage), and 2) a low-frequency accumulation history.

The section has been revised as follows:

*Methane feature matching allows a transfer of WAIS Divide ages to the RICE gas records, i.e. the RICE gas ages. To obtain the corresponding ice-core ice ages relevant for this study, Δage was calculated using a dynamic Herron-Langway firn densification model (Herron & Langway 1980) following Buizert et al. (2015), as described in detail in Lee et al. (2018). The model is forced using a site temperature history derived from the RICE stable water isotopes, and the firn column thickness is constrained by the isotopic* *composition of molecular nitrogen ($\delta^{15}N$ of $N_2$). In addition to Δage, this formulation of the Herron-Langway densification model produces as output a low-resolution accumulation rate history.*

In the new version of the manuscript, we have included the firn-model based accumulation history as well as the measured d15N-N2 values in figure 9c (now: figure 10e, dashed line and black dots):

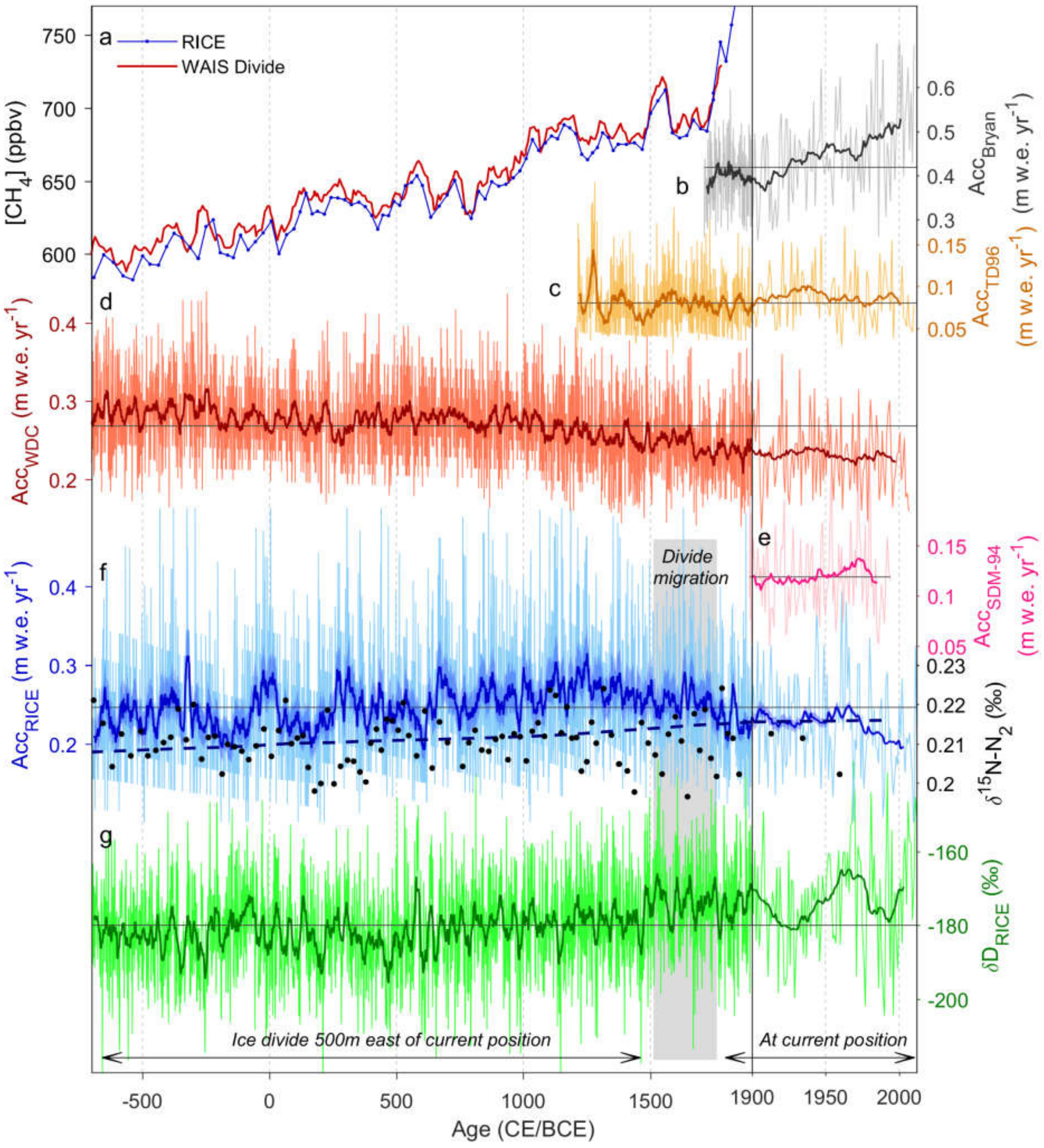

***Figure 10: a)** Measured methane concentrations from RICE (blue, on the RICE17 timescale) and from WAIS Divide (red, on the WD2014 timescale). **b)** Bryan, Antarctic Peninsula (grey) (Thomas et al. 2015), **c)** Talos Dome (TD96, orange) (Stenni et al. 2002), **d)** WAIS Divide (WDC, red) (Fudge et al. 2016), **e)** Siple Dome (SDM-94, pink) (Kaspari et al. 2004), and **f)** RICE (blue) accumulation histories over the past 2700 years, in annual resolution and 20-year smoothed versions (thick lines). WAIS Divide accumulation rates have been corrected for ice advection. The shaded blue area indicates the 95% confidence interval of the RICE accumulation rates.* The short-lived peak in accumulation rates around 320 BCE is likely to partly be an artefact caused by timescale inaccuracies in this period, during which RICE17 diverges from WD2014 (Fig. 9b). *Also shown are the gas-derived accumulation rates for this time interval (f, blue dashed line), and measurements of $\delta^{15}$N of $N_2$ informing on past firn column thickness (f, black dots; on the RICE gas timescale). **g)** RICE stable water isotope record (δD). Thick green line is a 20-year smoothed version of the isotope profile. Thin grey horizontal lines denote mean values of accumulation rates and δD over the displayed period. The migration period of the Roosevelt Island ice divide is marked with a grey box.*

We note some discrepancy between this accumulation history and the one derived from the RICE17 layer counts and thinning function, and we discuss these differences in the manuscript:

*The RICE17 accumulation history shows reasonable agreement with low-resolution accumulation rate output from the dynamic Herron-Langway firn densification model (Fig. 10f, dashed line). The gas-based accumulation rate history does not resolve high-frequency variations, but shows a slow increase in accumulation rates of 0.16cm/century, similar to that obtained from the ice core chronology prior to 1250 CE. In contrast to the accumulation rate history derived based on the layer thicknesses and thinning function, however, the firn-based accumulation rates continue to increase until present-day. Further, the absolute value of the inferred gas-based accumulation rates tend to generally underestimate the accumulation rates by ~4cm (16%).*

*We speculate that these discrepancies may have to do with the shift in RICE water isotope levels occurring around 1500 CE (Fig. 10g), which in the firn model is used to represent temperature change. It has been suggested that this shift is due to other factors than temperature (Bertler et al. 2018). Assuming that the model is based on a slightly too-cold temperature input prior to 1500 CE, the model would compensate by decreasing the accumulation rates during this time, in order to preserve a constant thickness of the firn column, as indicated by steady values of $\delta^{15}$N-$N_2$ (Fig. 10f, black dots).*

**What is the "model" mentioned in l. 45, p. 13?**

The "model" referred to here is a Lliboutry vertical ice-flow velocity profile fitted to observed vertical velocities. In the new version, this sentence has been rewritten as follows:

*We produce a thinning function appropriate for RICE using vertical velocity profiles obtained by fitting a simple ice-flow model (Lliboutry 1979) to englacial velocities deduced from radar measurements (Kingslake et al. 2014).*

**The discussion on the ASL influence on the accumulation rate in the region is both in the "Results" section and in the "Discussion". This is also the case for other ideas that are repeated several times and a reorganization and simplification of the manuscript is needed.**

We have carefully gone through the manuscript and reorganized, simplified and shortened the text. All text about the influence of ASL on RICE accumulation rates has been moved to the discussion section.

**The accumulation reconstruction should ideally have been compared to accumulation rate scenario used for the firn model as well as with water isotope profiles. It could strengthen the discussion and conclusion parts on the accumulation aspect that are rather short.**

In the new version of the manuscript, we compare the accumulation reconstruction from the firn modelling to the accumulation history from the RICE17 timescale, see comment above.

We have further expanded the discussion regarding the accumulation rate history, which is now evaluated in context of regional climate drivers, including regional sea ice extent.