Answers to Reviewer 1

Dear Referee 1,

Thank you very much for the constructive comments. We followed your suggestions and have extended and restructured the concerned sections. For clarity we add our comments into your review just below the respective paragraphs.

General Comments: This paper presents an initial timescale for the EGRIP ice core from Greenland. Overall, this manuscript is relatively straightforward and the scientific context and results are presented well. However, I have two primary concerns that I think need to be addressed before this manuscript is suitable for final publication.

(1) comments from Referees: The topic of this paper is transferring the existing GICC05 timescale to the new EGRIP core through volcanic tie points. While ample detail is provided on the existing ice cores and on measurement details, very little explanation is given to the details of linking GICC05 with the 373 tie points.

(1r) author's response: We will detail the description of how the match points themselves were assessed in the section "Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM" and add a paragraph discussing the distance of match points at its end:

(1c) author's changes: To provide in depth information, we added detailed information in subsection 2.4 "Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM". Now, we elaborate on how the match was actually done in much more detail and the initial paragraph reads now: "Patterns in the DEP records of NGRIP, NEEM and EGRIP were initially matched by one investigator. The same cores' ECM data were matched separately and independently by three different investigators. Both matches are mainly based on clearly identifiable volcanic peaks and also synchronous patterns of other events (Figure 7 in the revised manuscript), which not necessarily need to be of volcanic origin, but are assumed to reflect synchronous events. Based on these independent matches, the four investigators identified consistent and reliable common patterns, that are represented in the ECM and/or the DEP records from NGRIP and at least one of the other ice cores. For the confirmation of match points, all records of all three cores were loaded into the Matchmaker tool [Rasmussen et al., 2013] and assessed jointly by all four investigators in the different display options featured by the software. The Matchmaker tool allows easy identification of wrong match points via interactive plots and on-line evaluation of the match. To validate match points, we plot the depths of the common match points D_i (in EGRIP or NEEM) against d_i (NGRIP). The slope of each of these (depth, depth)-curves is the annual layer thickness ratio of the two cores, $r_i = \frac{D_{i+1}-D_i}{d_{i+1}-d_i}$. Points which deviate from the (depth, depth) curve or create jumps in r, are easily recognized and checked again. We only expect significant abrupt changes in r at times where the climate (and thus the relative accumulation rates) shifts due to changes in climate conditions [Rasmussen et al., 2006, Rasmussen et al., 2013, Seierstad et al., 2014, Winski et al., 2019], while the different ice-flow patterns at the cores' sites only lead to slow changes in r. Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years."

(2) comments from Referees: The entirety of this process, is briefly summarized in a short paragraph in section 2.4 whereby a simple linear interpolation is used to link these tie points and the uncertainty associated with GICC05 is transferred to GICC05- EGRIP-1, with little to no treatment of the additional uncertainties associated with the transfer. I think the methods the authors used may be fine, but they definitely need much more explanation, clarification and justification than is offered here.

(2r) author's response: The procedure of transferring the timescale by tie points is discussed in detail in Rasmussen et al. (2013; paragraph 3.2) for the transfer from NGRIP to NEEM. The transfer from NGRIP to EGRIP is entirely the same procedure with the same inferred uncertainties and errors. Rasmussen et al. (2013) discuss the additional uncertainty of the transfer from NGRIP GICC05modelext to NEEM: "The accuracy of the timescale at these points depends on three factors:

1. The NEEM timescale inherits the maximum counting error (MCE) of the NGRIP GICC05 timescale.

2. Differences between the shape of peaks and inaccuracies in the depth registration of the ECM data set introduce synchronization uncertainty on the order of centimetres. The estimated synchronization uncertainty was estimated to 10 cm (1σ) by [Rasmussen et al., 2008], and here we tentatively estimate its magnitude by calculating the effect on the (NEEM depth, NGRIP depth) relation of removing every second match point. The results support the estimated synchronization uncertainty of 10 cm (1σ), leading to timescale transfer uncertainties ranging from a few years to a maximum of a few decades at the deepest part of the record.

3. Although we believe the set of match points to be robust, there is a risk that some sections have been erroneously matched up, leading to a larger systematic depth offset.

As the MCE is typically 2 orders of magnitude larger than the matching uncertainty (when assuming no large systematic errors), we report GICC05modelext-NEEM-1 ages with the MCE uncertainty estimates only, but stress that observed phasing differences of up to a decade at the match-point depths could be artefacts from the timescale transfer."

(2c) author's changes: We extended the discussion in the section 2.5 and subsection 2.5.1:

2.5 Transfer of the GICC05 timescale to the EGRIP ice core

"The procedure of transferring the timescale is similar to the approach described in [Rasmussen et al., 2013]. Note that we hereby assume that the ratio of annual layer thicknesses is constant between the match points of EGRIP and NGRIP. For each 0.55 m EGRIP depth segment (the so-called bag), we obtain the equivalent NGRIP depth by linear interpolation between the depths of the match points D_i in EGRIP and d_i in NGRIP. We then assign a GICC05 age from the annually resolved GICC05 time scale for NGRIP [Vinther et al., 2006, Rasmussen et al., 2006].

The EGRIP timescale inherits the maximum counting error (MCE) from the GICC05 timescale. Our match covers the time period back to 14,967 a b2k where the associated MCE is 196 a. The inaccuracies in the depth registration were estimated by [Rasmussen et al., 2013] to 10 cm (1σ). For the joint assignment of DEP and ECM patterns, we repeat the assessment by [Rasmussen et al., 2013] for the (EGRIP depth, NGRIP depth) relation by computing the difference

δ_i between each EGRIP match point and the linear interpolated depth derived from the neighbouring points $\delta_i = (D_{i+1} - D_{i-1})/(d_{i+1} - d_{i-1}) * (d_i - d_{i-1}) + D_{i-1} - D_i$, thus merging all match points between EGRIP and NGRIP1 and EGRIP and NGRIP2 into one data set of 377 of the originally 381 match points for further statistical analysis. The difference in number occurs as δ is not defined for respective start and end points of both respective sequences. The statistical analysis of δ in Appendix D yields a standard deviation of 0.043 m for the depth assignment of a match point. As the annual layer thickness typically exceeds 0.04 m in the time period considered here, one expects an additional uncertainty for the peak assignment in the order of 1 yr. Larger errors would occur in the case of erroneously matched sections as discussed in [Rasmussen et al., 2013], but wrong matches are even more unlikely here than in previous work, as three instead of two cores were matched and *ibid.* the authors also point out that erroneously matched sections are particularly relevant for the older part of the core, where the discussion here covers a section with comparably plentiful match points.

2.5.1 Precision and accuracy of the time-scale transfer

The central mode of the (depth, depth)-differences δ as defined above follows a Gaussian normal distribution with a standard deviation of 0.043 m (see Appendix D). This demonstrates that the synchronization ties two cores together at the match points with high precision. Besides the central Gaussian normal distribution, the statistical analysis of δ identifies an overlaid second Gaussian normal distribution with a standard deviation of 0.19 m. We interpret this distribution as stemming from curvature of the (depth, depth)-curve and as indicative of the average amount of detail, that each point contributes to the description of this curvature. As this difference between the actual match point and the linear interpolation between the neighbouring points depends on the variable curvature of the (depth, depth)-curve, which reflects both accumulation conditions and the evolution of glaciological conditions at both coring sites, the values of δ will generally be time correlated and cannot be expected to be randomly distributed with depth. We thus estimate that the EGRIP time scale may have time-correlated uncertainties relative to NGRIP of up to a handful of years related to changes in relative accumulation variability and ice-flow conditions not captured by the match points. This uncertainty will be largest in time periods far from the match points and near climatic shifts where the accumulation changed abruptly and not necessarily by the same ratio at different ice coring sites.

Now we assess the combined uncertainties. The GICC05 timescale $t(D)$ inherits the associated maximum counting error from GICC05, and given the analysis of δ above, we conclude that, at the match points, the time scale is precise relative to NGRIP within about one year (1σ). However, when we want to know the age at an arbitrary EGRIP depth, additional uncertainties apply due to the interpolation between the match points. There are two dominant sources: As discussed above, variations in relative accumulation rates and ice flow may add up to a handful of years of additional uncertainty relative to GICC05, but there is also a contribution from the choice of interpolation scheme in between the match points. The difference introduced by the choice between the most widely used linear and cubic spline interpolation schemes [Press et al., 1992] is about an order of magnitude larger than the above-mentioned random uncertainty associated with the identification of the match points (see Appendix E).

We maintain linear interpolation for the time scale transfer despite the fact that the slope of the (depth, depth) curve changes instantaneously at the match points. While changes in this slope may in reality occur on many scales due to the intermittency of precipitation, wind-driven redistribution of snow, and relative changes in accumulation rates at the sites, the most significant of these changes are likely to happen at times of climate change rather than at the arbitrary depths of the match points. Considering this, one could consider an interpolation scheme where the change of curvature is distributed over the entire curve and/or concentrated at times of climate changes as derived from the proxies of the ice core. However, we believe that the advantage of obtaining a smoother (depth, depth)-curve does not compare favourably to the additional assumptions needed and the added complexity of the time-scale transfer."

We extended the discussion in the section 3.4 "Error analysis for the timescale transfer"

3.4 Error analysis for the timescale transfer

"We statistically treated the "leave-out analysis" (δ), which was already used in previous papers [Rasmussen et al., 2013] to estimate the uncertainty in match points. Binning the values revealed a robust mode that refers the statistical error of the match point assignment. The tails of the distribution relate to more curved intervals of the core. Cubic spline interpolation provides a similar estimate. However, when matching depths, we neither know the true curve nor how big the influence from the interpolation scheme is. We demonstrated that the two fundamentally different interpolation schemes of linear and cubic spline interpolation give a consistent result. The δ give qualitatively a similar pattern as the high-resolution difference of the interpolation schemes and has demonstrated its suitability to estimate the uncertainty of the interpolation scheme. They deviate more than the statistical uncertainty of the match-point assignment, but this is less than the tenfold of the statistical error for peak identification and for the timescale here it introduces an error of up to 4 years, while the inherited maximum counting error of the timescale increases from about 1 year to 2 centuries over the matched record."

We have added two sections in the Appendix (D and E):

Appendix D: Statistical analysis of the (depth, depth)-match with linear interpolation

"Each match point's depth assignment has an uncertainty due to the varying peak form, which is caused by regional deposition differences and short-term accumulation variations. This peak assignment uncertainty dominates the distribution of δ in sections where the EGRIP–NGRIP1/2 depth curve is straight. However, varying conditions at the time and place of the snow deposition or different ice flow pattern between the ice cores cause differently evolving annual layer thickness ratios $r_i = \frac{D_{i+1}-D_i}{d_{i+1}-d_i}$ and recognizable curvature of the (depth, depth)-curve. For the distribution function of δ, we expect a normal distribution of the peak assignment overlaid by a distribution from the curvature of the (depth, depth) curve, in the following referred to as "the refinement". For further statistical treatment, we bin the δ values. As $\delta \in [-0.42929\text{m}, 0.385968\text{m}]$, we counted the occurrence $N(i)$ of values for the $i = 0 \ldots 20$ intervals $[-(0.525+i*0.05)\text{m}, (-0.475+i*0.05)\text{m})$ in between -0.525 m and 0.525 m and display the data in the following histogram (ref. Fig. 1). The standard deviation of the counts is $\sigma(N) = \sqrt{N}$. $n = 14$ bins are occupied. The distribution of δ is presented in Fig. 1.

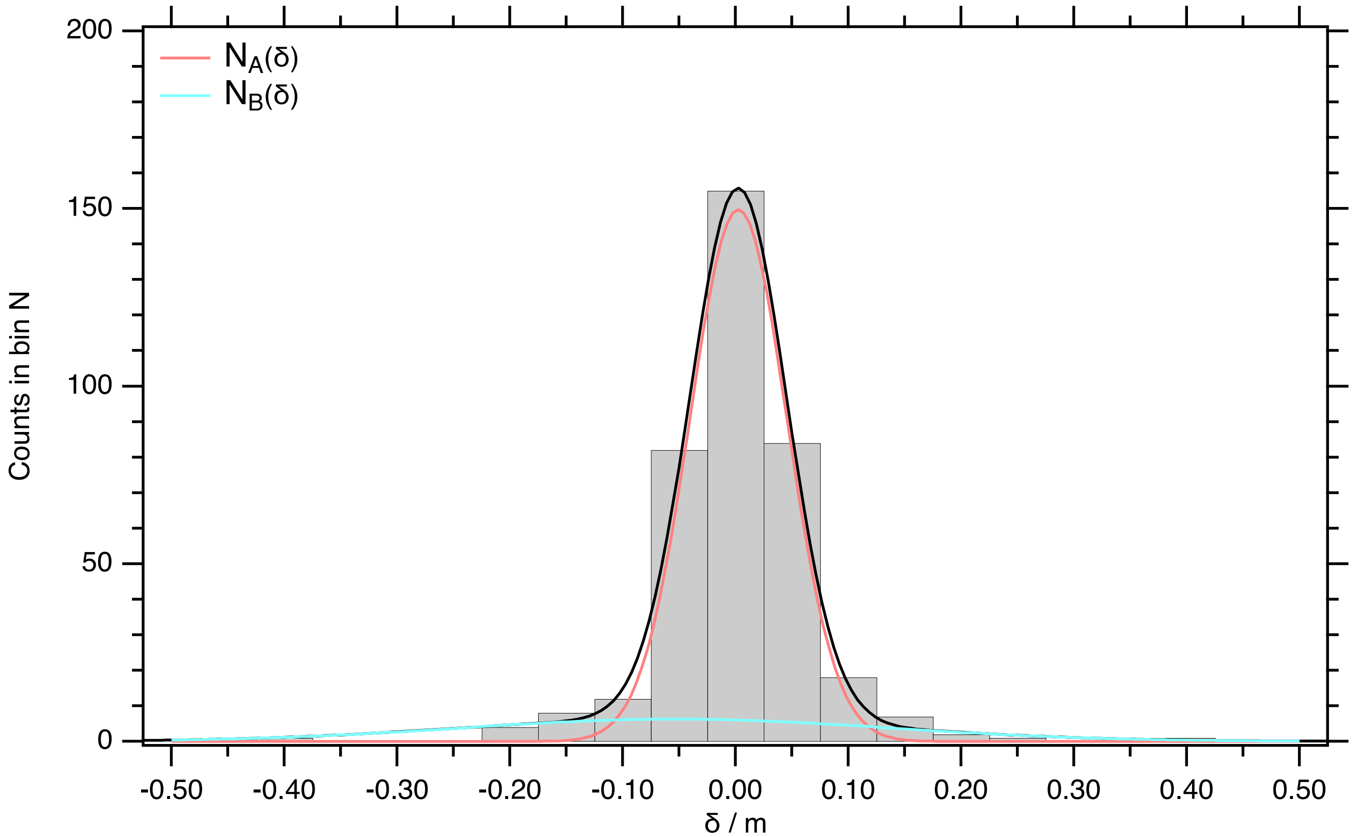

Figure 1: Histogram of the difference data with linear interpolation $\delta_i = (D_{i+1} - D_{i-1})/(d_{i+1} - d_{i-1})(d_i - d_{i-1}) + D_{i-1} - D_i$ for the match points between EGRIP–NGRIP1/2.

The Gaussian normal distribution for the peak assignment in the centre seems to be overlaid by a second Gaussian normal distribution representing the refinement of the depth scale. This is indicated by the quite wide tails of the distribution. Following the just posed assumption, that the refinement distance is statistically normal-distributed $N_B(\delta) = B\exp(-(\delta-\mu_B)^2/\sigma_B^2/2)/\sqrt{2\pi}/\sigma_B$ and that the uncertainty of the peak assignment in smooth intervals is normal-distributed $N_A(\delta) = A\exp(-(\delta-\mu_A)^2/\sigma_A^2/2)/\sqrt{2\pi}/\sigma_A$, we χ^2-fitted the sum $N(\delta) = N_A(\delta) + N_B(\delta)$. The weight of the χ^2 is the counting error $\sigma(N) = \sqrt{N}$. The fit of the $c = 6$ independent parameters converged and yielded a $\chi^2 = 4.7$ for the $f = n - c = 14 - 6 = 8$ degrees of freedom, indicating that the fitted distribution is supported by the data ($\int_{4.7}^{\infty} \chi^2(8) = 0.79$).

The χ^2-fit computes for the peak assignment distribution $N_A(\delta)$ a scaling factor $A = (16 \pm 1)\mathrm{m}$, the shift from the centre $\mu_A = (0.003 \pm 0.003)\mathrm{m}$ and a standard deviation $\sigma_A = (0.043 \pm 0.002)\mathrm{m}$. Similarly for the refinement distance $N_B(\delta)$: $B = (3 \pm 0.7)\mathrm{m}$, $\mu_B = (-0.05 \pm 0.04)\mathrm{m}$ and $\sigma_B = (0.19 \pm 0.04)\mathrm{m}$.

Solving $N_A(\delta_j) = N_B(\delta_j)$ for the roots $\delta_1 = -0.11m$ and $\delta_2 = 0.12m$ defines the inner interval that is dominated by the peak assignment statistics. 349 points are in the interval (δ_1, δ_2) and the direct statistical evaluation confirms $\sigma_A = 0.043m$ (in the main paragraphs of the paper we label this as statistical error for the peak assignment ΔD) and $\mu_A = 0.003$, where the skew (0.06) and the kurtosis (-0.05) are small and support normal distribution $\delta \in (-0.11\mathrm{m}, 0.12\mathrm{m})$. A Shapiro Wilk test confirms normal distribution of the peak assignment errors, as $W = 0.996$ and the corresponding p-Value $p = 0.54$.

As the refinement distance is overlaid by the peak assignment statistics in the centre of the distribution, none of the standard statistics is applicable, but the χ^2-fitted $N_B(\delta_i)$, can be χ^2-tested for the refinement-distance dominated bins. $\chi^2 = 4.0$ over the bins $i = 1, 2, 6, 7, 13, 14, 15, 17, 18$ in the tail that at most are marginally influenced by $N_A(\delta_i)$. The $n = 9$ bins together with initially $c = 3$ fitted parameters computes $f = n - c = 6$ degrees of freedom, which supports the refinement distance being normal distributed ($\int_{4.0}^{\infty} \chi^2(8) = 0.68$).

Appendix E: Statistical analysis of the (depth, depth)-match with cubic spline interpolation

Here, we quantify the difference between using linear interpolation and interpolation by cubic splines, which is a widely used scheme. The latter has the benefit of using smooth curves, such that the (depth, depth) curve and its derivatives are continuous, but as discussed above, several factors may cause the real (depth, depth) curve to be non-differentiable or even discontinuous, and we therefore maintain our practice of linear interpolation between the depths of the match points.

Analog to the definition of δ we define $\Sigma_i = S(D_1, \ldots, \cancel{D_i}, \ldots, D_n) - S(D_1, \ldots, D_i, \ldots, D_n)$, where $S(D_1, \ldots, D_i, \ldots, D_n)$ is a cubic spline calculated for all match points and $S(D_1, \ldots, \cancel{D_i}, \ldots, D_n)$ a cubic spline calculated for all but the i-th match point.

Analog to the above analysis with linear interpolation, we expect that each match point's depth assignment has an uncertainty due to the varying peak form, which is caused by regional deposition differences and short-term accumulation variations. This peak assignment uncertainty determines the distribution of Σ in sections where the EGRIP–NGRIP1/2 depth curve is straight and no systematic glaciological differences occur. However, varying accumulation conditions at the time and position of snow deposition or different ice flow patterns influencing the ice cores cause differently evolving annual layer thickness ratios $r_i = \frac{D_{i+1} - D_i}{d_{i+1} - d_i}$ which leads to curvature of the (depth, depth) curve. This curvature may not be captured if there are no match points at the relevant depth, and different interpolation schemes will make different predictions across intervals without match points. For the distribution function of Σ we thus expect two contributions: One from the uncertainty of peak assignment and the other one from the refinement.

For further statistical treatment, we bin the Σ values. As $\Sigma \in [- - 0.674604\mathrm{m}, 0.364446\mathrm{m}]$, we counted the occurrence $N(i)$ of values for the $i = 1 \ldots 21$ intervals $[-(0.725 + i * 0.05)\mathrm{m}, (-0.675 + i * 0.05)\mathrm{m})$ in between -0.675 m and 0.375 m and display the data in the following histogram (ref. Fig. 2). The standard deviation of the counts is $\sigma(N) = \sqrt{N}$. $n = 17$ bins are occupied. The distribution of Σ is presented in Fig. 2. The weight of the χ^2 is the counting error $\sigma(N) = \sqrt{N}$.

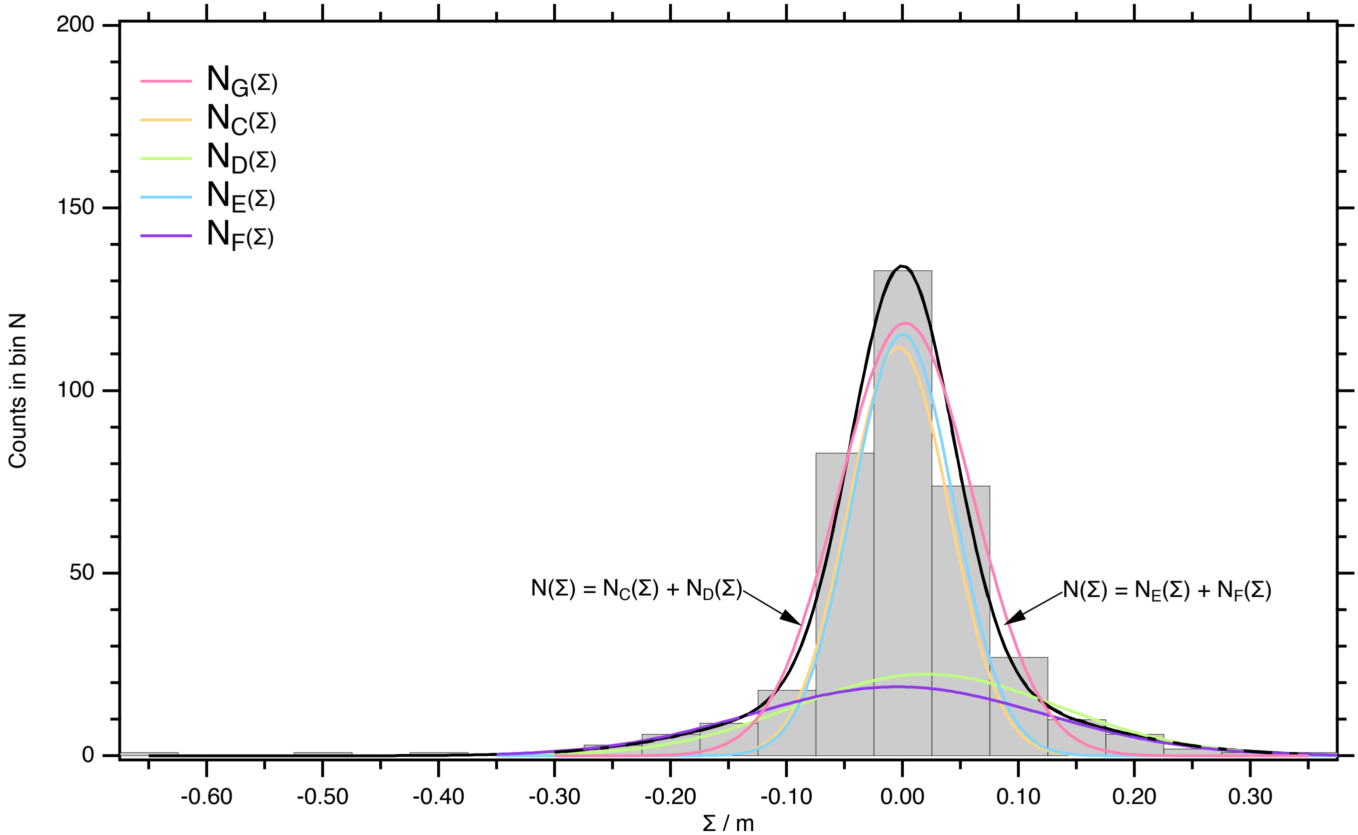

Figure 2: Histogram of the difference data with cubic spline interpolation $\Sigma_i = S(D_1, \ldots, \cancel{D_i}, \ldots, D_n) - S(D_1, \ldots, D_i, \ldots, D_n)$ for the match points between EGRIP—NGRIP1/2.

Like for the (depth, depth) differences for the linear interpolation δ, the distribution of Σ appears having too wide tails to match a Gaussian distributions. We support this by trying to fit a single Gaussian normal distribution $N_G(\Sigma) = G\exp(-(\Sigma - \mu_G)^2/\sigma_G^2/2)/\sqrt{2\pi}/\sigma_G$. to the data. Even when treating the 3 values below $\Sigma < 0.325$ as outliers and restricting the fit to the $n = 14$ bins around 0, we minimize $\chi^2 = 30.8$. For the $c = 3$ fitted constants, the degree of freedom is $f = 11$. This indicates that the fitted distribution is not supported by the data ($\int_0^{30.8} \chi^2(11) = 0.99$).

The Gaussian normal distribution for the peak assignment in the centre seems – as for the δ – to be overlaid by a second Gaussian normal distribution representing the refinement of the depth scale. Following the just posed assumption that the refinement distance is statistically normal-distributed $N_D(\Sigma)$ and that the uncertainty of the peak assignment in smooth intervals is normal-distributed $N_C(\Sigma)$, we tried to χ^2-fit $N(\Sigma) = N_C(\Sigma) + N_D(\Sigma)$ to the entire dataset with $c = 6$ fitting parameters. For the $n = 17$ bins of the entire dataset Σ we minimised $\chi^2 = 48.7$, which suggests the model does not describe the data (for details refer to Fig. 2, where the figures for a similar treatment as for rejecting $N_G(\Sigma)$ are provided).

By just treating the 3 values (out of 377 in total) below $\Sigma < 0.325$ as outliers, which is justified, when we are mainly interested in assessing the central part of the distribution, which refers to the match-point assignment. Thus, repeating the fit for the bins $i = 8, /ldots, 21$ ($n = 14$) an labelling the fitted function $N(\Sigma) = N_E(\Sigma) + N_F(\Sigma)$ to clearly distinguish the result from the fit to the entire dataset before, we are able to minimize $\chi^2 = 3.09$ for the $f = n - c = 11$ degrees of freedom, indicating that the fitted distribution is supported by the data ($\int_{3.1}^{\infty} \chi^2(11) = 0.93$).

The χ^2-fit computes for the peak assignment distribution $N_E(\Sigma)$ a scaling factor $E = (12.6 \pm 1.6)\mathrm{m}$, the shift from the centre $\mu_E = (-0.0003 \pm 0.004)\mathrm{m}$ and a standard deviation $\sigma_E = (0.044 \pm 0.004)\mathrm{m}$. Similarly for the refinement distance $N_F(\Sigma)$: $F = (6.0 \pm 1.5)\mathrm{m}$, $\mu_F = (0.004 \pm 0.013)\mathrm{m}$ and $\sigma_F = (0.13 \pm 0.02)\mathrm{m}$.

For the linear interpolation scheme (ref. to Appendix D) the peak assignment contribution $(N_A(\delta)$ dominates the central bins. Only 4% of the counts are attributed to the refinement $(N_B(\delta))$ and we could define the interval where to perform a direct statistical analysis of the δ values for the peak assignment mode from the intersections of $N_A(\delta)$ and $N_B(\delta)$. For the cubic spline interpolation scheme 16% of the counts are contributing to the refinement $N_F(\Sigma)$ in the central bins. Thus the roots $\Sigma_1 = -0.089m$ and $\Sigma_2 = 0.087m$ of $N_E(\Sigma_k) = N_F(\Sigma_k)$ do not define the complete inner interval, where the peak assignment contributes and it does not as clearly dominate the distribution of Σ. The peak assignment and the refinement modes do not separate as clearly as for the linear interpolation, and a Shapiro Wilk test for the (Σ_1, Σ_2) interval fails. When extending the interval to $(-0.16\mathrm{m}, 0.16\mathrm{m})$ – which covers the contributions of the peak assignment mode well –, the direct statistical analysis for the 348 points estimates a standard deviation of $0.056\mathrm{m}$, skew of 0.06 and a kurtosis of 0.21. This suggest a symmetrical distribution that is slightly higher with wider wings, which is consistent with the above observation of the refinement mode being recognizable in interval and the standard deviation is overestimated. A Shapiro Wilk test supports normal distribution in the interval $(-0.16\mathrm{m}, 0.16\mathrm{m})$, as $W = 0.995$ and the corresponding p-Value p=0.38. As we already excluded outliers for the analysis, there is no meaning in the statistical analysis of the refinement distance and we assume Σ as a measure for the systematic deviation when using cubic spline interpolation.

The cubic spline scheme confirms the above observed maximal error of the match points $\Delta D = 0.043\mathrm{m} = \sigma_A \sigma_E = 0.044$. When restricting $|\delta|, |\Sigma| \leq 0.375\mathrm{m}$, then both δ and Σ have 3 match points exceeding this threshold and both distributions fit a profile with a standard deviation of $\sigma_F = \sigma_B$ (without 3 outliers) $= 0.13\mathrm{m}$ for the refinement each match point contributes in average. This means that one of the interpolation schemes is not superior to the other, but comparing them illustrates the uncertainty associated with interpolation in between the match points.

Now, we calculate the systematic deviation between linear and cubic spline interpolation from datasets in 0.01 m resolution. ζ_i denotes the maximal absolute difference in the interval between the i-th and (i+1)-th match point, which is a direct measure of systematic differences due to the interpolation schemes.

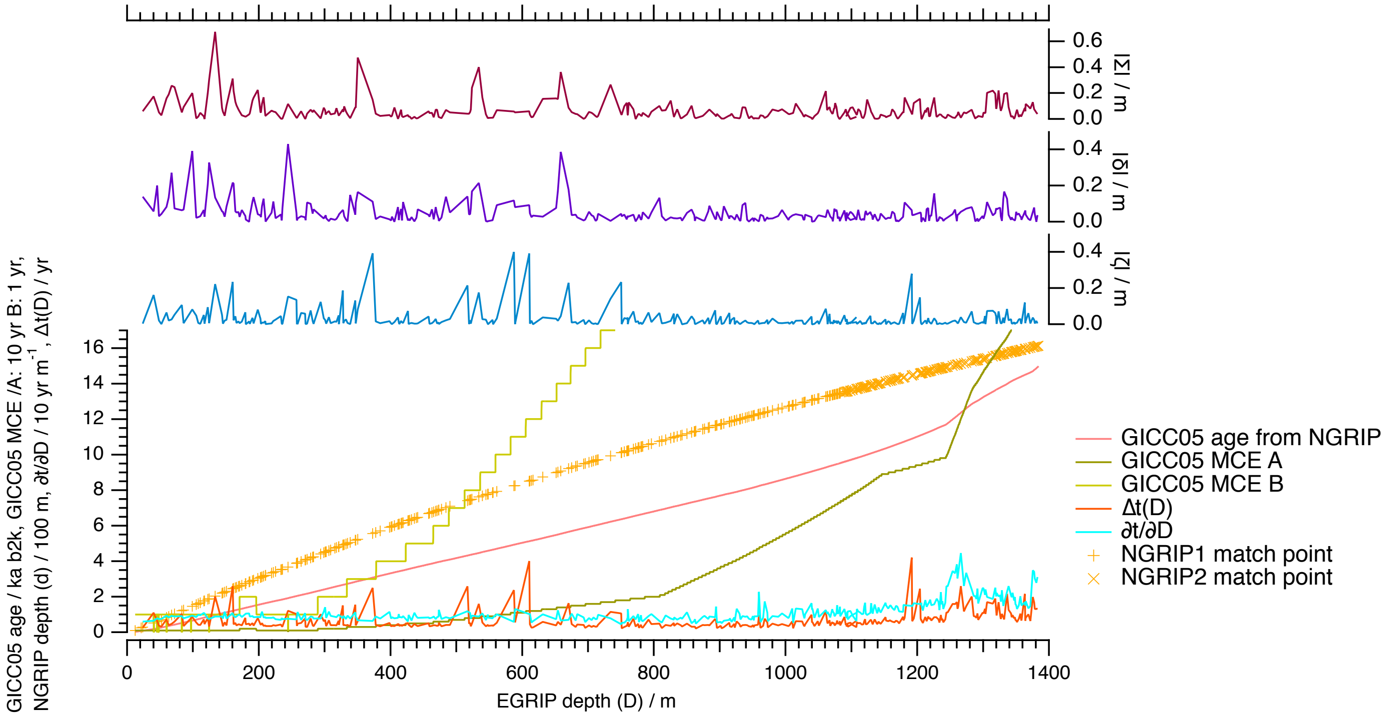

Figure 3: The (EGRIP, NGRIP) match points, (EGRIP-depth, GICC05-time)-scale, the (EGRIP-depth, GICC05-MCE)-curve, $|\delta|$, $|\Sigma|$, $|\zeta|$, $\frac{\partial t_{\text{GICC05}}}{\partial D_{\text{EGRIP}}}$, $\Delta t(D) = \left|\frac{\partial t}{\partial D}\right| \sqrt{(\Delta t)^2 + \zeta^2}$

$|\zeta|$ and $|\delta|$ are both less than 0.4 m and exhibit a similar pattern, while $|\Sigma|$ has less in common with both δ and ζ. $|\zeta|$ is a good measure for the interpolation uncertainty along the record as it is the direct comparison of two fundamentally different interpolation approaches (see Figure 3).

For linear interpolation, the statistical error for the computed depth in between two match points is limited by the maximal error of the match points $\Delta D = 0.043\text{m}$ and the error of the interpolated depth D is therefore $\sqrt{(\Delta D)^2 + \zeta^2}$. To propagate the depth error and estimate the additional error of the time match, we start from the highest resolution published GICC05 dating of NGRIP with 2.5 cm and 5 cm depth resolution above and below 349.8 m respectively [Vinther et al., 2006, Rasmussen et al., 2006] and linearly interpolate the EGRIP depth (D) onto the NGRIP depth (d) to get the time scale t(D) for EGRIP. We calculate $\frac{\partial t_{\text{GICC05}}}{\partial D_{\text{EGRIP}}}$ in the high resolution dataset and sample it at the match points.

The matching error related to the timescale transfer $\Delta t(D) = \left|\frac{\partial t}{\partial D}\right| \sqrt{(\Delta t)^2 + \zeta^2}$ is maximally about 4 years, exceeds the MCE on two occasions in the uppermost 200 m by 1 year, and becomes increasingly smaller compared to the MCE for increasingly deeper parts of the record (see Figure 3)."

(3) comments from Referees: Please see the comment below for Line 225, since I also think that some further analysis is needed both in justifying the interpolation scheme as well as in quantifying the timescale uncertainty.
(3r) author's response: This is discussed with the response to referee comment for line 225.
(3c) author's changes: The changes are described with the response to referee comment for line 225.
(4) comments from Referees: There are issues with writing clarity and grammar with some mistakes (which I have not completely listed). These issues make it difficult to completely understand the

manuscript. While the quality of writing is high enough to understand most of the science presented in this manuscript, I would recommend that the authors spend time refining the grammar and sentence structure of the paper to improve readability. While these issues are important, I believe that they can be addressed by the authors in a revised version of this manuscript. The research presented so far clearly represents a lot of work and it is exciting to see new progress from the EGRIP project. Thank you for your efforts so far!
(4r) author's response: We acknowledge that this has to be done!
(4c) author's changes: We carefully edited the manuscript and made some grammatical changes (refer to the synopsis of the revised and the original manuscript please). Below we address all the individual comments.
(5) comments from Referees:Specific Comments: Line 6: Are the 373 match points spaced throughout the entire ice core?
(5r) author's response: The match points are reasonably distributed throughout the entire ice core. The maximum distance to the neighbouring match points is 26.6 m (490.06m-516.67m), corresponding to around 224 yr difference and the minimum distance is 0.21m between match points (1206.45m-1206.67m), corresponding to around 3 years. Note: When compiling the datasets for release, we realized a small inconsistency, which we corrected by adding 8 more match points over the brittle zone 373 to 381). We revised our figures and the manuscript accordingly. We also chose to add a short not on why we kept a certain minimum distance in between match points to reduce noise on e.g. the annual layer thickness record.
(5c) author's changes: We changed the number of match points and added "typically spaced less than 50 years apart" in the abstract, as the reviewer seems to want know if the spacing of the match points is reasonable. The sentence reads now: "We transfer the annual-layer-counted Greenland Ice Core Chronology 2005 (GICC05) from the NGRIP core to the EGRIP ice core by means of 381 match points, typically spaced less than 50 years apart."
To provide in depth information, we added the detailed information in subsection 2.4 "Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM": "Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years."
(6) comments from Referees: Line 7-8: How deep is the core in total? Do you have a total age estimate?
(6r) author's response: As the abstract is limited in length, we add this information in the data and methods section.
(6c) author's changes: We added the following half-sentence to section 2.2.1: "The average annual accumulation rate is about 100 kg m-2 yr-1 (0.11 m i.e. yr-1) for the period 1607–2011 as determined from a firn core close to the main EGRIP drilling site [Vallelonga et al., 2014]. Radar-soundings suggest the ice thickness to exceed 2550 m and traced radar layers from the NGRIP site suggest that the drill site preserves an undisturbed climatic record of at least 51 kyr [Vallelonga et al., 2014]. The camp currently moves about 51 m to the North-Northeast each year [Dahl-Jensen et al., 2019]."
(7) comments from Referees: Line 15: change 'reflect' to 'reflecting'. Not sure what 'immediate'

means in this context.

(7r) author's response: We added "that" and omitted "immediate", which was meant to strengthen the close relation of the proxies to the atmospheric proxies or even direct measurement of greenhouse gases.

(7c) author's changes: The sentence reads now: "The dating of an ice core establishes the depth–age relationship to derive a chronology of past climatic conditions from the measured proxy parameters, which reflect past atmospheric conditions and biogeochemical events along the core."

(8) comments from Referees: Figure 1: Excellent figure.

(8r) author's response: Thank you very much!

(9) comments from Referees: Line 78: Change "was" to "were".

(9c) author's changes: Changed.

(10) comments from Referees: Lines 78-94: Are these procedures novel and unique to this study? If so, I would recommend including a diagram or schematic. If very similar methods have been using previously, referencing them in this section would be helpful.

(10r) author's response: Similar methods have not been described previously, so it is not done with just referencing them. The system is – in principle – the one as described in [Wilhelms et al., 1998]. The paragraph you refer to, describes improvements and typical measurements with the device.

(10cc) author's changes: We added the following schematic Figure 4 to the 2.3.1 section to illustrate the description in the text to be clear for the non-expert readers.

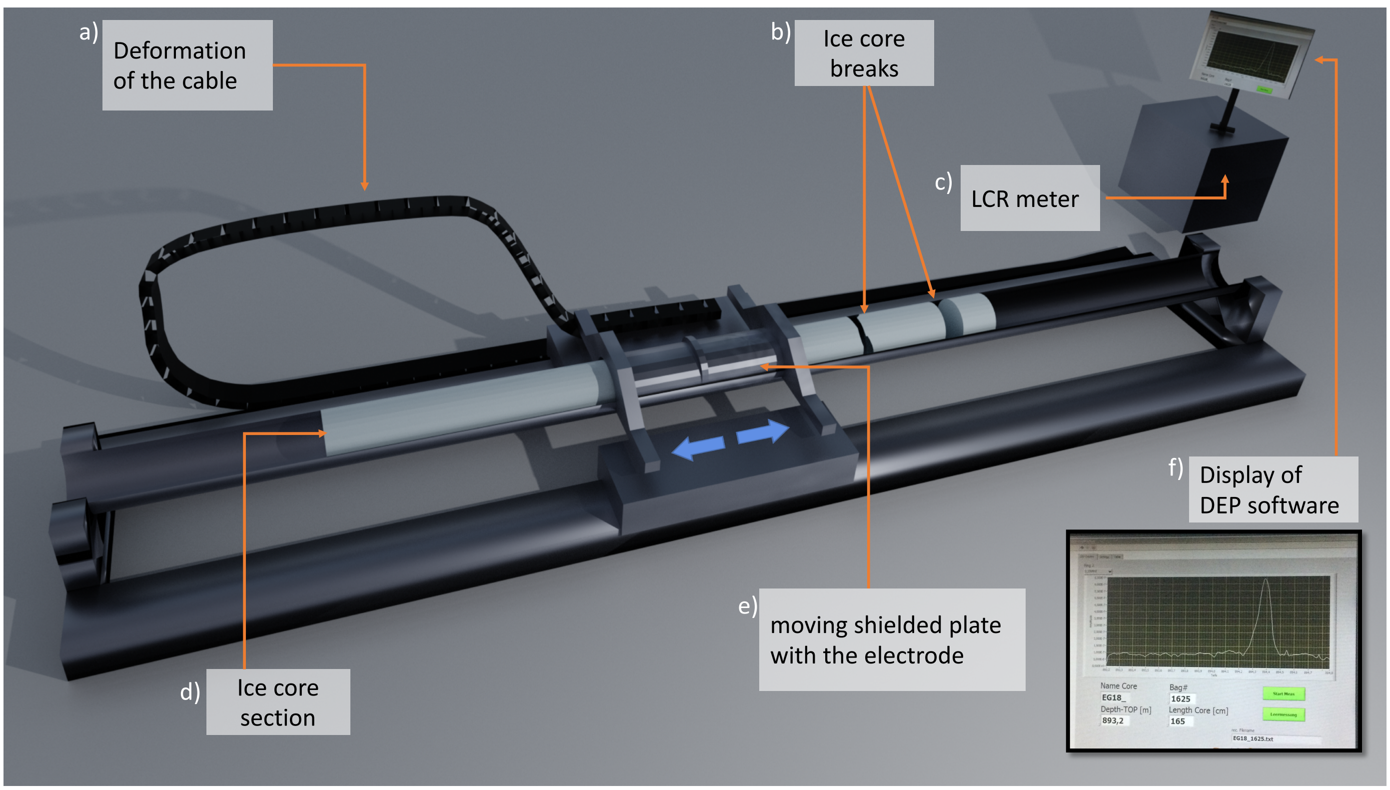

Figure 4: Schematic of the DEP instrument.

(11) comments from Referees: Figure 3: I would suggest writing out in plain language the y-axis label and including units in the axis labels and/or caption.

(11c) author's changes: Changed as suggested (Figure 5).

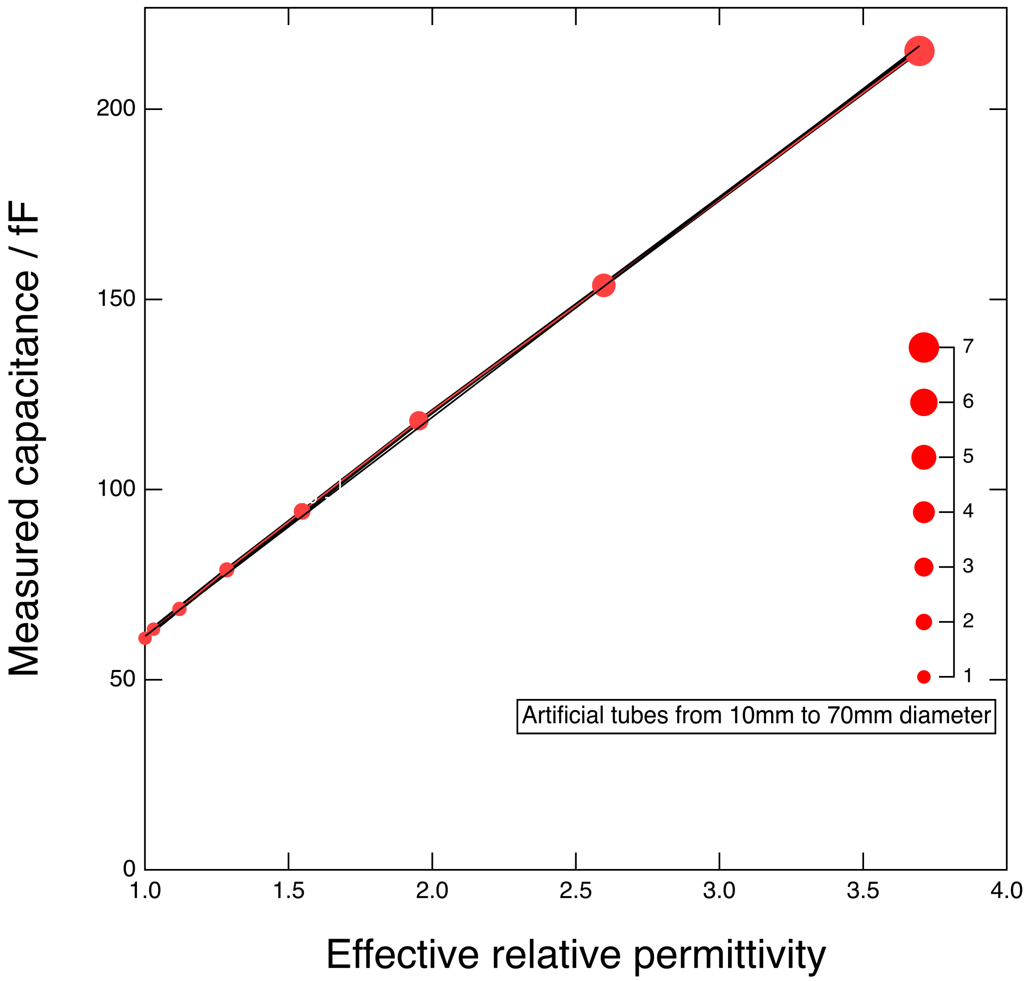

Figure 5: Calibration curve of the measurements with artificial tubes and free-air measurement for DEP device.

(12) comments from Referees: Lines 113-114: It would be interesting to know some information about the amount of breaks or missing ice at various depths. I would suggest adding a few descriptive statistics on core quality at different depth and especially in the brittle zone.

(12c) author's changes:

We added the following information to the 2.2.1 section. "The EGRIP brittle zone is of better quality than the brittle ice from previous Greenland ice core projects such as NEEM and NGRIP. For the EGRIP core, Figure 6 presents a quality index on the basis of the ratio between validated and total measured DEP and ECM sample points. This quality index falls below 0.3 between 505 m (4220 a b2k) and 1210 m (11163 a b2k) depth, which is consistent with the brittle zone between 550 m and 1250 m according to the field season reports Dahl2019. The quality index calculated from the earlier released NGRIP and NEEM DEP data is presented in Appendix A "Quality index for the NGRIP and NEEM ice cores."

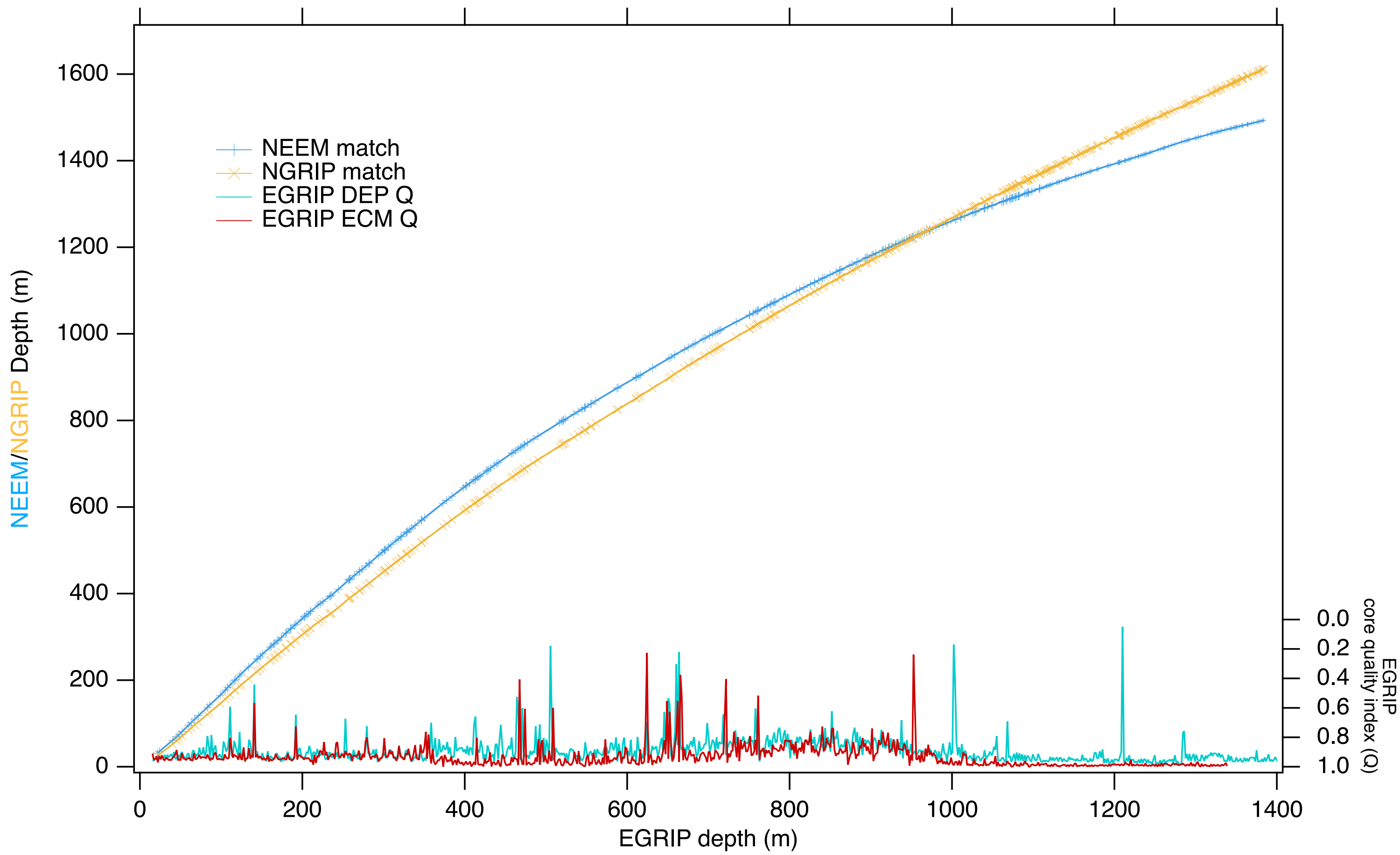

Figure 6: Match points between EGRIP, NEEM (blue) and NGRIP (yellow) ice cores based on the DEP and ECM data sets. The core quality index Q as derived from the validated DEP and ECM data, respectively.

We have added a section for the NGRIP and NEEM ice cores quality in the Appendix (A):

Appendix A: Quality index for the NGRIP and NEEM ice cores

For the NEEM and NGRIP ice cores we calculated similar quality indices as provided for EGRIP above. They are presented together in Figure 7.

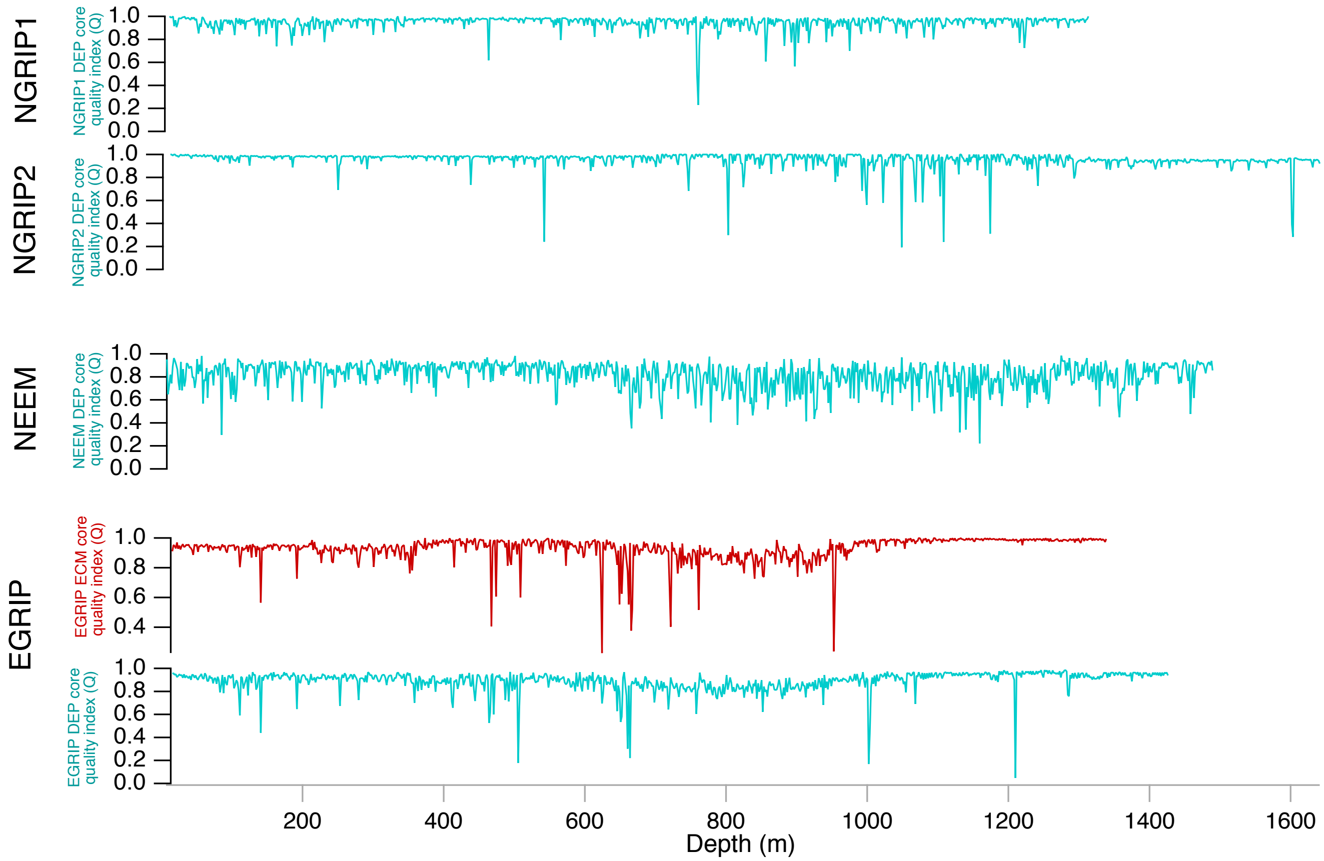

Figure 7: Quality indices for the EGRIP, NGRIP and NEEM ice cores.

(13) comments from Referees: Lines 119-120: It is unclear to me what 'it' or 'protocol' are referring to in this sentence.

(13r) author's response: Initially, the "gold standard" DEP protocol was to note all breaks, classify bad core quality sections with e.g. missing slices and core catcher marks in a hand written protocol book in a code that is easily processed into a record of validated/non validated core sections. For the three deep cores the processing staff did not stick strictly to the protocol format in a consistent way. On the other hand, when really locking at the records the fraction of rejected core sections is pretty big and a significant amount of data can be validated after observing a consistent and intact permittivity signal. This procedure can be automated by calculating a strongly smoothed average of the permittivity, setting a threshold and removing sections that fall below the threshold. To make the edges a little nicer the removed section is extended to the depth where it reaches the average before resp. after dropping below resp. exceeding the threshold. This was described in section 2.3. of [Rasmussen et al., 2013]. The conductivity is less sensitive to bad core quality, which leads to a really robustly validated conductivity record, when taking the decision on the permittivity record. Finally, this automated procedure delivers a comparable result, with much less effort, and most important: it is much more consistent in between all three cores.

(13c) author's changes: We changed the section 2.3.1 and focused on the actually used procedure. It reads now: "The automated procedure as described in [Rasmussen et al., 2013] (section 2.3) is much faster, more consistent in between the three different cores, and has proven to be superior to any approach based on a hand-written protocol, which depends on the judgement of the operator when identifying intervals of bad core. As the permittivity is very sensitive to bad core quality and the conductivity is much less prone to bad core quality, the outlined validation procedure leads to a robustly validated conductivity record."

(14) comments from Referees: Lines 123-124: This sentence needs more context. Why does the DEP data need temperature correction? How did you accomplish this and at what stage in your procedure? I (and most readers) have not been to EGRIP, so we will need some explanation of what the 'science trench' and 'core buffer' mean and their implications for the DEP data.

(14r) author's response: In contrast to the permittivity, the conductivity is strongly dependent on temperature. The temperature correction does not affect the identification of conductivity patterns of DEP peaks between synchronised ice cores. Therefore it is not relevant for the synchronisation in this paper. However, it is relevant when using absolute conductivity readings, especially with respect to the attenuation of radar waves in the ice. As people will use the dataset for this purpose, a warning has to be placed somewhere in the paper. The processing mode changes in between projects and teams. The temperature is difficult to reconstruct later as many people are involved and the measurement of the temperature of the core when processing is difficult as the equilibration time between moving it from the relatively cold storage area (buffer) to the science trench with much more impact from the surface air temperature as more people move in and out may vary in between teams. For the cores here we can't reliably reconstruct the precise temperature during the measurement, so we will not provide temperature corrected data.

(14c) author's changes: We replaced the sentence, it reads now: "Due to the varying temperature in processing area throughout the field seasons, the core was not processed at a consistent temperature and we don't have the temperature readings avail to provide consistently harmonized conductivity data. The missing temperature correction does not affect the use of conductivity peaks for synchronization purposes in between ice cores, which is relevant for the discussion here. When e.g. deriving radar wave absorption coefficients from the presented conductivity record, one would have to be very cautious and have this limitation of the data in mind."

(15) comments from Referees: Figure 4: What percentage of the data was removed? For permittivity it looks like the 'bad quality' measurements encompass a large amount of data.

(15r) author's response: As we discussed in the first version of manuscript (2.2.1 section, lines 115-125), the ice cores exhibit breaks, broken-off slices are clearly identifiable in the permittivity record by dropping spikes. For the validation of the data, any drop below a certain threshold (cf. the red line in Figure 4 in the revised manuscript) identifies a spike to be rejected, where the segment to be rejected is extended to about the average of the permittivity record. In this way, with an average with 11% data was not validated in the entire ice core (especially in the brittle zone). It is not bad quality measurements. The measurement is recorded along all the core, even on "damaged" sections, which can even be identified in the permittivity record and thus be removed from the validated dataset.

(15c) author's changes: A core quality index was introduced under item 12, which answers the question.

(16) comments from Referees: Line 143: I suggest switching 'used' to 'final'.

(16c) author's changes: Changed as suggested.

(17) comments from Referees: Line 150-151: I am having difficulty following this section since 'bag marks' and 'break marks' have not been clearly defined.

(17r) author's response: Each 1.65 m ice core section contains the equivalent of three 0.55 m bags, and the position of the bag marks separating the first and second bags and the second and third bags, respectively. The break mark is referring to the any break on the ice core sections.

(17c) author's changes: Introduced the definition of break marks somewhat further up. The section reads now: "Also, the core-break positions were registered along with measurement by moving the electrodes of the ECM instrument to the respective break position after the core scan, and registering the position in the data file. During the processing, these recorded break marks were used to trim off artefacts and produce the final ECM data set. Data from each day were calibrated using independent measurements of the physical dimensions of the ECM measurement setup. The first and last few millimetres of recorded data are affected by the proximity to the end of the core and were removed. Areas with dips in the signal around logged core breaks were also muted during processing. Details on the acquisition and processing of the ECM record are laid out in Appendix C “Details on the ECM procedures.”

(18) comments from Referees: Figure 6: Why not show Mazama data from NGRIP? In any case, this is a very convincing figure.

(18r) author’s response: The MAZAMA data on the figure is not from NGRIP, because it is unpublished geochemical data from Siwan Davies. The statistics in the table (SD and D2 are however based on the NGRIP data). Although she was happy for the depth to be used, she wants to publish the data in a specific tephra paper, which is in preparation, first.

(19) comments from Referees: Section 2.4: Did you set quantitative thresholds for how much accumulation variability and core smoothness, or were the results inspected qualitatively. If the former, what were the assumptions you used?

(19r) author’s response: The accumulation variability was inspected qualitatively. The match is described in “Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM”, also the chosen minimal distance of the match points. Distance. In response to reviewer remark (2), the errors of the new timescale are discussed in depth in the added discussion to this section 2.5.

(19c) author’s changes: The discussion is addressed in handling of reviewer comment (23) and (2).

(20) comments from Referees: Figure 8: There should be only two Es in NEEM on the y-axis label. Also what do the pink/red bars in the brittle ice zone signify?

(20r) author’s response: In item 12 we introduced a quality index which replaces the brittle zone indication.

(20c) author’s changes: We have fixed the y-axis label.

(21) comments from Referees: Section 3.2: If I understand correctly, you found 3 matching tephra horizons out of 373 total matches. Is this correct? How many other tephra events have been sampled so far? How many more do you plan to sample? Have there been many other events sampled that do not match any event in NGRIP or NEEM? This continuous tephra sampling is very impressive and interesting and more details would be appreciated.

(21r) author’s response: So far, only the DEP /ECM peaks were investigated for tephra in EGRIP, as the project is still in an early stage for tephra screening. This targeted sampling led to the identification of 13 tephra layers in total, three of which link to NGRIP. The other layers have not yet been linked geochemically to other ice cores. They will be traced in NEEM and NGRIP as a next step. Eliza Cook took continuous samples for tephra in the field, with an 11 cm depth resolution, and these will be mounted onto slides and investigated by optical microscopy over the next few years, due to the high number of samples. It has been shown [Davies et al., 2010] that tephra layers are often found without coeval chemical peaks in DEP or ECM, so we anticipate many more ’cryptotephra’ ash deposits to be found. Furthermore, there is no detailed tephra framework published yet for the Holocene. Eliza Cook and Siwan Davies are working on continuous sampling for tephra in NGRIP and, with some samples for NEEM and GRIP a. The former has been continuously sampled between 5 ka to the beginning of the Holocene (and back to the glacial), and the other cores have only been spot sampled in the Holocene, to trace the most interesting layers found in NGRIP. These remain unpublished but will undoubtedly lead to many more correlations between all the ice cores and will be published at a later date.

(21c) author's changes: n.a.

(22) comments from Referees: Line 221: 1383.84 meters in EGRIP right?

(22r) author's response: Yes. 1383.84 meters in EGRIP.

(23) comments from Referees: Line 225: What is the longest section between tie points? 0-2 years seems an unrealistically low uncertainty to report if there is no annual layer counting. We can see in Figure 9 that accumulation rate changes on multiple timescales and presumably has variations within the spacing of your tie points as well. None of the purely mathematical interpolation methods will account for this possibility. I think you need to include some analysis that incorporates the observed variation in annual layer thickness, either from layers visible in the EGRIP ice core or from meteorological data. You can use this data in conjunction with your tie points and their spacing to generate more realistic estimates of uncertainty and potentially improve the timescale itself.

(23r) author's response: As we have discussed before in Line 6, "The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years." Figure 9 shows the annual layer thickness between the match points. Here we used the ages of the match points themselves against annual layer thicknesses between them to make our plot (not interpolation data). We added the detailed information of interpolations in subsection 2.5 and two Appendix sections (D and E).

(23c) author's changes: Regarding uncertainty of interpolations please see changes (2c). At the end of the section "Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM" we added a paragraph discussing the distance of match points: "Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years."

(24) comments from Referees: Line 226-230: I'm afraid I do not fully understand either of these sentences, which I think are important. I would suggest adding clarification.

(24c) author's changes: We changed the paragraph, it reads now: "Along with this publication we release a time scale for each 0.55 m section ("bag"). For each EGRIP depth, the corresponding NGRIP depth was found by linear interpolation between the match points, and the GICC05 age was then determined from the published GICC05 time scale for NGRIP. The maximal uncertainty resulting from the choice of interpolation scheme is assessed in detail (see Appendix E1) and is about four years. The relatively smooth (depth, depth) relation of EGRIP–NGRIP and EGRIP–NEEM (see Figure 6) shows that the ratios of annual layer thicknesses between cores do not vary noticeably between match points. Figure 8 shows that EGRIP has thinner annual layers than both NEEM and NGRIP ice cores in the upper parts of the cores as also expected from the lower surface accumulation. Ice found in the EGRIP core originates from snow that was accumulating upstream, and accumulation rates increase upstream as the flow line approaches GRIP and NGRIP, where present-day accumulation is about twice of that at EGRIP tc-8-1275-2014,Riverman,karlsson2020.

Surprisingly, annual layers in EGRIP remain almost constant back to 8 ka b2k (Figure 9 in the revised manuscript), while the layer thicknesses in large parts of the Holocene part of the NGRIP and NEEM cores thin linearly due to ice flow. We believe that it is a coincidence that the combined effects of the increasing upstream accumulation and flow-induced thinning at EGRIP balance out for the last 8 ka. Despite the lower accumulation at EGRIP, annual layers in EGRIP eventually get thicker than the annual layers in the NEEM and NGRIP ice cores. Below an EGRIP depth of around 700 m, annual layers in EGRIP are thicker than the layers from the same period in the NEEM core, and similarly below 1000 m, EGRIP annual layers are thicker than those in NGRIP (Figure 8).There are some gaps in the EGRIP ice-core record due to the brittle zone. However, the smoothness of the depth vs. depth plot in Figure 6 and the annual layer thickness ratio in Figure 8 robustly support our time scale based on the match points."

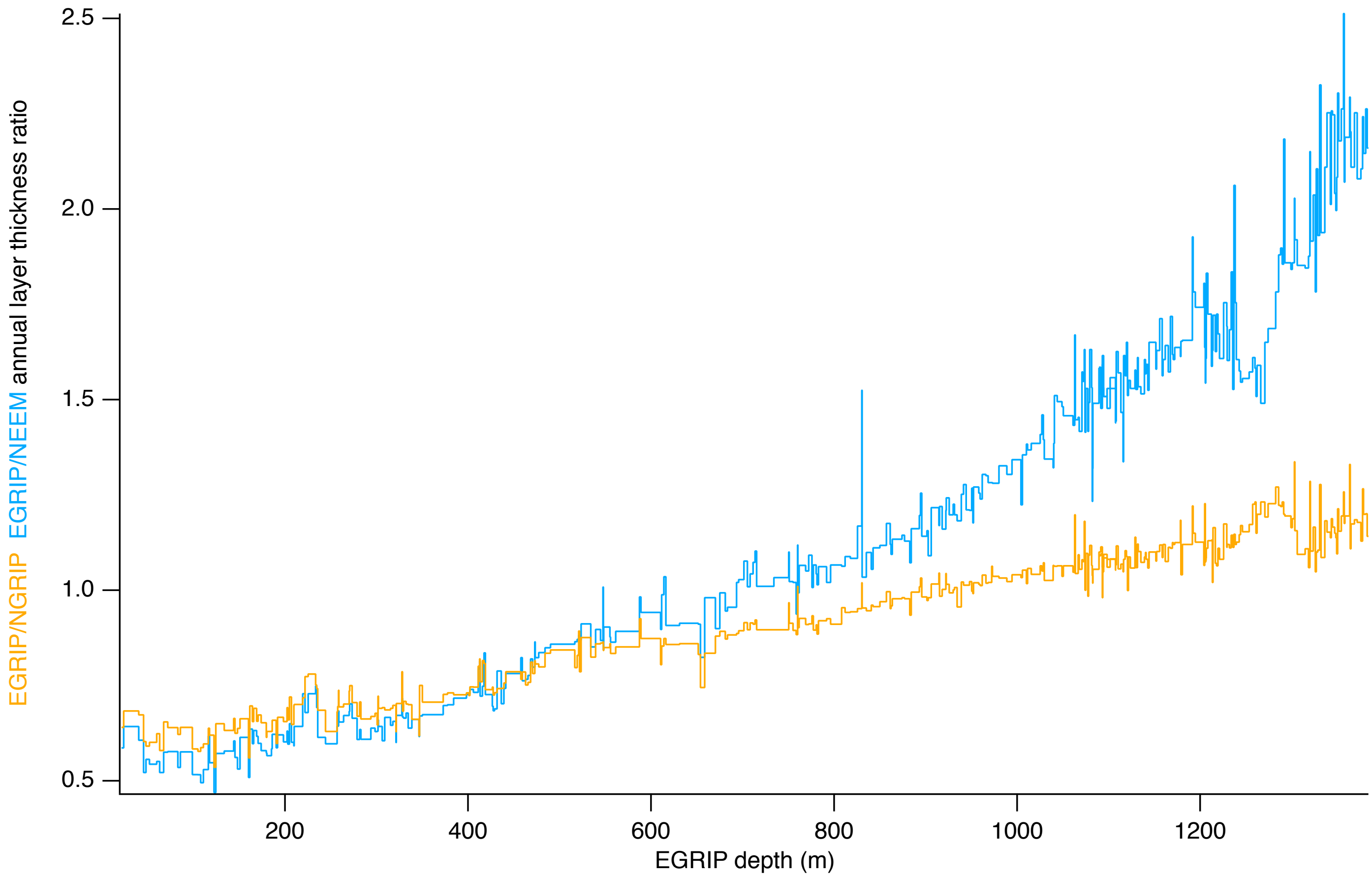

Figure 8: The EGRIP/NGRIP (orange) and EGRIP/NEEM (blue) annual-layer thickness ratio (left axis) calculated between neighbouring match points.

(25) comments from Referees: Line 236: How do you know the upstream accumulation is higher? Is there a reference for this? Or are you inferring this from the flatness of the 0-8 ka accumulation curve in Fig. 9? How do you separate the spatial versus temporal signal in reconstructed accumulation?
(25r) author's response: Has been added in the paragraph as discussed in Reviewers remark (24).
(25c) author's changes: See no. (24) above.
(26) comments from Referees: Line 239-240: The phrase "EGRIP layers start to get thinner, but

remain nearly constant in thickness" seems to be a direct contradiction. Please clarify

(26r) author's response: This was clarified in the changes made for the reviewer remarks above, esp. (24).

(27) comments from Referees: Line 249: How deep is the full core and what is its anticipated age?

(27r) author's response: This information was added to section EGRIP: Radar-soundings suggest the ice thickness to exceed 2550 m and traced radar layers from the NGRIP site suggest that the drill site preserves an undisturbed climatic record of at least 51 kyr [Vallelonga et al., 2014].

(27c) author's changes: n.a.

(28) comments from Referees: Line 260: Why not upload the timescale also at annual resolution to be more useful for other users? I'm assuming that you will include match point data for all 373 matches as well at the 3 tephra horizons reported here.

(28r) author's response: The annually resolved time scale will mainly be useful when the data upon which it is based are also available. The full-resolution NGRIP CFA data set will be released in connection with another paper which is currently in review, and the plan is to release the GICC05 annual layer count in the same context.

(28c) author's changes: n.a.

Answers to Reviewer 2

Dear Referee 2,

Thank you very much for reviewing our manuscript and for your constructive comments. We sincerely appreciate the time you have spent on our manuscript. Please find the detailed point-by-point response to your comments below.

(29) comments from Referees: Mojtabavi et al. present a first chronology for the EastGRIP ice core. The chronology extends to 15ka and is based on volcanic events identified with electrical measurements as well as three tephra layers. The work provides many useful methods and the chronology appears accurate; however, the paper is sloppily written. This is a methods heavy paper despite the technologies being mature. There is little other analysis in the manuscript beyond basic plots of annual layer thickness.

An initial timescale is a useful result. The authors describe the electrical measurements well, something that has not been done as part of recent papers. This may be because the methods have changed little from the papers of the 80s and 90s that describe them. Regardless, I found the discussions mostly useful. Timescale papers are often a challenge to write because they take lots of work, but little in the way of direct scientific conclusions come of the timescale alone – the papers that measure specific climate parameters which depend on the timescale get the high profile results. Thus, the lack of new insight is not necessarily a negative. However, I kept asking myself if the work presented is sufficient for a stand-alone publication, because in many ways it feels like an interim timescale – useful, but not needed to be published.

(29r) author's response: It is an interim timescale until an annual-layer-counted timescale will be become available (possibly a multi-core annual-layer counted time scale updating/replacing GICC05), but it will likely take several (if not many) years before such a time scale becomes available for the past 15 ka, so in that context, we believe that having a time scale to work with in the meantime is valuable. The delay of this year's field season due to the Corona virus outbreak even prolongs the time span till the whole core is available. The timescale will be the basis for several topical papers focussing on shorter time intervals, as e.g. the Holocene, younger Holocene or transition and different proxies. From that point of view it makes sense to publish one proper treatment of the timescale and not repeat it in several papers that need the timescale as a fundamental basis for their discussions. The detailed descriptions of the DEP system and associated procedures comprise the evolution and improvements of the system during the past two decades compared to [Wilhelms et al., 1998] and have not been described in detail before, while they are relevant for the treatment of our data.

(29c) author's changes: n.a.

(30) comments from Referees: I reviewed previous ice-core timescale papers published in Climate of the Past to better understand the contribution of this manuscript relative to its peers. I compared to Winski t al. (2019) for SPICEcore, Ramussen et al. (2013) for NEEM, and Sigl et al. (2016) and Buizert et al. (2015) for WAIS Divide. Each of these papers is quite different than this work. However, what stands out is that the larger scope of each of these manuscripts. Winski et al. is most comparable, being an ice-phase timescale only; however, it presents a timescale for the full ice core (55 ka), includes chemical in addition to electrical measurements, and provides annual layer interpolation for the Holocene although it does not provide any tephra analysis. Sigl et al. is also an icephase timescale only, but presents 31ka of annual layers that provides a reference chronology for all of Antarctica, if not all ice cores – it is clearly in a different class of both effort and impact. The Rasmussen et al. paper is more comparable being the most recent timescale published for a Greenlandic core. It develops an ice-phase timescale with similar methods to this manuscript, but does so for entirety of the nonfolded core and also includes a gas timescale. There is a considerable analysis of the accumulation rate history from the core as well. Buizert et al. determine the gas timescale (and ice timescale for ages older than 31ka) and, because of the low deltaage, this work is a major improvement for Antarctic timescales. Thus, Mojtabavi et al. are considerably short of the benchmark set by previous timescale papers in Climate of the Past.

I am not sure, however, that a comparison to other papers is the appropriate metric. Or rather, I think the editor is better suited to make this call. I think my role is better limited to whether what is presented in the paper is useful. In this case, my question becomes: is this publication useful beyond what simply publishing the timescale and electrical data sets would be. And I believe it is, even if by only a little. There are 10 figures, but most are rather simple. Despite this, I found the text interesting and the detail useful, despite the sloppy writing. Making electrical measurements of 1400m of ice is time consuming and both the timescale and electrical measurements are undeniably useful. I wish the authors had described why they decided to truncate the timescale at 15ka. More EastGRIP ice is it simply a logistical one – like a grant running out? I provide additional comments below and will leave the decision of whether this manuscript achieves the standards of Climate of the Past to the editor. But I will add that if the authors wish to add analysis, comparing the EastGRIP timescale to that predicted by the traced radar layers (Vallelonga et al., 2014; Christianson et al., 2014) used in site selection would be interesting and useful.

(30r) author's response: The manuscript presents new ECM and DEP data (and a thorough account of new DEP processing) and these data sets will be released with the paper (down to 1383.84 m). In addition, for the first time we will release the DEP data from NGRIP1 (down to 1298.705 m) and NEEM (down to 1493.297 m) ice cores, and publishing this manuscript will open these data sets to analysis by the community.

- GICC05-EGRIP-1 time scale for the EGRIP ice core
- Specific conductivity measured with the dielectric profiling (DEP) technique on the EGRIP ice core, 13.77-1383.84 m depth

- Permittivity measured with the dielectric profiling (DEP) technique on the EGRIP ice core, 13.77-1383.84 m depth
- Concentration of hydrogen ions measured with the Electrical Conductivity Method (ECM) on the EGRIP ice core (down to 1383.84 m depth)
- Specific conductivity measured with the dielectric profiling (DEP) technique on the NEEM ice core (down to 1493.297 m depth)
- Permittivity measured with the dielectric profiling (DEP) technique on the NEEM ice core (down to 1493.297 m depth)
- Specific conductivity measured with the dielectric profiling (DEP) technique on the NGRIP1 ice core (down to 1372 m depth)
- Permittivity measured with the dielectric profiling (DEP) technique on the NGRIP1 ice core (down to 1372 m depth)

The current data reach into MIS 3, and even if the current drilling and processing plans hold, it will take at least two years before the complete EGRIP ECM/DEP data sets will be ready. Regarding your question of why we stop specifically at 15 ka: The density of the match points in the Holocene, GS-1 (often called the Younger Dryas) and GI-1 (or the Bølling-Allerød) is so much higher than in the glacial (and especially in the LGM) that the nature of the time scale transfer procedure is different, making it a natural point to cut. Also, ice-flow modelling will be more important to understand the deeper than the upper half of the core, and this work is not ready yet. Therefore, this study goes back through the Holocene and last glacial termination. As your suggestion to compare our results with the traced radar layers [Vallelonga et al., 2014, Christianson et al., 2014]. We have found out that the resolution and depth precision of the traced radar layers is insufficient to really be useful.

(30c) author's changes: The above explanation why only going back 15 ka, because of match point density we add as authors changes for the following detailed comment (31c).

(31) comments from Referees: Detailed comments: Introduction – the introduction is lacking a review of relevant literature and how timescales are being developed and used. With the exception of two Joughin references for NEGIS, every reference is for GICC05. This is not a full introduction. This should be a subsection on GICC05, with an actual introduction that is much broader in scope and discusses the work beyond this group's narrow niche. The lack of any GISP2 references regarding annual layer interpretation is also notable.

(31r) author's response: Annual layer counting is not within the scope of this paper. Annually counted records are also compared and accessed on the basis of identifiable match points. The GISP2 project was implemented more than 25 years ago and the main analysis was published almost 2 decades ago, to significant extent in the AGU special issue "Greenland Summit Ice Cores" in 1997, where annual layer counting of the GISP2 core was presented. We have cited the [Vinther et al., 2006, Rasmussen et al., 2006],paper, where GRIP, NGRIP and DYE-3 were re-counted resp. counted further back in time within the effort to create the GICC05 timescale. There is detailed discussion of the findings for GICC05 in comparison to the GISP2 results, by means of comparison at well identifiable match points for a similar time period to the one covered here. This was 14 years ago and since GISP2 only the group around the University of CPH has been active in acquiring ice core records beyond few thousand years in Greenland. Where several members of the GISP2 consortium are now partners within the efforts we undertake in Greenland.

(31c) author's changes: We added a subsection for the GICC05:

2.1 GICC05

"The annual-layer-counted Greenland Ice Core Chronology 2005 (GICC05) is derived from measurements of stable water isotopes in the DYE–3, GRIP and NGRIP (see Figure 1 in the revised manuscript) ice cores for the period back to 7.9 ka b2k [Vinther et al., 2006] and high-resolution measurements of chemical impurities, conductivity of the ice, and visual stratigraphy from the GRIP and NGRIP ice cores for the period between 7.9 ka and 14.7 ka b2k [Rasmussen et al., 2006]. For the period from 14.7 ka to 42 ka b2k, the dating of the cores is based on annual layer counting in the visual stratigraphy, the electrical conductivity profiles, and a set of chemical impurities data [Andersen et al., 2006]. The timescales are compared to time scales of different other climate archives at suitable tie points, like e.g. marine sediment cores [Svensson et al., 2006]. For the NGRIP core, the GICC05 time scale has been extended even further into the glacial, back to 60 ka b2k by annual layer counting [Svensson et al., 2008] and ice-flow modelling [Wolff et al., 2010]. For the older parts [Wolff et al., 2010] the NGRIP ss09sea06bm model time scale, shifted to younger ages by 705 years, has been spliced onto the end of the GICC05 timescale, thereby forming the so-called GICC05modelext chronology. The GICC05modelext was also applied to the central Greenland GRIP and GISP2 cores by more than 900 marker points and verification with 24 tephra horizons [Seierstad et al., 2014]. In summary, the GICC05modelext timescale is the consistent reference frame for the entirety of Greenland deep cores."

(32) comments from Referees: L11-12: I don't understand what this last sentence is trying to say

(32c) author's changes: The sentence is changed to: "For the next years, this initial timescale will be the basis for climatic reconstructions from EGRIP high-resolution proxy data sets, like e.g. stable water isotopes, chemical impurity or dust records."

(33) comments from Referees: L14: The first sentence needs to be reworded. The grammar is not correct.

(33c) author's changes: The sentence reads now: "The dating of an ice core establishes the depth–age relationship to derive a chronology of past climatic conditions from the measured proxy parameters, which reflect past atmospheric conditions and biogeochemical events along the core."

(34) comments from Referees: L15: What is the point of the second sentence? Which core? Why 25,000 years

(34c) author's changes: We have removed this sentence as we found this is not really essential to mention here.

(35) comments from Referees: L23 – be specific about what EastGRIP will tell us about ice dynamics at the onset of NEGIS

(35c) author's changes: We added the following sentence to the introduction section: "A main objective of the EGRIP project is to study the dynamics of the ice flow in the NEGIS ice stream by analysing the ice core's rheology and its relation to the deformation of the ice."

(36) comments from Referees: L23 – be specific about the ages being investigated. "half way through the glacial period" is very vague

(36c) author's response: The remark was relating to the original EGRIP proposal. We clarified the 15 ka, this paper is focussing on and relate to the present interglacial and the transition from the last glacial in the same paragraph.

(36c) author's changes: We have removed the remark.

(37) comments from Referees: L28 – given that you stop this timescale at 15ka, is how the GICC05 is built beyond 14.7ka really very important?

(37r) author's response: The remark addresses the introduction section. Few lines are spent to outline how the GICC05modelext timescale was established and as we match till 14.96 kyr b2k, there are 3 references out of the mentioned 4 that address the sections of GICC05 that are used for the match here. On the other hand a good match below also supports the match above.

(37c) author's changes: n.a.

(38) comments from Referees: L30: Sentence starting "The time scale" says nothing.

(38r) author's response: This was a fraction that was left behind during an edit and indeed says nothing.

(38c) author's changes: We reworded together with section addressed in 37r above: "For the period from 14.7 ka to 42 ka b2k, the dating of the cores is based on annual layer counting in the visual stratigraphy, the electrical conductivity profiles, and a set of chemical impurities data [Andersen et al., 2006]. The timescales are compared to time scales of different other climate archives at suitable tie points, like e.g. marine sediment cores [Svensson et al., 2006]."

(39) comments from Referees: L32 – "back" is written twice

(39r) author's response: We deleted the first occurrence.

(39c) author's changes: The sentence is changed to: "For the NGRIP core, the GICC05 time scale has been extended even further into the glacial, back to 60 ka b2k by annual layer counting [Svensson et al., 2008] and ice-flow modelling [Wolff et al., 2010]."

(40) comments from Referees: L36 – I don't think chemo-stratigraphic is a good abbreviation/conglomeration. Just say how they were synchronized

(40r) author's response: The term chemo-stratigraphic is taken from [Seierstad et al., 2014] and is common in the literature to describe chemical peak matching. Whether to hyphenate, may depend on journal style.

(40c) author's changes: n.a.

(41) comments from Referees: L38 – Use active voice

(41c) author's changes: The sentence is changed to: "To apply this approach to the EGRIP core, we have profiled the upper 1383.84 m of the EGRIP core using ECM and DEP in the field during the 2017, 2018 and 2019 field seasons."

(42) comments from Referees: L40 – why only this time range? Ice from deeper has already been collected, and presumably measured

(42r) author's response: See changes (31c) and (34c).

(42c) author's changes: n.a.

(43) comments from Referees: L42: NEEM should be defined on first usage. And do you ever define NGRIP?

(43r) author's response: self-evident, of course.

(43c) author's changes: We fixed it in the introduction, in the abstract there are still abbreviations. If it should be fixed in the abstract, please tell us.

(44) comments from Referees: L51: change "around" to "about". Around has spatial connotations which makes it confusing to use here.

(44c) author's changes: Changed.

(45) comments from Referees:2.1.2 – Isn't this just a repeat of the introduction?

(45r) author's response: We introduced a GICC05 paragraph in the data and methods section and moved most of the detailed discussion there, where it appears along with the paragraphs on EGRIP, NGRIP and NEEM.

(46) comments from Referees: L55 – why mention older parts of the GICC05 timescale – you are only going back to 15ka

(46r) author's response: see comments (31c) and (37c).

(47) comments from Referees: L70 – "Dielectric profiling (DEP) has been introduced as a system for rapid dielectrical profiling: : :". The sloppiness of the writing needs to be addressed.
(47r) author's response: Dielectric profiling (DEP) is a proper noun for a method/device and rapid dielectric profiling is what it is used for. So we believe that the sentence makes sense.
(47c) author's changes: We also added the schematic Figure 4 to the 2.3.1 section as suggested by reviewer 1, and added more description. Please see comment (10c).
(48) comments from Referees: L71 – delete "recorded"
(48c) author's changes: Done.
(49) comments from Referees: L78 – change "was" to "Were"
(49c) author's changes: Changed.
(50) comments from Referees: L79 – you don't need "respectively"
(50c) author's changes: Done.
(51) comments from Referees: L80 – provide the typical values so that the you can illustrate the variations are indeed Slight
(51r) author's response: Pure glacier ice's conductivity is in the order of 15µS/m. The conductance $G = \sigma C0/\varepsilon 0 = 15S/m * 63fF/(8.854pF/m) = 110nS$. The ice permittivity is ≥ 2 and the capacitance therefore $C \geq 125fF$. (Figure 4 in the revised manuscript). But it is more obvious, when converting the given values to comparable changes of the material properties, the reader can check himself against the baseline in Figure 4 in the revised manuscript.
(51c) author's changes: We added the following sentence to the Appendix B: Calibration and corrections to the DEP data: "The slight capacitance and conductance variation on the order of less than 4 fF and 500 pS, thus corresponding to relative permittivity changes of 4 fF/63 fF = 0.06 and conductivity changes of (500 pS)/(63 fF)*(8.8542 pF) = 70 nS, along the DEP device is due to the unavoidable deformation of the cables (Figure 4a) when moving the scanning electrode along the device (Figure 4e)." Compared to the properties of pure glacier ice (ref. to Fig. 4) these variations are in the order of 2% for the permittivity and 5‰ for the conductivity. Additionally, an offset of few nS residual conductance may remain even after performing the correction routines of the LCR meter (inductance L, capacitance C, resistance R) bridge (Figure 4c)."
(52) comments from Referees: L82 – what offset?
(52r) author's response: The residual conductance variation due to the deformation of the cables.
(52c) author's changes: We reworded for clarity and the sentence reads now: "Additionally, an offset of few nS residual conductance may remain even after performing the correction routines of the LCR meter (inductance L, capacitance C, resistance R) bridge (Figure 4c)."
(53) comments from Referees: L83-85 – this needs to be reworded for clarity
(53r) author's response: We added Figure 4 that presents a cable carrier that is deformed during movement.
(53c) author's changes: We added the following sentence to the Appendix B: Calibration and corrections to the DEP data: "As a correction in the few percent range we correct the offset, introduced by the changing stray admittance due to the varying cable geometry (Figure 4a) due to their movement during the measurement, by subtracting the course of free-air measurements from the respective measurement of a core section along the DEP device when processing the data."
(54) comments from Referees: L85-85 – if these variations are slight, why spend so much time writing about them? Is this necessary?
(54r) author's response: We addressed the variations in reviewer comment 51 and demonstrate they are about 2% and 5‰. When using the data for e.g. synthetic radargrams the errors are in a range to be considered.
(54c) author's changes: n.a.

(55) comments from Referees: L95-105 – This paragraph needs to be reworked. There are a lot of details here, many of which aren't actually needed for this work and that don't seem to have a real point. Yes, the free air capacitance matters for some things, but lay this out logically. And if the reader doesn't need to know this for this work, say it in a sentence rather than a paragraph.

(55r) author's response: We restructured the whole DEP section and the information of this paragraph is distributed and put where being in a better context. The assessment of procedures and errors is mainly relevant to further use of the data, which is also discussed in the text. It is not relevant to that extent for the synchronisation of the cores. We moved this part to Appendix B "Calibration and corrections to the DEP data".

(56) comments from Referees: L101 – there is no reason to cite an in prep paper here. You can just say that this is something that is or could be done in the future.

(56c) author's changes: We have removed this prep citation.

(57) comments from Referees: L109 – what is the unit here?

(57r) author's response: Relative permittivity is dimensionless.

(57c) author's changes: We clarified by adding "relative" permittivity in Figure 5:"the effective relative permittivity of the setup"

(58) comments from Referees: L132 – how much data total was not collected?

(58r) author's response: Around 8.5 m was not collected between 1295 to 1395!

(58c) author's changes: We added the information by extending a sentence to: "The section about 1285–1385m was corrected in this way, where in total about 8.5 m of the 100 m were not measured. Furthermore, we relied more heavily on the ECM record than on the DEP record when matching peaks within sections with known problems."

(59) comments from Referees: L138 – I don't think you really mean "calibrated". I think "adjusted" would be a fairer Description

(59c) author's changes: Changed as suggested.

(60) comments from Referees: L156-160 – Why do this conversion if you are only going to say it's not correct and not important? Just stop the bad practice of reporting this as acidity, which is known to be wrong. Readers from outside our field may not quickly notice that the acidity is known to be not accurate.

(60r) author's response: The conversion is not accurate, even an inaccurate acidity conversion is more physical meaningful than the measured current. As long as we give the details of the conversion and a better conversion is not available, we argue that this is a meaningful way to show the data

(60c) author's changes: n.a.

(61) comments from Referees: L180-193. I understand what they authors are trying to get at here, but the wording is difficult to follow. This section needs to be rewritten.

(61c) author's changes: The changes are described with the response to referee 1 comment. Please see comment (1c).

(62) comments from Referees: L195 – what is a "slight annual layer thickness variation"?

(62r) author's response: We assume similar annual layer thickness variability between EGRIP and NGRIP, corresponding to an only slowly varying slope of the NGRIP vs EGRIP match-point depth curve (see Figure 6). We expected only significant change in annual layer thickness at the two drill sites at climatic transitions and thinning factor due to ice flow only changes slowly with depth. Rasmussen et al. (2013) used the same assumption and approach for interpolating between NEEM and NGRIP match points.

(62c) author's changes: n.a.

(63) comments from Referees: L197 – This paragraph needs to be rewritten as well. I don't under-

stand how the depths and ages are being transferred among cores. Why is there an interpolation for each ice core bag? If you are interpolating between match points, is which bag the ice is part of irrelevant?

(63r) author's response: The entire paragraph has been re-written when addressing reviewer comment (2) of reviewer 1.

(63c) author's changes: please see comment (2c).

(64) comments from Referees: L200 – where do you discuss uncertainties based on linear and cubic spline interpolations?

(64r) author's response: The changes are described with the response to referee 1 comment. Please see comment (2c).

(64c) author's changes: please see comment (2c).

(65) comments from Referees: L207 – what was the decision process for which tie points were kept and which were not?

(65r) author's response: this was already discussed, when addressing reviewer 1 comment (23).

(65c) author's changes: At the end of the section "Synchronization of dielectric profiling and electrical conductivity measurement records of EGRIP, NGRIP & NEEM" we added a paragraph discussing the distance of match points: "Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years."

(66) comments from Referees: L209-211 – This is not a sentence

(66c) author's changes: The sentence reads now: "The ECM and DEP do not follow each other closely in the 1245–1283 m interval because of the alkaline nature of the ice associated with stadial conditions in EGRIP. This is due to high dust levels neutralizing the acidity of the ice [Ruth et al., 2003, Rasmussen et al., 2013]."

(67) comments from Referees: L226 – I don't understand what you are trying to say here about getting ages with linear interpolation of EGRIP? How different? What is unrealistic? What is the correlation of recent annual accumulation rates between NGRIP and EGRIP? Is there a justification that the annual variability in NGRIP is appropriate to map to EGRIP? Why are you referencing Rasmussen et al. 2013?

(67r) author's response: We rewrote and updated the paragraph.

(67c) author's changes: We changed the paragraph, it reads now: "Along with this publication we release a time scale for each 0.55 m section ("bag"). For each EGRIP depth, the corresponding NGRIP depth was found by linear interpolation between the match points, and the GICC05 age was then determined from the published GICC05 time scale for NGRIP. The maximal uncertainty resulting from the choice of interpolation scheme is assessed in detail (see Appendix E1) and is about four years. The relatively smooth (depth, depth) relation of EGRIP–NGRIP and EGRIP–NEEM (see Figure 6) shows that the ratios of annual layer thicknesses between cores do not vary noticeably between match points. Figure 8 shows that EGRIP has thinner annual layers than both NEEM and NGRIP ice cores in the upper parts of the cores as also expected from the lower surface accumulation. Ice found in the EGRIP core originates from snow that was accumulating upstream, and accumulation rates increase upstream as the flow line approaches GRIP and NGRIP, where present-day accumulation is about twice of that at EGRIP tc-8-1275-2014,Riverman,karlsson2020. Surprisingly, annual layers in EGRIP remain almost constant back to 8 ka b2k (Figure 9 in the revised manuscript), while the layer thicknesses in large parts of the Holocene part of the NGRIP and NEEM cores thin linearly due to ice flow. We believe that it is a coincidence that the combined effects of the increasing upstream accumulation and flow-induced thinning at EGRIP balance out for the last 8 ka. Despite the lower accumulation at EGRIP, annual layers in EGRIP eventually get thicker than the annual layers in the NEEM and NGRIP ice cores. Below an EGRIP depth of around 700 m, annual layers in EGRIP are thicker than the layers from the same period in the NEEM core, and similarly below 1000 m, EGRIP annual layers are thicker than those in NGRIP (Figure 8).There are some gaps in the EGRIP ice-core record due to the brittle zone. However, the smoothness of the depth vs. depth plot in Figure 6 and the annual layer thickness ratio in Figure 8 robustly support our time scale based on the match points."

(68) comments from Referees: L229 – rewrite this sentence

(68c) author's changes: The sentence reads now: "The relatively smooth (depth, depth) relation of EGRIP–NGRIP and EGRIP–NEEM (see Figure 6) shows that the ratios of annual layer thicknesses between cores do not vary noticeably between match points."

(69) comments from Referees: L236 – "supposedly" Cite a source for this information and write with precision.

(69r) author's response: The references Vallelonga et al. (2014), Riverman et al. (2019) and Karlsson et al. (2020) were added to the sentence before starting from L235 and we corrected the grammar.

(69c) author's changes: Added a further sentence: "Ice found in the EGRIP core originates from snow that was accumulating upstream, and accumulation rates increase upstream as the flow line approaches GRIP and NGRIP, where present-day accumulation is about twice of that at EGRIP tc-8-1275-2014,Riverman,karlsson2020."

(70) comments from Referees:Figure 9: The large changes in annual layer thickness variation over short periods are a bit concerning in some locations. Most notably, at 13ka, where the annual layer thickness varies by a factor of 3 or so from 0.03m to 0.09m. This looks to me like a bad match in between two good matches. The authors need to more rigorously assess instances of abrupt layer thickness change.

(70r) author's response: We have fixed the issue. Two match points were very close to each other that caused this large change. We added further description on the distance of match points.

(70c) author's changes: " Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years."

Note: The language of the manuscript was polished.

References

[Andersen et al., 2006] Andersen, K. K., Svensson, A., Johnsen, S. J., Rasmussen, S. O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Steffensen, J. P., Dahl-Jensen, D., Vinther, B. M., and Clausen, H. B. (2006). The Greenland Ice Core Chronology 2005, 15–42ka. Part 1: constructing the time scale. *Quaternary Science Reviews*, 25(23):3246 – 3257.

[Christianson et al., 2014] Christianson, K., Peters, L., Alley, R., Anandakrishnan, S., Jacobel, R., Riverman, K., Muto, A., and Keisling, B. (2014). Dilatant till facilitates ice-stream flow in northeast greenland. *Earth and Planetary Science Letters*, 401:57–69.

[Dahl-Jensen et al., 2019] Dahl-Jensen, D., Kirk, M., Koldtoft, I., Popp, T., and P, S. J. (2019). Field season 2019 East GReenland Ice core Project (EGRIP) 2015-2020: Third year of EGRIP deep drilling.

[Davies et al., 2010] Davies, S., Wastegård, S., Abbott, P., Barbante, C., Bigler, M., Johnsen, S., Rasmussen, T., Steffensen, J., and Svensson, A. (2010). Tracing volcanic events in the ngrip ice-core and synchronising north atlantic marine records during the last glacial period. *Earth and Planetary Science Letters*, 294(1):69 – 79.

[Press et al., 1992] Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P. (1992). *Numerical Recipes in C: The Art of Scientific Computing (2d ed.; Cambridge)*. Cambridge Univ. Press.

[Rasmussen et al., 2013] Rasmussen, S. O., Abbott, P. M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Chappellaz, J., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Kipfstuhl, S., Laepple, T., Seierstad, I. K., Severinghaus, J. P., Steffensen, J. P., Stowasser, C., Svensson, A., Vallelonga, P., Vinther, B. M., Wilhelms, F., and Winstrup, M. (2013). A first chronology for the North Greenland Eemian Ice Drilling (NEEM) ice core. *Climate of the Past*, 9(6):2713–2730.

[Rasmussen et al., 2006] Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U. (2006). A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research: Atmospheres*, 111(D6).

[Rasmussen et al., 2008] Rasmussen, S. O., Seierstad, I. K., Andersen, K. K., Bigler, M., Dahl-Jensen, D., and Johnsen, S. J. (2008). Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications. *Quaternary Science Reviews*, 27(1):18 – 28.

[Ruth et al., 2003] Ruth, U., Wagenbach, D., Steffensen, J. P., and Bigler, M. (2003). Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period. *Journal of Geophysical Research: Atmospheres*, 108(D3).

[Seierstad et al., 2014] Seierstad, I. K., Abbott, P. M., Bigler, M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Johnsen, S. J., Pedersen, D. S., Popp, T. J., Rasmussen, S. O., Severinghaus, J. P., Svensson, A., and Vinther, B. M. (2014). Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale 18o gradients with possible Heinrich event imprint. *Quaternary Science Reviews*, 106:29 – 46.

[Svensson et al., 2008] Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Parrenin, F., Rasmussen, S. O., Röthlisberger, R., Seierstad, I., Steffensen, J. P., and Vinther, B. M. (2008). A 60 000 year Greenland stratigraphic ice core chronology. *Climate of the Past*, 4(1):47–57.

[Svensson et al., 2006] Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Rasmussen, S. O., Röthlisberger, R., Steffensen, J. P., and Vinther, B. M. (2006). The Greenland Ice Core Chronology 2005, 15–42ka. Part 2: comparison to other records. *Quaternary Science Reviews*, 25(23):3258 – 3267.

[Vallelonga et al., 2014] Vallelonga, P., Christianson, K., Alley, R. B., Anandakrishnan, S., Christian, J. E. M., Dahl-Jensen, D., Gkinis, V., Holme, C., Jacobel, R. W., Karlsson, N. B., Keisling, B. A., Kipfstuhl, S., Kjær, H. A., Kristensen, M. E. L., Muto, A., Peters, L. E., Popp, T., Riverman, K. L., Svensson, A. M., Tibuleac, C., Vinther, B. M., Weng, Y., and Winstrup, M. (2014). Initial results from geophysical surveys and shallow coring of the Northeast Greenland Ice Stream (NEGIS). *The Cryosphere*, 8(4):1275–1287.

[Vinther et al., 2006] Vinther, B. M., Clausen, H. B., Johnsen, S. J., Rasmussen, S. O., Andersen, K. K., Buchardt, S. L., Dahl-Jensen, D., Seierstad, I. K., Siggaard-Andersen, M.-L., Steffensen, J. P., Svensson, A., Olsen, J., and Heinemeier, J. (2006). A synchronized dating of three Greenland ice cores throughout the Holocene. *Journal of Geophysical Research: Atmospheres*, 111(D13).

[Wilhelms et al., 1998] Wilhelms, F., Kipfstuhl, J., Miller, H., Heinloth, K., and Firestone, J. (1998). Precise dielectric profiling of ice cores: a new device with improved guarding and its theory. *Journal of Glaciology*, 44(146):171–174.

[Winski et al., 2019] Winski, D. A., Fudge, T. J., Ferris, D. G., Osterberg, E. C., Fegyveresi, J. M., Cole-Dai, J., Thundercloud, Z., Cox, T. S., Kreutz, K. J., Ortman, N., Buizert, C., Epifanio, J., Brook, E. J., Beaudette, R., Severinghaus, J., Sowers, T., Steig, E. J., Kahle, E. C., Jones, T. R., Morris, V., Aydin, M., Nicewonger, M. R., Casey, K. A., Alley, R. B., Waddington, E. D., Iverson, N. A., Dunbar, N. W., Bay, R. C., Souney, J. M., Sigl, M., and McConnell, J. R. (2019). The sp19 chronology for the south pole ice core – part 1: volcanic matching and annual layer counting. *Climate of the Past*, 15(5):1793–1808.

[Wolff et al., 2010] Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., and Svensson, A. (2010). Millennial-scale variability during the last glacial: The ice core record. *Quaternary Science Reviews*, 29(21):2828 – 2838.

A first chronology for the East GReenland Ice–core Project (EGRIP) over the Holocene and last glacial termination

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Abstract.

This paper provides the first chronology for the deep ice core from the East GReenland Ice-core Project (EGRIP) over the Holocene and the late last glacial period. We rely mainly on volcanic events and common ~~patterns of peaks in~~ peak patterns recorded by dielectric profiling (DEP) ~~, electrical conductivity measurements~~ and electrical conductivity measurement (ECM) ~~and tephra records~~ for the synchronization between the EGRIP, NEEM and NGRIP ice cores in Greenland. We transfer the annual-layer-counted Greenland Ice Core Chronology 2005 (GICC05) ~~timescale~~ from the NGRIP core to the EGRIP ice core by means of ~~373 match points~~381 match points, typically spaced less than 50 years apart. The NEEM ice core ~~is only used for supporting~~ has previously been dated in a similar way, and is only included to support the match-point identification. We name our EGRIP time scale GICC05-EGRIP-1. Over the uppermost 1383.84 m, we establish a depth–age relationship dating back to 14,~~965~~ 967 a b2k (years before the year 2000 CE). Tephra horizons provide an independent validation of our match points. In addition, we compare the ratio of ~~annual layer thicknesses~~ the annual layer thickness between ice cores ~~in-between~~ in between the match points to assess our results in view of the different ice-flow patterns and accumulation regimes of the different periods and geographical regions. ~~This initial timescale is the basis of interpretation and refinement of the presently~~

~~derived~~ For the next years, this initial timescale will be the basis for climatic reconstructions from EGRIP high-resolution ~~data sets of chemical impurities~~proxy data sets, like e.g. stable water isotopes, chemical impurity or dust records.

1 Introduction

The dating of an ice core establishes the depth–age relationship to ~~construct~~ derive a chronology of past climatic conditions from the measured proxy parameters, ~~reflect immediate~~ which reflect past atmospheric conditions and biogeochemical events ~~. The climatic studies of the corewill focus on high-resolution climate records of greenhouse gasses, water isotopes, physical properties and impurities through the last 25,000 years covering the onset of the present interglacial, the climatic optimum 8,000 years ago and the industrial period of the past two hundred years.~~

~~In relation to~~ along the core. Concerning the ice sheet as a whole, the depth–age relation is needed to map the ice sheet's internal architecture to interpret and understand the climatic evolution and the behaviour of ~~individual ice streams~~ ice streams (MacGregor et al., 2015). This is a particular focus of the East GReenland Ice-core Project (EGRIP). The drill site has been chosen close to the onset of the North East Greenland Ice Stream (NEGIS) (see Fig. 1), which is the largest ice stream of the Greenland ice sheet (Joughin et al., 2010, 2018). ~~The idea behind~~ A main objective of the EGRIP project is to study the dynamics of the ice flow in the NEGIS ~~. In addition to the objectives related to ice dynamics, obtaining climate records going at least half way through the glacial period is expected.~~ ice stream by analysing the ice core's rheology and its relation to the deformation of the ice.

The main objective of this work is to facilitate analysis of the data from the core by transferring the GICC05 timescale, which has already been transferred from NGRIP to the GRIP, GISP2, and NEEM deep ice cores (Seierstad et al., 2014; Rasmussen et al., 2013) , to EGRIP by aligning features in the DEP and ECM data sets of the EGRIP, NGRIP and NEEM ice cores. We establish a timescale for the time period of the Holocene and the last glacial termination. We stop specifically at 15 ka b2k, as the density of the match points in the period of Holocene, GS-1 (often called the Younger Dryas) and GI-1 (or the Bølling-Allerød) is much higher than in the glacial (and especially in the Last Glacial Maximum, LGM). We present this timescale to enable climate studies while work on a revised layer-counted timescale is ongoing.

The GICC05modelext timescale was transferred from NGRIP to the North Greenland Eemian (NEEM) ice core by matching 787 match points of mainly volcanic origin identified in the electrical conductivity measurement (ECM) and dielectric profiling (DEP) records and – where available – verified by tephra horizons (Rasmussen et al., 2013). To apply this approach to the EGRIP core, we have profiled the upper 1383.84 m of the EGRIP core using ECM and DEP in the field during the 2017, 2018 and 2019 field seasons. We rely mainly on volcanic events as reflected in the common peak pattern in the DEP and ECM records for the synchronization between the EGRIP ice core and the NGRIP1 and NGRIP2 cores. The NEEM ice core is included in order to support match-point identification, while the GICC05 ages are transferred from NGRIP to EGRIP. Three identified tephra horizons independently verify the correct match of the ice cores.

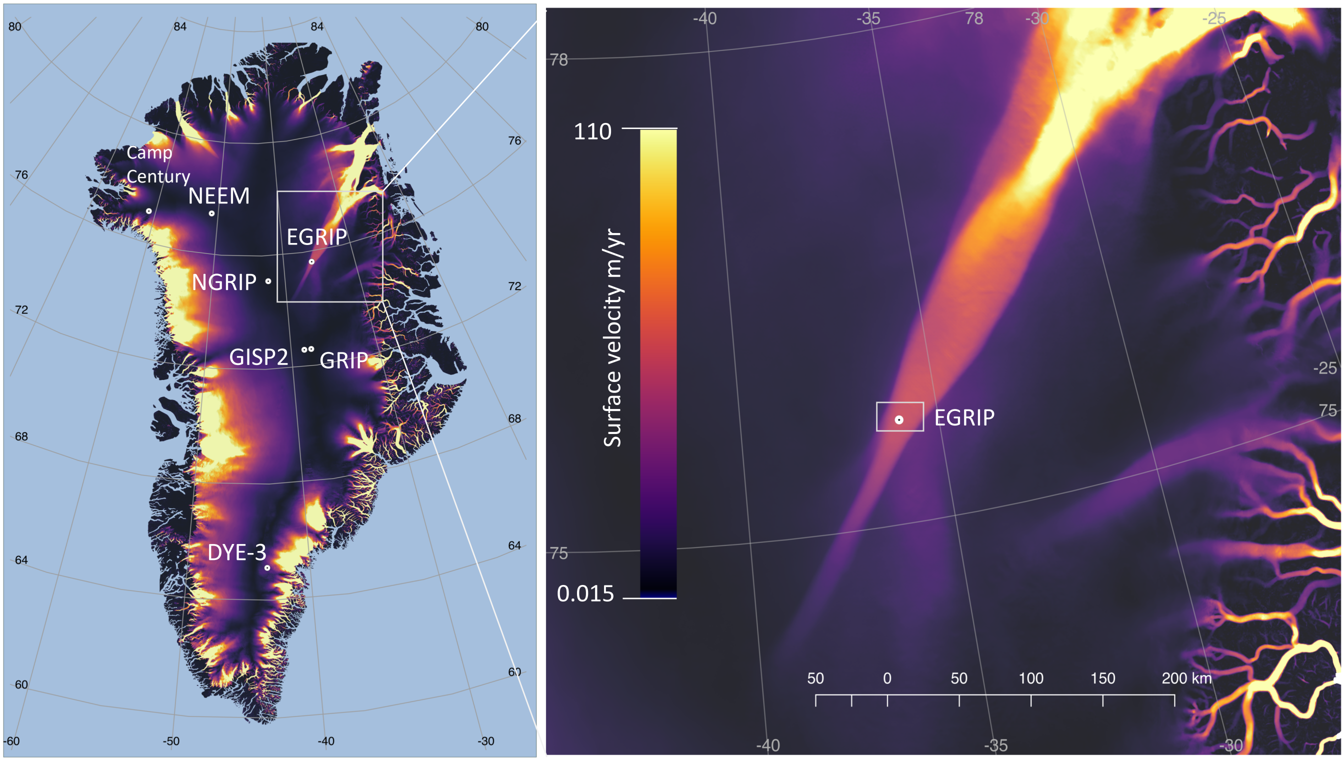

Figure 1. Locations of deep ice-core drill sites: EGRIP, NEEM, NGRIP, GRIP, GISP2, DYE–3, and Camp Century in Greenland, and close-up of the EGRIP drill site inside the North East Greenland Ice Stream (NEGIS). Colours show surface flow velocities from satellite data (Joughin et al., 2018).

2 Data and methods

2.1 GICC05

The annual-layer-counted Greenland Ice Core Chronology 2005 (GICC05) is derived from measurements of stable water isotopes in the DYE–3, GRIP and NGRIP (see Fig. 1) ice cores for the period back to 7.9 ka b2k (Vinther et al., 2006) and high-resolution measurements of chemical impurities, conductivity of the ice, and visual stratigraphy from the GRIP and NGRIP ice cores for the period between 7.9 ka and 14.7 ka b2k (Rasmussen et al., 2006). For the period from 14.7 ka to 42 ka b2k, the dating of the cores is based on annual layer counting in the visual stratigraphy, the electrical conductivity profiles, and a set of chemical impurities data (Andersen et al., 2006). The ~~time scale is~~ timescales are compared to time scales of different other climate archives ~~like marine cores at tie points~~ at suitable tie points, like e.g. marine sediment cores (Svensson et al., 2006). For the NGRIP core, the GICC05 time scale has been extended even further ~~back~~ into the glacial, back to 60 ka b2k by annual layer counting (Svensson et al., 2008) and ~~extended by~~ ice-flow modelling (Wolff et al., 2010). ~~The~~ For the older parts (Wolff et al., 2010) the NGRIP ss09sea06bm model time scale, shifted to younger ages by 705 years, has been spliced onto the end of the GICC05 timescale, thereby forming the so-called GICC05modelext timescale was transferred from NGRIP to the NEEM ice core by matching 787 match points of mainly volcanic origin identified in the electrical conductivity measurement (ECM) and dielectric profiling (DEP) records and – where available – verified by tephra horizons (Rasmussen et al., 2013) chronology. The GICC05modelext was also applied to the central Greenland GRIP and GISP2 cores by chemo-stratigraphic matching of more than 900 marker points and verification with 24 tephra horizons (Seierstad et al., 2014). In summary, the GICC05modelext timescale is the consistent reference frame for the entirety of Greenland deep cores.

The upper ∼ 1400 m of the EGRIP core has been profiled by means of ECM and DEP in the field during the 2017, 2018 and 2019 field seasons. The objective of this study is to establish an initial chronology for the EGRIP ice core over the Holocene and last glacial termination by applying the GICC05 timescale to the EGRIP core. We rely on volcanic events: the common patterns of peaks in the DEP and ECM records, and identified tephra horizons for the synchronization between the EGRIP ice core, the North Greenland Eemian (NEEM) ice core, and the NGRIP1 and NGRIP2 coresfrom the North Greenland Ice Core Project. The NEEM ice core is used for supporting match-point identification, while the GICC05 ages are transferred from NGRIP to EGRIP.

Locations of deep ice-core drill sites: EGRIP, NEEM, NGRIP, GRIP, GISP2, DYE–3, and Camp Century in Greenland, and close-up of the EGRIP drill site inside the North East Greenland Ice Stream (NEGIS). Colours show surface flow velocities from satellite data (Joughin et al., 2018).

3 Data and methods

2.1 Ice-core data sets over the Holocene and last glacial termination

2.1.1 EGRIP

Here, we processed and analysed new DEP , ECM and tephra measurements in the upper ∼ 1400 and ECM records and selected cryptotephra layers in the uppermost 1383.84 m of the EGRIP ice core. At the start of drilling the drilling operation in 2016, the drilling site was located at 75°38′N and 35°60′ 75°38′N and 35°60′W (see Fig. 1). The average annual accumulation rate is around about 100 kg m-2 yr-1 (0.11 m i.e. yr-1) for the period 1607–2011 as reconstructed based on determined from a firn core close to main EGRIP drill site the main EGRIP drilling site citeptc-8-1275-2014. Radar-soundings suggest the ice thickness to exceed 2550 m and traced radar layers from the NGRIP site suggest that the drill site preserves an undisturbed climatic record of at least 51 kyr (Vallelonga et al., 2014). The camp currently moves around about 51 m to the North-Northeast each year (Dahl-Jensen et al., 2019). Fig 2 shows presents an overview of the sections of ice for each core that ice-core sections we used in this study.

2.1.2 NGRIP

The GICC05 is a Greenland annual-layer-counted chronology based on data from several cores reaching about 60.2 ka back in timeThe EGRIP brittle zone is of better quality than the brittle ice from previous Greenland ice core projects such as NEEM and NGRIP. For the older parts (Wolff et al., 2010) the NGRIP ss09sea06bm model time scale, shifted to younger ages by 705 years, has been spliced onto the end of the GICC05 timescale, thereby forming the so-called EGRIP core, Figure 8 presents a quality index on the basis of the ratio between validated and total measured DEP and ECM sample points. This quality index falls below 0.3 between 505 m (4220 a b2k) and 1210 m (11163 a b2k) depth, which is consistent with the brittle zone between 550 m and 1250 m according to the field season reports (Dahl-Jensen et al., 2019). The quality index calculated from the earlier released NGRIP and NEEM DEP data is presented in Appendix A "Quality index for the NGRIP and NEEM ice cores".

2.1.2 NGRIP

The GICC05modelext chronology, which was also applied to the NEEM core. The synchronization used ECM data supplemented by DEP signals for matching the deeper part. timescale, as discussed in detail in paragraph 2.1 above, is well established for the NGRIP ice core. To fully exploit the potential of DEP records for matching, we processed unpublished DEP data from the NGRIP1 core for the upper part (down to 1298 m), and we used the NGRIP2 (below 1298 m) that was published with the NGRIP ECM data in Rasmussen et al. (2013). The NGRIP1 and NGRIP2 cores have a depth offset of around 0.43 m between corresponding events in the overlapping section (Rasmussen et al., 2013).

2.1.3 NEEM

The firn core NEEM–2008–S1 refers to the originates from the NEEM access hole of the NEEM main core, drilled during the 2008 field season to a depth of 103 m (Gfeller et al., 2014). We used only ECM data for the matching of the upper 100 m, as DEP analyses were not madewas not measured on the access-hole core. Below this depth, both DEP and ECM were used to transfer the GICC05 timescale from the NGRIP to the NEEM core (Rasmussen et al., 2013). The shallow and deep cores overlap, forming a continuous record. To check the quality of the ECM data on the NEEM–2018–S1 core, we compared the data to high electrolytical meltwater conductivity measurements (Gfeller et al., 2014) and find good correspondence between peaks in the two datasets.

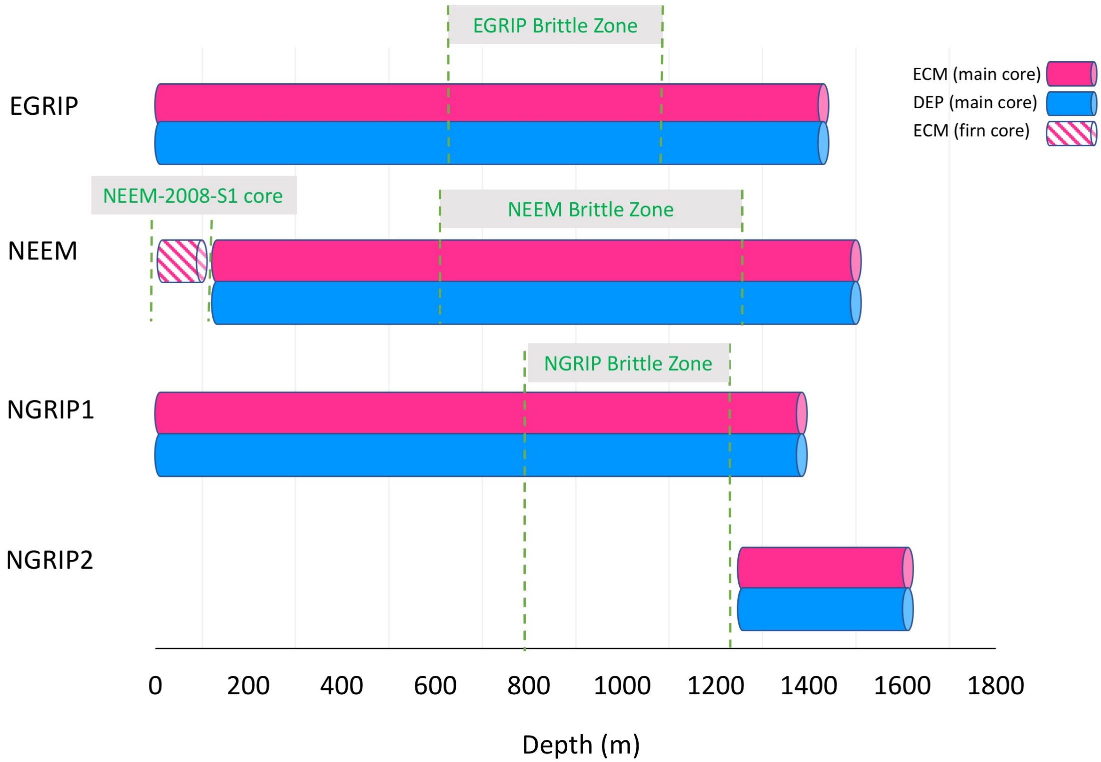

Figure 2. Overview of dielectrical profiling (DEP) and electrical conductivity measurements (ECM) that we used for the synchronization between ice cores over the Holocene and late last glacial periods.

2.2 Field measurements and data processing

2.2.1 Dielectric profiling (DEP)

Dielectric Profiling (DEP) has been introduced as a system for rapid ~~dielectric profiling~~ scanning of ice cores' electric permittivity and conductivity shortly after drilling ~~(Moore and Paren, 1987). The recorded~~ (Moore and Paren, 1987; Wilhelms et al., 1998) . The permittivity and conductivity of ice and firn are determined by their respective densities and conductivities (Wilhelms, 2005). The conductivity is related mainly to acidity, salt and ammonia concentrations of ice cores (Moore et al., 1992, 1994). The dielectric stratigraphy of the EGRIP, NEEM and NGRIP cores were recorded directly during the field seasons with the DEP device described by Wilhelms et al. (1998) (Figure 3), in the discussion below referred to as "deep-core DEP". DEP is the first measurement within the processing line directly on site. A few minutes before scanning, the core is moved from the core ~~buffer~~ storage to the DEP table. Further along the processing line, the ice core is split into the different aliquots. For all three ice cores, DEP measurements were ~~performed in~~ carried out on 1.65 m long sections (Figure 3d).

For the calibration of the DEP device , free-air measurements without ice was recorded frequently, usually at least twice daily before processing started and finished, respectively. The slight capacitance and conductance variation on the order of less than 4 fF and 500 pS along the DEP device is due to the unavoidable deformation of the cables when moving the scanning electrode along the device. Additionally, a few nS of residual conductance may remain even after performing the correction routines of the LCR meter (inductance L, capacitance C, resistance R) bridge. This offset, introduced by the changing stray admittance due to the varying cable geometry during the measurement, is additive and treated by subtracting the course of free-air measurementsalong the DEP device when processing the data.

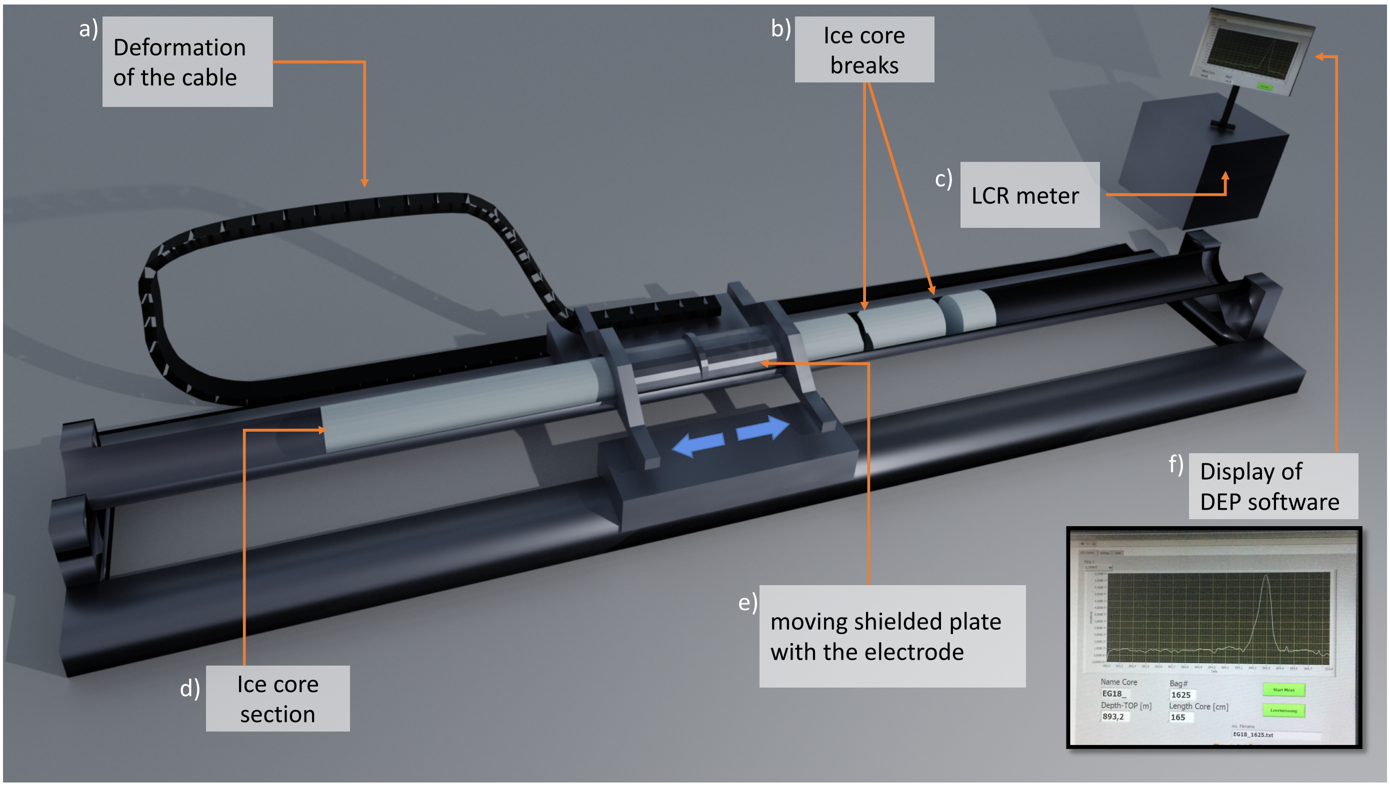

Figure 3. Schematic of the DEP instrument.

All cores were scanned with the deep-core DEP device as described in Wilhelms (1996) and Wilhelms et al. (1998) and the entire scan of a core's section was calibrated with average values of the calibration measurements. For the processing of the NGRIP cores, reproducibility was ensured by laying the cables out to move freely in the same way for all measurements in between two recorded free-air measurements. This was improved for the NEEM and EGRIP processing by placing the cables into cable channels, that enforce repeatable deformation.

and NEEM cores we have improved some features and adapted procedures that were developed for a different DEP device (Wilhelms, 2000), not yet described elsewhere in the application for the processing of data recorded with the deep-core DEP device. The free-air measurement scans the empty capacitor along the DEP device , where the conductance of the air as the

~~capacitor's dielectric vanishes. Thus, the conductance of a scanned ice core is straightforwardly corrected by subtraction of the conductance of the free air measurement. In contrast, the recorded free air capacitance is composed from the capacitance of the empty device and the fraction to be corrected due to cable stray and possibly further small residual offsets in the order of few 1 fF after correction. The computation of the fraction to correct for cable stray therefore requires the knowledge of the DEP device's actual free air capacitance. The free air capacitance is also a factor in the computation of the ice's material properties from the capacitor's capacitance and conductance readings, when filled with the ice core sample as a dielectric.~~

~~All cores were scanned with the DEP deviceas described in (Wilhelms, 1996; Wilhelms et al., 1998). The theoretical value of 63.4 fF and the measured free air capacitance for a precisely adjusted DEP bench coincide within 2 fF. The small difference might well be due to mechanical tolerances like the electrode length in the range of a few tenths of a mm~~identification of peaks is sufficient for the discussion in this paper. However, ~~for a slightly differently adjusted device (one with slightly more clearance to the core, for example), the deviation from the ideal value of the free air capacitance might be a few fF higher.Precise permittivity and resultingly precise free air capacitance values mainly make a difference when computing the wave propagation speed of radar waves while modelling synthetic radargrams (Eisen et al., 2006). As the datasets will also be used for this purpose later (Mojtabavi et al., 2019), we determined the free air capacitance by averaging the measured capacitance over deep core sections and dividing with the expected permittivity of ice of 3.18 ± 0.1 which computes the free air capacitance with 3% relative error, which is only about 2 fF absolute error for the free air capacitance.~~

~~For the NGRIP and the NEEM cores, we had no other means to precisely determine the free air capacitance as outlined above. For the EGRIP core processing, the DEP bench was upgraded with a rack to mount tubes of different diameters concentric to the DEP electrodes and record the capacitance along the DEP device. The tube in the electric field increases the capacitance of the arrangement and Wilhelms (2000) derives the theory to calculate the effective permittivity of the setup. For the calibration, tubes with radius in approximately 10 mm increments between 0–70mm represented effective permittivities between 1 to 4 (Figure B1). The result is a calibration curve which holds for the calculation of a consistent free air capacitance for the correction of DEP measurement of the EGRIP core. The free air capacitance is the proportionality factor of the measured capacitance and the effective permittivity, i.e. the slope of the graph in Figure B1~~the data released with this paper will also be valuable for investigations relying on well-calibrated material properties with absolute calibration, like e.g. modelling of synthetic radargrams. To provide a comprehensive presentation of the basis of the transfer of the timescale here, we outline the relevant discussion to operating the DEP system, while the related discussion on precision of the measured material properties, which are of more relevance for later use of the calibrated data, are presented in Appendix B "Calibration and corrections to the DEP data".

~~Calibration curve of the measurements with artificial tubes and free-air measurement for DEP device~~

Due to the drilling procedure and properties of the ice, ice cores can exhibit breaks, broken-off slices or may in some instances (especially in the brittle zone) be fragmented (Figure 3b). The missing pieces and free surfaces with possibly high conductivity have the potential to introduce artefacts into the DEP record. These are clearly identifiable in the permittivity record by dropping spikes. For the validation of the data, any drop in permittivity below a certain threshold (cf. the red line in Figure 4) identifies a spike to be rejected, where the segment to be rejected is extended ~~to about the~~ from the spike to where the signal approaches the average of the permittivity record. The procedure is automated procedure as described in Rasmussen et al. (2013) . This automated validation (section 2.3) is much fasterand comparably good as the standard way of noting deficient core sections in a field protocol, accessing each noted area on a single case basis and validating the data. It even does not depend on the quality of the protocol, as it might have a wrong note about depth of the ice cores breaks. In this way, it not only validates the permittivity record but also the conductivity record. The NEEM, the EGRIP and , more consistent in between the three different cores, and has proven to be superior to any approach based on a hand-written protocol, which depends on the NGRIP recordswere validated in this way.judgement of the operator when identifying intervals of bad core. As the permittivity is very sensitive to bad core quality and the conductivity is much less prone to bad core quality, the outlined validation procedure leads to a robustly validated conductivity record.

The automated validation straight forwardly leads to a definition of a core quality index $Q \in [0,1]$ by calculating the total length of validated core sections divided by the standard DEP and ECM run lengths of 1.65 m for all three cores. For the EGRIP core, the core quality indices as derived from the DEP and ECM records, respectively, are presented in Fig. 8.

At this point, the DEP data is not yet corrected for the temperature variation in the science trench or core-buffer, however this correction does not affect the use of conductivity peaks for synchronization purposes between ice cores.

When processing the EGRIP core, over a certain period the operators erroneously did not reset the starting position of the scanning electrode of the DEP device, which . This is clearly identifiable in the records . It resulted in measuring too early before the starting position and resulted in recording already ahead of the core's top depth (blue arrows in Figure 5), then recording the correct length increment, but resultingly taking measurements over the (correctly set) length of the section, but missing the corresponding length at the bottom end of the core section. The respective core section has to be shifted accordinglysections have been shifted accordingly, but the missing end sections, which were not recorded, cannot be recovered. The reconstructed DEP record was then compared and validated against the ECM record to assign the correct depths. The section about 1285–1385m was corrected in this way, where in total about 8.5 m of the 100 m were not measured. Furthermore, we relied more heavily on the ECM record than on the DEP record in when matching peaks within sections with known problems. Figure 5 illustrates the corrections in the interval 1299.10–1302.05 m, where a 35 cm data gap between two scanned sections cannot be reconstructed as it was not recorded due to the wrong positioning of the electrode.

2.2.2 Electrical conductivity measurements (ECM)

For the EGRIP core, we recorded ECM profiles with the technique described by Hammer (1980) directly in the field. The ECM signal is related to acidity concentrations of ice cores, even with high concentrations of neutral salt (Moore et al., 1992). NGRIP (Dahl-Jensen et al., 2002) and NEEM (Rasmussen et al., 2013) were measured using identical similar equipment during the respective processing campaigns in the field. For each measurement, the hand-held hand-dragged ECM instrument was moved along the depth axis of the ice-core sections' microtomed microtome-polished surface (three-bag sections, around about 1.65 m long). In order to calibrate the ECM data, as described in Rasmussen et al. (2013), the ice temperature was measured for each run. In addition, to ensure the ECM quality, we repeated our measurement at least twice for each core section and checked the profiles for the best quality of the measurements. Also, the core breaks were registered by reading out the positions of

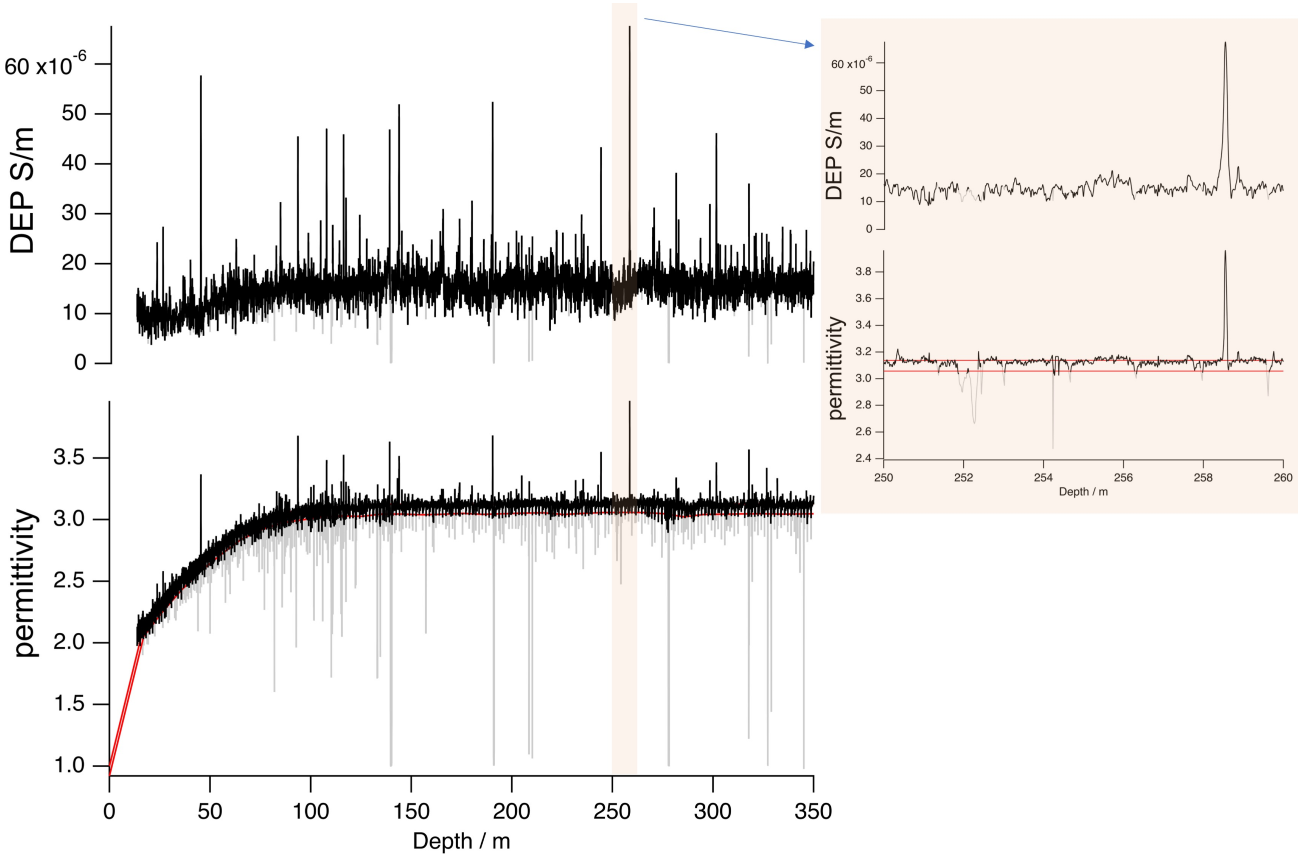

Figure 4. Example of DEP data processing (removing core breaks from the raw data). ~~The permittivity measurement~~ Raw data is plotted in grey and ~~after processing~~ validated data in black~~(bottom)~~. ~~The~~ We define insufficient data by permittivity drops below the threshold (indicated by the red line) and ~~shows bad quality of ice-core sections~~reject it during validation. ~~As seen above (~~Permittivity is presented in the top ~~),~~ ~~corresponding conductivity before processing data (grey)~~ and ~~after processing data (black)~~conductivity in the bottom diagram. The insert shows the details for a short section (250–260 m).

~~the hand-held ECM instrument at~~ core-break positions were registered along with measurement by moving the electrodes of the ECM instrument to the respective break position after the ~~measurement of each core section~~core scan, and registering the position in the data file. During the processing, ~~the recorded breaks~~ these recorded break marks were used to trim off artefacts and produce the ~~used~~ final ECM data set. Data from each day were calibrated using independent measurements of the physical dimensions of the ECM measurement setup. The first and last few millimetres of recorded data are affected by the proximity to the end of the core and were removed. Areas with dips in the signal around logged core breaks were also muted during processing. ~~The depth scale of the ECM profile was assigned based on the recorded movement of the electrodes interpolated between the logged top and bottom depth of individual ice-core sections. To investigate the quality of the depth assignment, a bag mark position analysis was carried out on~~ Details on the acquisition and processing of the ~~section below the brittle zone~~

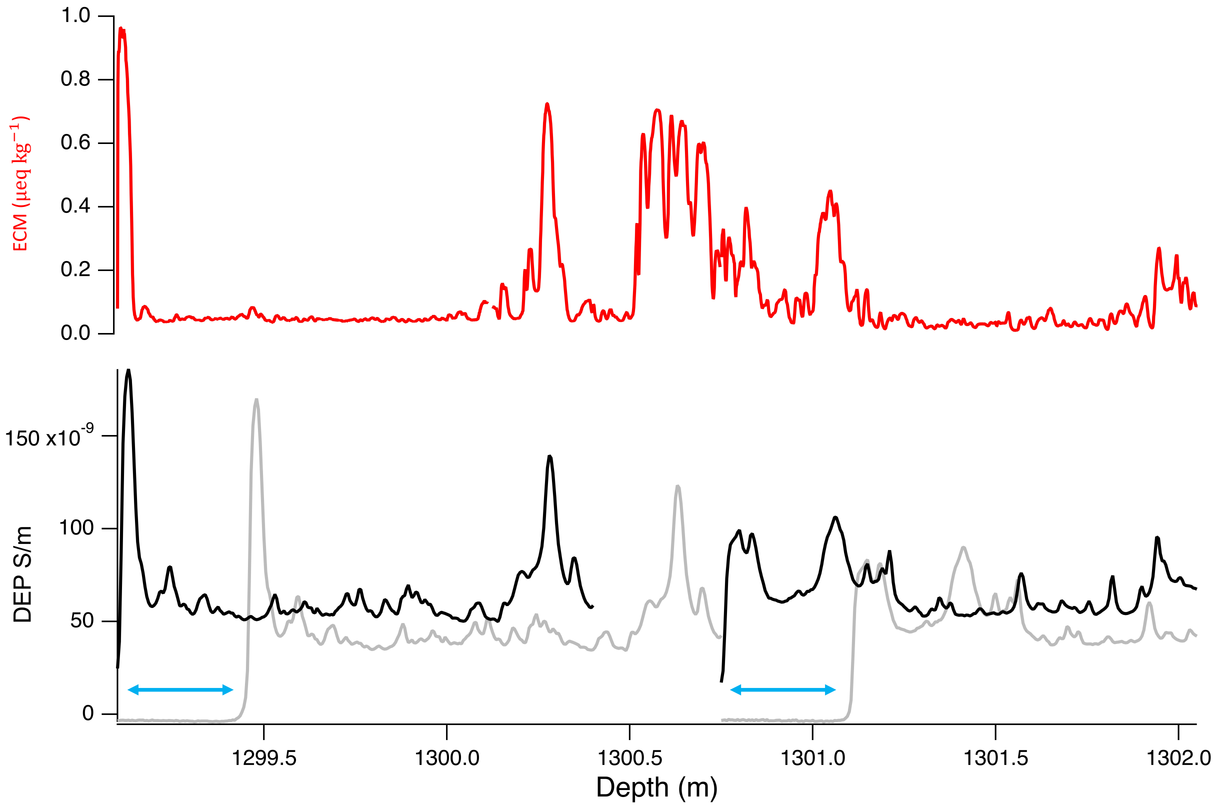

Figure 5. Example of the DEP data gap length and relative precision of ECM vs DEP depth assignment. The DEP measurement with a wrong depth in grey and after shifting depth in black. There is a gap of 35 cm (1300.4–1300.75 m) between two DEP measurements. Blue arrows show the early measurements before the starting position of the core. Corresponding ECM data in red.

in EGRIP, ∼1160–1760 m. Only ice core sections with a core length of 1.65 m were included in the analysis. Each 1.65 m section contains the equivalent of three 0.55 m bags, and the position of the bag marks separating the first and second bags and the second and third bags, respectively, are known. During ECM measurements, these bag marks are logged (just as the break marks), but not used for the processing. After processing of the ECM signal, the position of logged bag marks were interpolated onto the same depth scale as the processed ECM signal, making it possible to compare the true depth of these marks to their depths in the processed data. The distance in depth between logged and expected positions of individual bag marks were calculated for all sections included in the analysis. It was found that the depth assignment of the bag marks were almost always accurate within 20 mm, with mean distance $\mu = 8.3$ mm and standard deviation $\sigma = 7.9$ mm. The ECM record are laid out in Appendix C "Details on the ECM procedures".

The ECM current, i (in μA), was converted to ice acidity (in μequiv. $H^{+}kg^{-1}$) by using the relationship $[H^{+}] = 0.045 \times i^{1.73}$, as suggested by Hammer (1980). Even though conversion from current to acidity and calibration curves have been shown to be ice-core dependent, the matching and synchronization of the ice cores is independent of the absolute values of the calibrated ECM signal as it relies on recognition of similar patterns and peaks in the acidity records (Rasmussen et al., 2013).

The quality of the processed data were checked by comparing independently processed ECM data by three investigators. No major disagreements were found when comparing, and one set of data was agreed on for further use in matching.

2.2.3 Tephra horizons

~~Tephra sampling of the EGRIP core~~ The EGRIP core was continuously sampled for tephra analysis in the field ~~was continuous~~ to maximize the ~~identification~~ probability for detection of volcanic ash deposits, particularly invisible deposits that ~~are comprised of~~ exhibit low concentrations and/or small grain sizes, known as cryptotephra (Davies, 2015). ~~A strip~~ An aliquot of ice was ~~cut~~ prepared from the outer curved edge of each 55 cm ice core section and subsampled at ~~a~~ 11 cm resolution, providing approximately 30 ml of meltwater per sample. ~~Of these, sections of ice that contained~~ Samples from sections with either significant peaks (Figure 3f) in the DEP and ECM or visible layers were separated and prioritized for screening, whereby centrifuged samples were evaporated onto frosted glass microscope slides and ~~mounted~~ covered in epoxy resin to enable scanning by high-magnification light microscopy, as described by Cook et al. (2018). Electron probe ~~microanalysis~~ micro-analysis (EPMA) by wavelength dispersive spectrometry (WDS) was performed to determine the major element ~~compositions~~ composition of individual grains in each deposit (Hayward, 2012) and EPMA measurements were performed using a Cameca SX100 electron probe microanalyzer at the Tephrochronology Analytical Unit, University of Edinburgh. This system has five wave dispersive (WD) spectrometers and was calibrated daily using internal calibration standards as described by Hayward (2012). ~~Operating conditions were optimized for~~ With optimized instrument settings for the analysis of small cryptotephra grains (<20 μm diameter)~~and~~ , EGRIP samples were analysed with either a 5 or 3 μm beam diameter. ~~Analysis of secondary standards was performed to identify instrumental~~ Secondary standards were analysed to capture instrument drift. The geochemical composition of each layer was compared to deposits in NGRIP and positive matches were used to establish the independent tie-points ~~between cores shown~~ in between cores listed in Table 1. Major element biplots (Figure 6) show graphical correlations for each NGRIP–EGRIP tephra match point, and these are supported by similarity coefficient (Borchardt et al., 1972) and statistical distance (D^2) (Perkins et al., 1995, 1998) tests.

Table 1. Geochemical matches between EGRIP and NGRIP were supported by the similarity coefficient test (SC) of Borchardt et al. (1972) and statistical distance (D2) test of Perkins et al. (1995, 1998). Here we provide SC and D2 values for major elements (normalized to 100%) where 5 major elements (with >%1wt) were used for SC calculations for sample pairs with rhyolitic composition and 7 elements were used for sample pairs with basaltic composition. Values >0.95 suggest products are from the same volcanic source. For D2, seven major elements were used for the comparisons (with >0.01 %wt). The value for testing the statistical distance values at the 99% confidence interval is 18.48 (seven degrees of freedom).

EGRIP Bag	Depth range	NGRIP /GRIP match	SC	D^2
177	96.91–97.02 m	NGRIP 142.61–142.71 m	0.985	1.65
1627	894.41–894.52 m	NGRIP 1163.65–1163.80 m	0.977	4.88
2094	1151.59–1151.70 m	NGRIP 1408.88–1408.89 m (Mortensen et al., 2005)	0.965	5.945

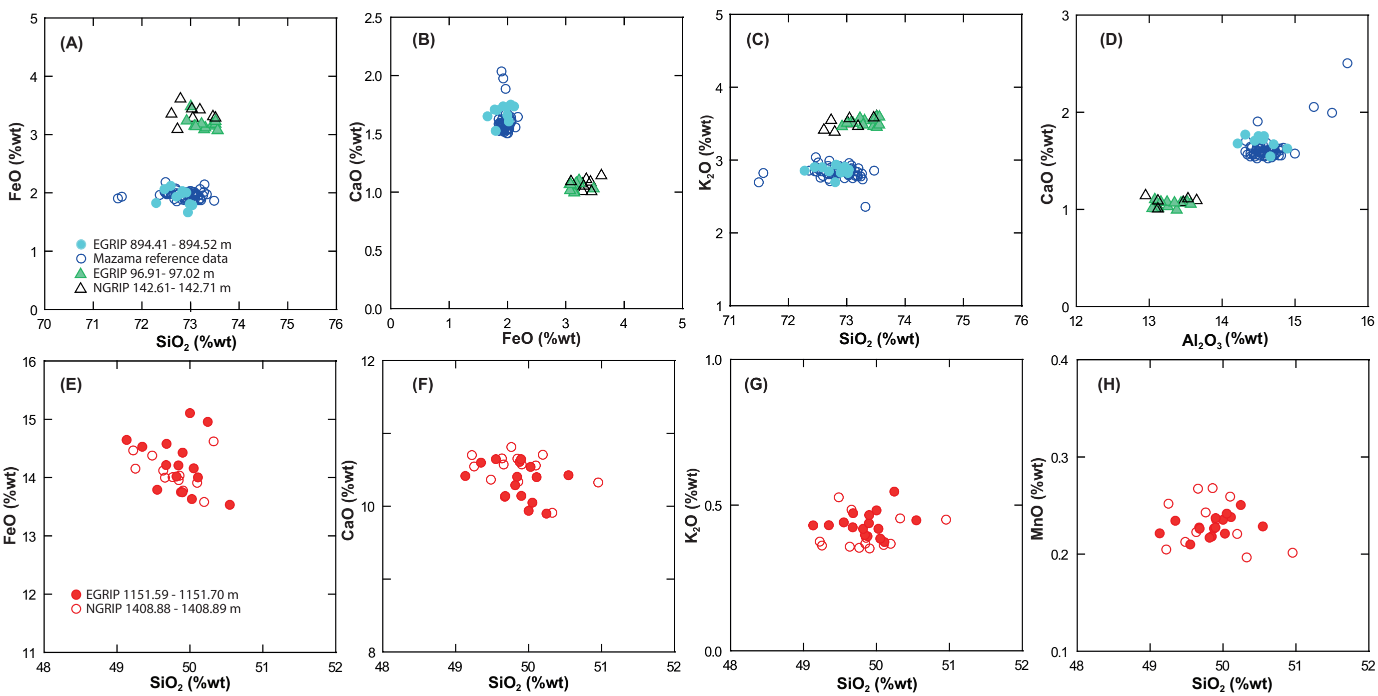

Figure 6. Element–element biplots showing geochemical matches between EGRIP and NGRIP samples with the exception of EGRIP 894.41–894.52 m (EGRIP bag 1627), which is shown here with Mazama data from Jensen et al. (2019). Geochemical data are normalised to 100% (anhydrous basis) and analyses with totals below 94 %wt were excluded. Plates (A–D) for EGRIP bags 177 and 1627, Plates (E–H) for EGRIP bag 2094.

2.3 Synchronization of dielectric profiling and electrical conductivity measurement records of the ice coresEGRIP, NGRIP, NEEM

Patterns in the DEP and records of NGRIP, NEEM and EGRIP were initially matched by one investigator. The same cores' ECM data were matched between ice cores separately and independently , by three different investigators. Both matches are mainly based on the volcanic events and also non-volcanic events clearly identifiable volcanic peaks and also synchronous patterns of other events (see Fig. 7), which not necessarily need to be of volcanic origin, but are assumed to reflect synchronous events. Based on these independent matches, the four investigators identified consistent and reliable common patterns, that are represented in the ECM and/or the DEP records from NGRIP and at least one of the other ice cores. All sections were matched between NGRIP, NEEM and EGRIP synchronously, meaning all three ice coreshad been combined on the screen. To finalize For the confirmation of match points, common patterns were selected and confirmed with all records of all three cores were loaded into the Matchmaker tool (Rasmussen et al., 2013) and assessed jointly by all four investigators for each dataset. In order to find match points between ice cores, we used the Matchmaker tool (Rasmussen et al., 2013) that can track offset match points during matching phases when aligning and evaluating data. The most sensitive test to in the different display options featured by the software. The Matchmaker tool allows easy identification of wrong match points via interactive plots and on-line evaluation of the match. To validate match pointsis to plot the depth of , we plot the depths of the common match points for two ice cores, $\Delta D(i) = D(i) - D(i+1)$$D_i$ (in EGRIP or NEEM) against d_i (NGRIP). The slope of each of these (depth, depth)-curves is the annual layer thickness ratio of the two cores, $\Delta d(i) = d(i) - d(i+1)$ and the ratio $r = \Delta D(i)/\Delta d(i)$ of annual layer thicknesses, where D and d are the depths of the common volcanic or non-volcanic events in two different cores$r_i = \frac{D_{i+1}-D_i}{d_{i+1}-d_i}$. Points which deviate from the (depth, depth) curve or create jumps in r, are easily recognized and checked again. We only expect significant abrupt changes in r at times where the climate (and thus the relative accumulation rates) shifts due to changes in climate conditions (Rasmussen et al., 2006, 2013; Seierstad et al., 2014; Winski et al., 2019), while the different ice-flow patterns at the cores' sites only lead to slow changes in r. We expected only significant change in

Short-term accumulation variability due to both climatic factors and wind-driven redistribution of snow on the surface can lead to relatively large variations in the ratio of layer thicknesses between different cores, especially when match points are only a few years apart. To reduce short-term accumulation-rate variability in the final timescale, we re-evaluated intervals with large variability in annual-layer-thickness ratios, and removed too closely spaced match points. The final minimum distance between match points is 0.22 m (1206.45m-1206.67m), corresponding to around 3 years. Overall, the smoothness of the (depth vs. depth) curve of match points with different climate conditions and climate transitions in ice-core sections (Rasmussen et al., 2006, 2013; Seierstad et al., 2014; Winski et al., 2019). Furthermore, these tests are provided to investigate our results based on glaciologically realistic outcomes, for example, the different ice-flow pattern and accumulation regimes at the different sites in Greenland (Rasmussen et al., 2013)match points are reasonably evenly distributed throughout the entire ice core, and the maximum distance between neighbouring match points is 26.6 m (490.06 m – 516.67 m), corresponding to a time interval of 224 years.

2.4 Transfer of the GICC05 timescale to the EGRIP ice core

The procedure of transferring the timescale is similar to the approach described in (Rasmussen et al., 2013). Note that we hereby assume that the ratio of annual layer thicknesses is constant between the match points of EGRIP and NGRIP. For each 0.55 m EGRIP depth segment (the so-called *bag*), we obtain the equivalent NGRIP depth by linear interpolation between the depths of the match points D_i in EGRIP and d_i in NGRIP. We then assign a GICC05 age from the annually resolved GICC05 time scale for NGRIP (Vinther et al., 2006; Rasmussen et al., 2006).

We transferred the The EGRIP timescale inherits the maximum counting error (MCE) from the GICC05 time scale to the EGRIP ice core by interpolation between match points for each ice core bag (i. e.,0.55 m depth intervals). First, we assumed a slight timescale. Our match covers the time period back to 14,967 a b2k where the associated MCE is 196 a. The inaccuracies in the depth registration were estimated by (Rasmussen et al., 2013) to 10 cm (1σ). For the joint assignment of DEP and ECM patterns, we repeat the assessment by (Rasmussen et al., 2013) for the (EGRIP depth, NGRIP depth) relation by computing the difference δ_i between each EGRIP match point and the linear interpolated depth derived from the neighbouring points $\delta_i = (D_{i+1} - D_{i-1})/(d_{i+1} - d_{i-1}) * (d_i - d_{i-1}) + D_{i-1} - D_i$, thus merging all match points between EGRIP and NGRIP1 and EGRIP and NGRIP2 into one data set of 377 of the originally 381 match points for further statistical analysis. The difference in number occurs as δ is not defined for respective start and end points of both respective sequences. The statistical analysis of δ in Appendix D yields a standard deviation of 0.043 m for the depth assignment of a match point. As the annual layer thickness variation between the ice cores based on the reasonable assumption of accumulation variability and from the smoothness curve of the depth of common match points(see section 2.3). Therefore, the EGRIP depths were transferred to NGRIP depths by linear interpolation between match points typically exceeds 0.04 m in the time period considered here, one expects an additional uncertainty for the peak assignment in the order of 1 yr.

Larger errors would occur in the case of erroneously matched sections as discussed in (Rasmussen et al., 2013), but wrong matches are even more unlikely here than in previous work, as three instead of two cores were matched and *ibid.* the authors also point out that erroneously matched sections are particularly relevant for the older part of the core, where the discussion here covers a section with comparably plentiful match points. By this approach, the ages are obtained from the GICC05

2.4.1 Precision and accuracy of the time-scale transfer

The central mode of the (depth, depth)-differences δ as defined above follows a Gaussian normal distribution with a standard deviation of 0.043 m (see Appendix D). This demonstrates that the synchronization ties two cores together at the match points with high precision. Besides the central Gaussian normal distribution, the statistical analysis of δ identifies an overlaid second Gaussian normal distribution with a standard deviation of 0.19 m. We interpret this distribution as stemming from curvature of the (depth, age)relation based on NGRIP depths (Rasmussen et al., 2013). depth)-curve and as indicative of the average amount of detail, that each point contributes to the description of this curvature. As this difference between the actual match point and the linear interpolation between the neighbouring points depends on the variable curvature of the (depth, depth)-curve, which reflects both accumulation conditions and the evolution of glaciological conditions at both coring sites, the values of δ will generally be time correlated and cannot be expected to be randomly distributed with depth. We thus estimate that the EGRIP time scale may have time-correlated uncertainties relative to NGRIP of up to a handful of years related to changes in relative accumulation variability and ice-flow conditions not captured by the match points. This uncertainty will be largest in time periods far from the match points and near climatic shifts where the accumulation changed abruptly and not necessarily by the same ratio at different ice coring sites.

Now we assess the combined uncertainties. The GICC05 includes the so-called Maximum Counting Error (MCE)in which the uncertain layers are counted as 1/2 ± 1/2 yr (Rasmussen et al., 2013). We timescale $t(D)$ inherits the associated maximum counting error from GICC05, and given the analysis of δ above, we conclude that, at the match points, the time scale is precise relative to NGRIP within about one year (1σ). However, when we want to know the age at an arbitrary EGRIP depth, additional uncertainties apply due to the interpolation between the match points. There are two dominant sources: As discussed above, variations in relative accumulation rates and ice flow may add up to a handful of years of additional uncertainty relative to GICC05, but there is also a contribution from the choice of interpolation scheme in between the match points. The difference introduced by the choice between the most widely used linear and cubic spline interpolations to estimate uncertainty and precision of the interpolated timescale between interpolation schemes (Press et al., 1992) is about an order of magnitude larger than the above-mentioned random uncertainty associated with the identification of the match points (see Appendix E).

We maintain linear interpolation for the time scale transfer despite the fact that the slope of the (depth, depth) curve changes instantaneously at the match points. While changes in this slope may in reality occur on many scales due to the intermittency of precipitation, wind-driven redistribution of snow, and relative changes in accumulation rates at the sites, the most significant of these changes are likely to happen at times of climate change rather than at the arbitrary depths of the match points. Considering this, one could consider an interpolation scheme where the change of curvature is distributed over the entire curve and/or concentrated at times of climate changes as derived from the proxies of the ice core. However, we believe that the advantage of obtaining a smoother (depth, depth)-curve does not compare favourably to the additional assumptions needed and the added complexity of the time-scale transfer.

3 Results and discussion

3.1 Synchronization of the EGRIP, NEEM and NGRIP cores

A total of 249 257 match points between the EGRIP, NEEM and NGRIP1 ice cores and 124 match points between EGRIP, NEEM and NGRIP2 (total of 373 381 match points) with an additional three tephra horizons were identified. Figure 7 shows an example section of ECM/DEP records matched between ice cores. The total match points between the ice cores are shown on Figure 8. In the process of combining match points from all investigators, some match points were removed due to differences in the peak shapes between DEP and ECM data or when there were too many match points very close to each other. There are fewer match points in the interval 600–1100 m due to the brittle zonein sections in , which in particular influences the NEEM and NGRIP1 . The sections of alkaline ice associated with stadial conditions in EGRIP where the cores. The ECM and DEP do not follow each other closely in the 1245–1283 m interval because of the alkaline nature of the ice associated with stadial conditions in EGRIP. This is due to high dust levels neutralizing the acidity of the ice (Ruth et al., 2003; Rasmussen et al., 2013).

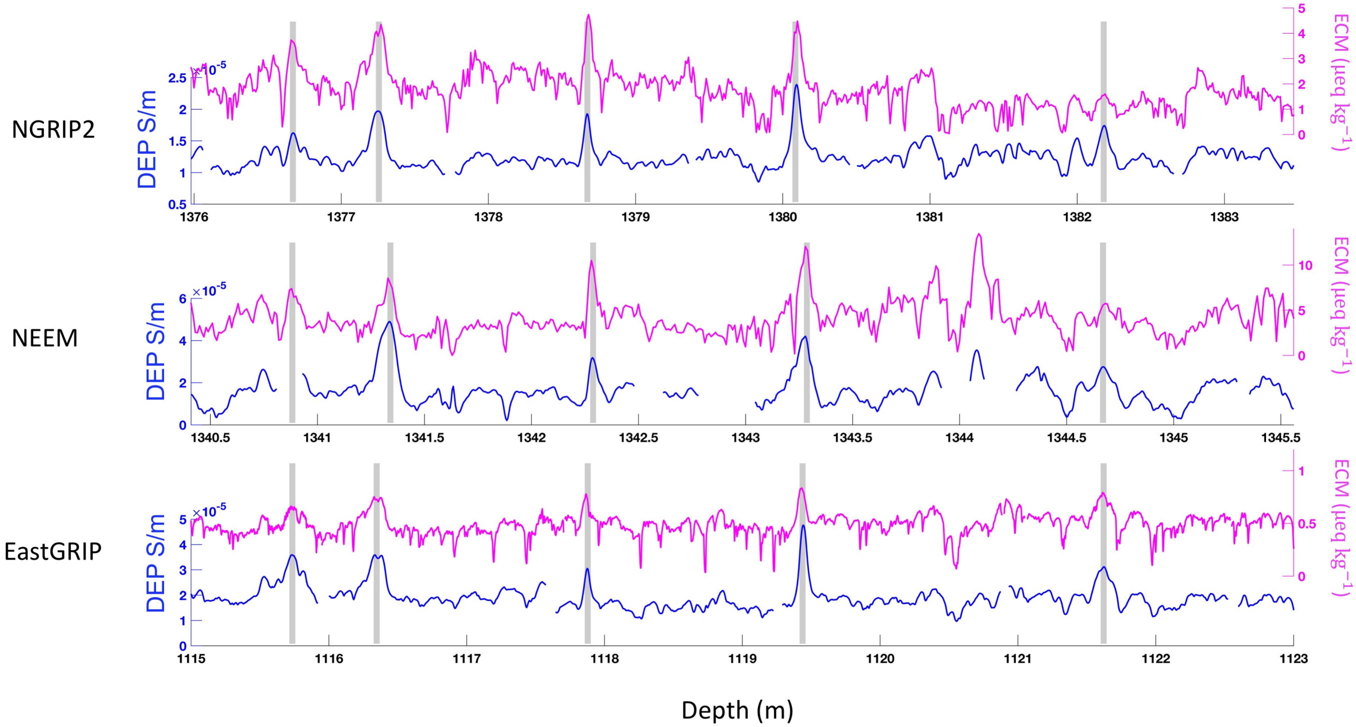

Figure 7. Example of the ECM and DEP data ~~matching~~ match between the NGRIP2 (top), NEEM (middle) and EGRIP (bottom) cores. The match points are marked by grey bands.

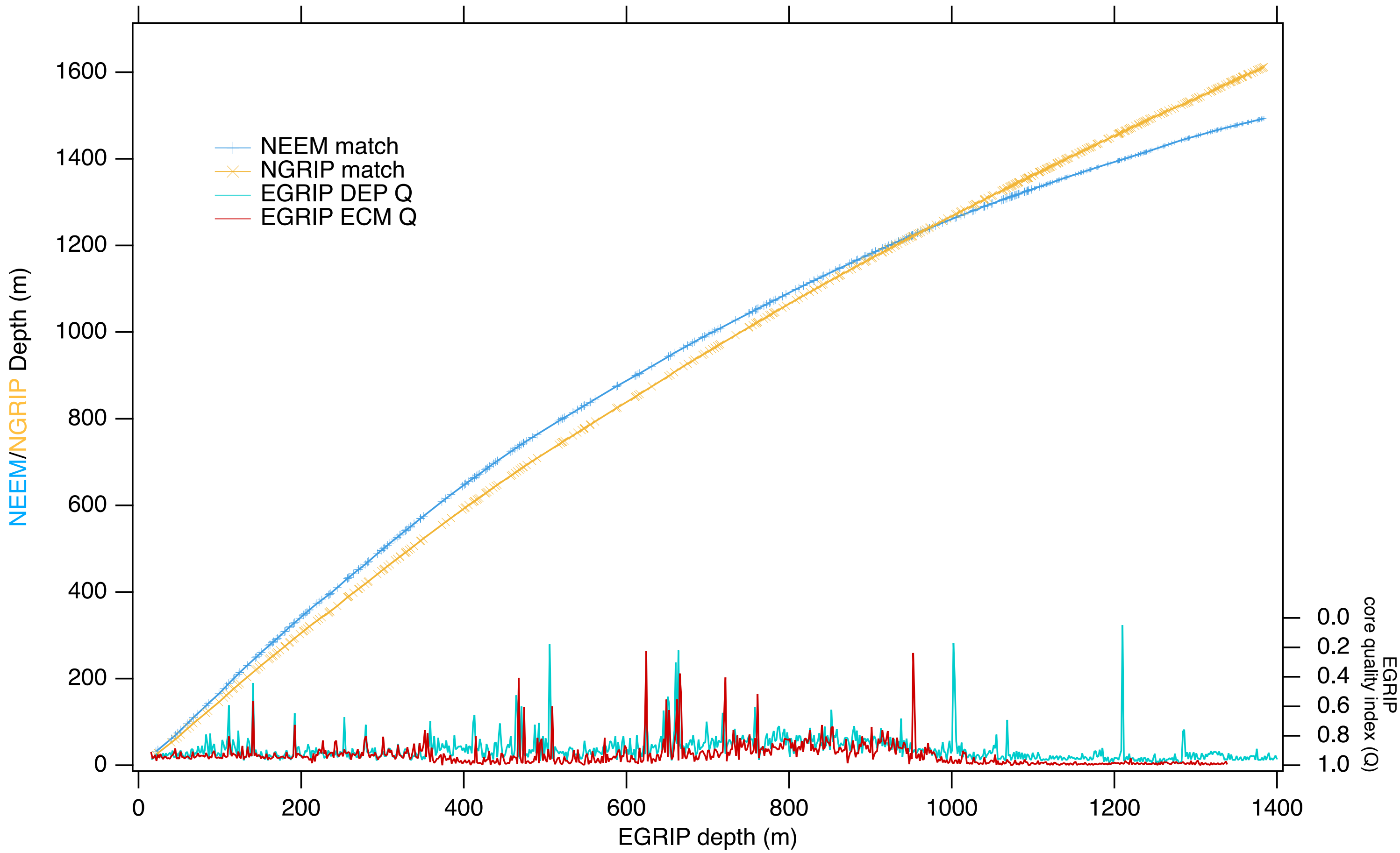

Figure 8. Match points between EGRIP, NEEM (blue) and NGRIP (yellow) ice cores based on the DEP and ECM data sets. The core quality index Q as derived from the validated DEP and ECM data, respectively.

3.2 Tephra horizons identified for the chronology

Three tephra horizons have been located in EGRIP (Table 1). The locations of these horizons were consistent with the DEP and ECM based synchronization. The tephra horizons thus provide an independent validation for our match points. In addition, ongoing tephra investigations will likely provide additional points for synchronization between ice cores in intervals without DEP and ECM match points.

3.3 GICC05-EGRIP-1

As described in section 2.4, the ~~timescale was transferred from the NGRIP~~ GICC05 (depth, age) timescale was transferred from the NGRIP to the EGRIP ice core based on ~~373~~ 381 match points. ~~The~~ We name the relationship between depth and age for EGRIP over the Holocene and early last glacial periods ~~is named~~ GICC05-EGRIP-1 and present the average annual layer thickness between the match points ~~is presented (~~in Figure 9~~)~~.

We synchronized the records of the ~~EGRIP, NEEM and NGRIP~~ ice cores back to 14.96 ka b2k which corresponds to EGRIP depth 1383.84 m, NEEM depth 1493.29 m~~and~~ , and NGRIP2 depth 1611.98 m~~depth, respectively. Note that we assumed that the ratio of annual layer thicknesses is constant~~ . Along with this publication we release a time scale for each 0.55 m section ("bag"). For each EGRIP depth, the corresponding NGRIP depth was found by linear interpolation between the match points~~of EGRIP and NGRIP. The depths in NGRIP of the match points were interpolated to the EGRIP, and then the ages are obtained from the NGRIP~~ , and the GICC05 ~~(depth, age) relation. We used different methods of interpolation~~ age was then determined from the published GICC05 time scale for NGRIP. The maximal uncertainty resulting from the choice of interpolation scheme is assessed in detail (see Appendix E1) and is about four years. The relatively smooth (~~linear vs. cubic spline interpolation) between match points to estimate the uncertainty of these different interpolations. The difference in result is around 0–2 yr for most sections. Therefore, obtaining the age directly from the EGRIP (~~depth, ~~age) with the assumption of constant~~ depth) relation of EGRIP–NGRIP and EGRIP–NEEM (see Figure 8) shows that the ratios of annual layer thicknesses between ~~match points and interpolating ages~~ cores do not vary noticeably between match points~~provide different results and that is an unrealistic pattern for the accumulation rates (Rasmussen et al., 2013). The smooth relationship between the depths of the EGRIP and the NEEM respectively NGRIP depths match points is due to the smooth change of relative annual layer thicknesses.~~ . Figure 10 shows that EGRIP has thinner annual layers than both NEEM and NGRIP ice cores ~~when the upper part of the three records are compared. This is because lower accumulation leads to thinner annual layers. Due to increasing upstreamaccumulation rates and less thinning at EGRIP compared to NGRIP and NEEM~~in the upper parts of the cores as also expected from the lower surface accumulation. Ice found in the EGRIP core originates from snow that was accumulating upstream, and accumulation rates increase upstream as the flow line approaches GRIP and NGRIP, where present-day accumulation is about twice of that at EGRIP (Vallelonga et al., 2014; Riverman et al., 2019; Karlsson et al., 2020) . Surprisingly, annual layers in EGRIP ~~eventually gets thicker with depth compared to annual layers in~~ remain almost constant back to 8 ka b2k (Figure 9), while the layer thicknesses in large parts of the Holocene part of the NGRIP and NEEM cores thin linearly due to ice flow. We believe that it is a coincidence that the ~~NEEM and NGRIP ice cores . In EGRIP, the flow regime is different, compared to an ice core close to the ice divide like NEEM and NGRIP. By pure coincidence the~~ combined effects of the increasing upstream accumulation and flow-induced thinning ~~give roughly constant annual layer thicknesses back to ∼ 8000 yr in EGRIP~~ at EGRIP balance out for the last 8 ka. Despite the lower accumulation at EGRIP, annual layers in EGRIP eventually get thicker than the annual layers in the NEEM and NGRIP ice cores. ~~(Figure 9). The accumulation upstream is supposedly higher than at the EGRIPsite and thus as older ice comes from upstream and had more time to thin the annual layers become equal thickness in the EGRIP ice core. In most ice cores in the proximity of ice divides, the annual layer thickness drops almost linearly with depth for the Holocene part of the record. As NGRIP and NEEM layers get thinner in this way (Rasmussen et al., 2013), EGRIP layers start to get thinner but remains nearly constant in thickness.~~ Below an EGRIP depth of around 700 m, annual layers in EGRIP are thicker than the layers from the same period in the NEEM core, and similarly below 1000 m, EGRIP annual layers are thicker than those in NGRIP (Figure 10).

There are some gaps in the EGRIP ice-core record due to the brittle zone. However, we believe the smoothness of the depth vs. depth plot in Figure 8 and the annual layer thickness ratio in Figure 10 shows a good agreement for robustly support our time scale based on the match points. As described in section 2.4, the uncertainty of the GICC05-EGRIP-1 timescale is based on the maximum counting error (MCE) of the GICC05 timescale. When more annual layer data become available it can provide more details for the EGRIP ice coreand the time scale can be improved by layer counting .

EGRIP annual layer thicknesses (dark blue line, left y-axis) between the match points. The EGRIP depth–age relationship (right y-axis) with match points (red dots) and the tephra horizons (black squares).

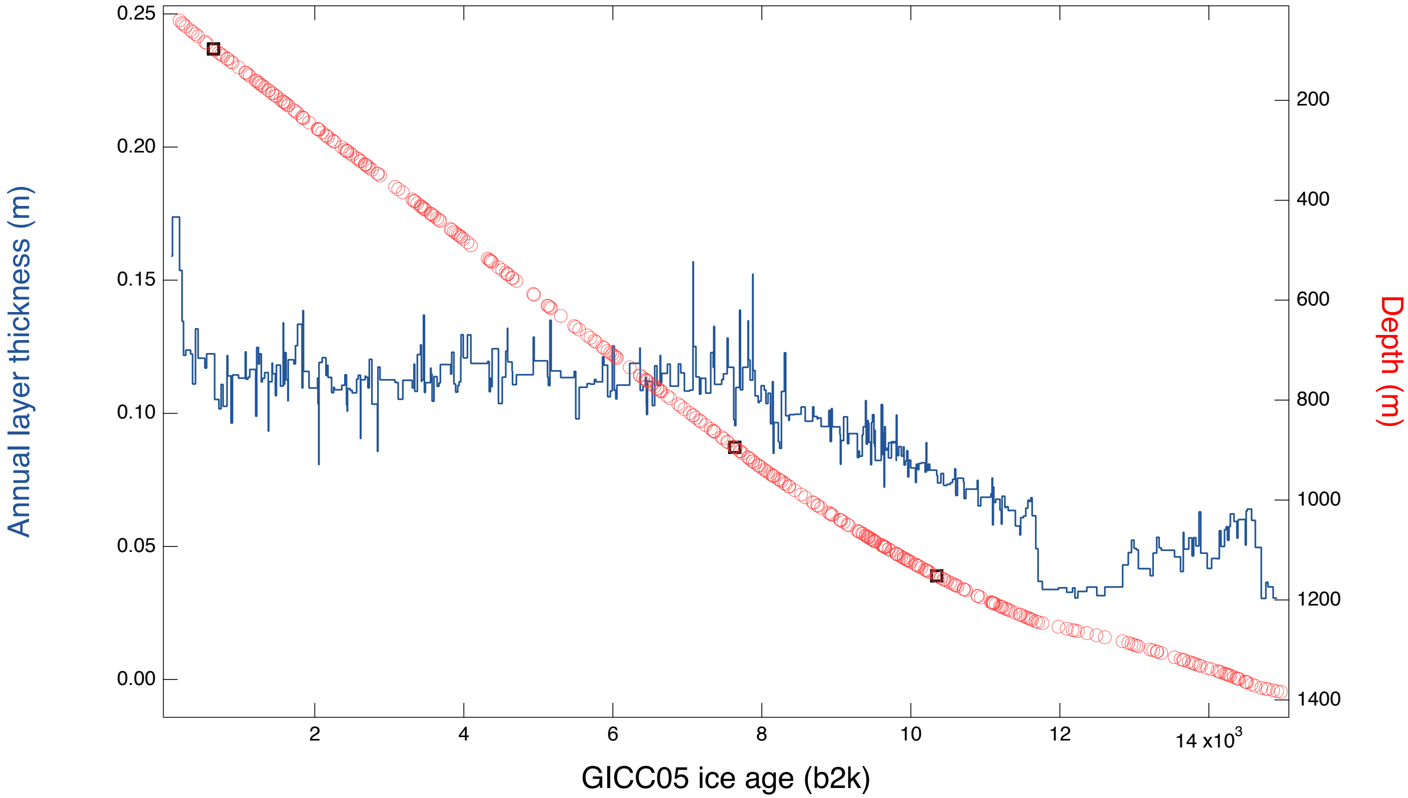

Figure 9. Average EGRIP annual layer thicknesses (dark blue line, left y-axis) between the match points. The EGRIP depth–age relationship (right y-axis) with match points (red dots) and the tephra horizons (black squares).

~~The NGRIP/EGRIP (orange) and NEEM/EGRIP (blue) annual-layer thickness ratio (left axis) between the match points.~~

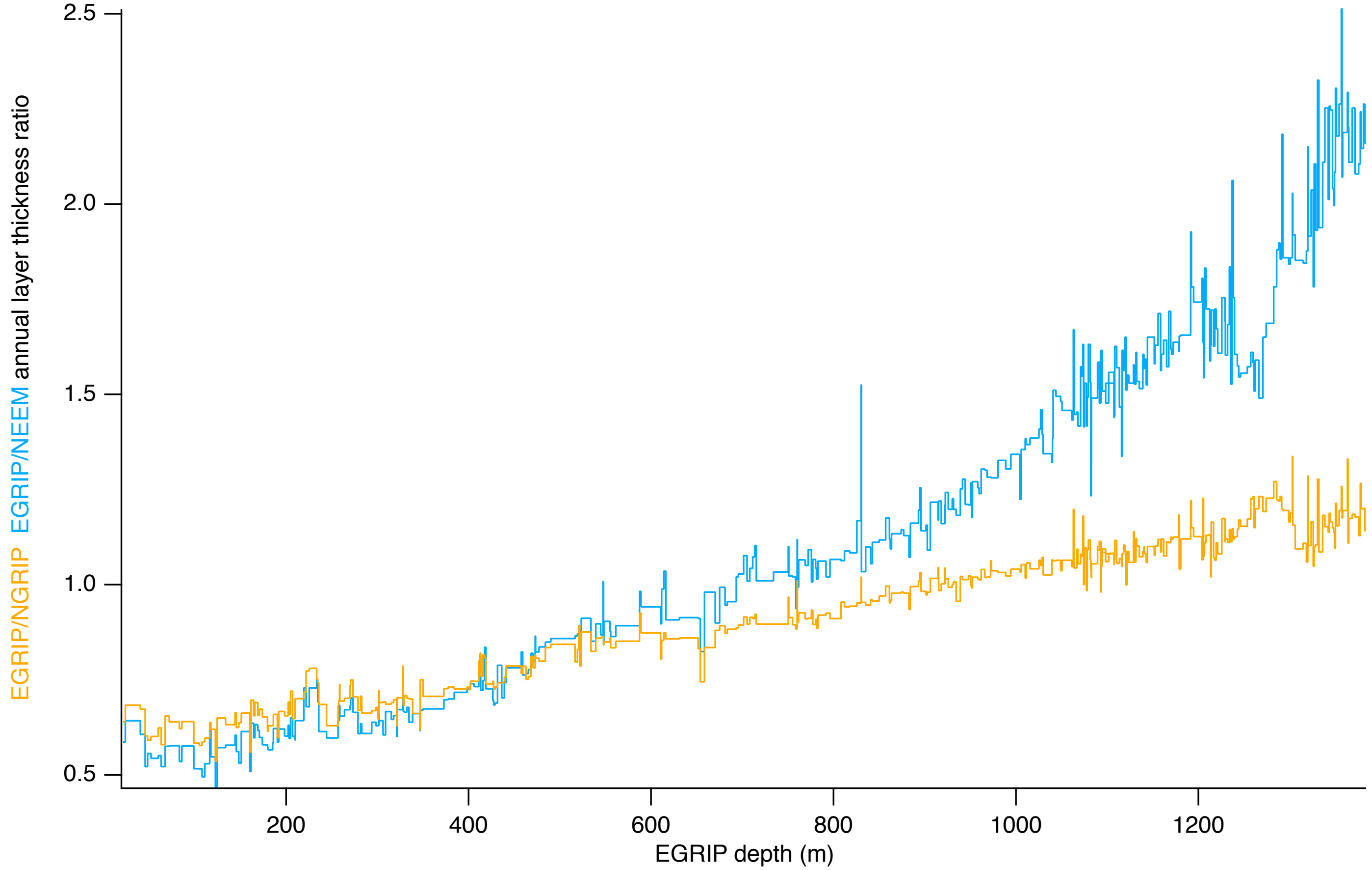

Figure 10. The EGRIP/NGRIP (orange) and EGRIP/NEEM (blue) annual-layer thickness ratio (left axis) calculated between neighbouring match points.

3.4 Error analysis for the timescale transfer

We statistically treated the "leave-out analysis" (δ), which was already used in previous papers (Rasmussen et al., 2013) to estimate the uncertainty in match points. Binning the values revealed a robust mode that refers the statistical error of the match point assignment. The tails of the distribution relate to more curved intervals of the core. Cubic spline interpolation provides a similar estimate. However, when matching depths, we neither know the true curve nor how big the influence from the interpolation scheme is. We demonstrated that the two fundamentally different interpolation schemes of linear and cubic spline interpolation give a consistent result. The δ give qualitatively a similar pattern as the high-resolution difference of the interpolation schemes and has demonstrated its suitability to estimate the uncertainty of the interpolation scheme. They deviate more than the statistical uncertainty of the match-point assignment, but this is less than the tenfold of the statistical error for peak identification and for the timescale here it introduces an error of up to 4 years, while the inherited maximum counting error of the timescale increases from about 1 year to 2 centuries over the matched record.

4 Conclusions

We have established the initial chronology for the EGRIP deep ice core in Greenland which encompasses the Holocene and late glacial periods. We have established the depth–age relation for the upper ∼ ~~1400~~ 1383.84 m of the core back to approximately 14.96 ka b2k based on the GICC05 time scale and labelled it GICC05-EGRIP-1. After field measurements and processing of the ice-core data, we ~~rely~~ relied on the DEP and ECM records for the synchronization, using ~~373~~ 381 match points between EGRIP, NEEM and NGRIP ice cores. The identification of tephra match points between the EGRIP and NGRIP ~~cores~~ core provide an independent tool for validating this synchronization. ~~The~~ We used the ratio of annual layer ~~thicknesses~~ thickness between ice cores ~~has been used~~ as a tool to evaluate our match points~~based on the different ice flow patterns and accumulation regimes in the different regions~~. This first timescale can help to interpret, design sampling strategies and improve ~~understanding of~~ the understanding of the forthcoming EGRIP data sets.

5 Supplementary data

With the final version of this paper we will publish the following data sets at www.pangaea.de and www.iceandclimate.dk/data:

~~– ECMdata from EGRIP in 1 mm resolution~~

– GICC05-EGRIP-1 time scale for the EGRIP ice core

– Specific conductivity measured with the dielectric profiling (DEP) technique on the EGRIP ice core, 13.77-1383.84 m depth

– Permittivity measured with the dielectric profiling (DEP) technique on the EGRIP ice core, 13.77-1383.84 m depth

– Concentration of hydrogen ions measured with the Electrical Conductivity Method (ECM) on the EGRIP ice core (down to 1383.84 m ~~). – DEPdata from EGRIP~~ depth)

– Specific conductivity measured with the dielectric profiling (DEP) technique on the NEEM ice core (down to ~~1383.84 m),~~ 1493.297 m depth)

– Permittivity measured with the dielectric profiling (DEP) technique on the NEEM ice core (down to 1493.297 m depth)

– Specific conductivity measured with the dielectric profiling (DEP) technique on the NGRIP1 ice core (down to 1372 m ~~) in 5 mmresolution. – The match points (including the tephra horizons depths) used for the time scale transfer. – The EGRIP (depth, age) relation in 0.55 m ("bag")resolution.~~ depth)

– Permittivity measured with the dielectric profiling (DEP) technique on the NGRIP1 ice core (down to 1372 m depth)

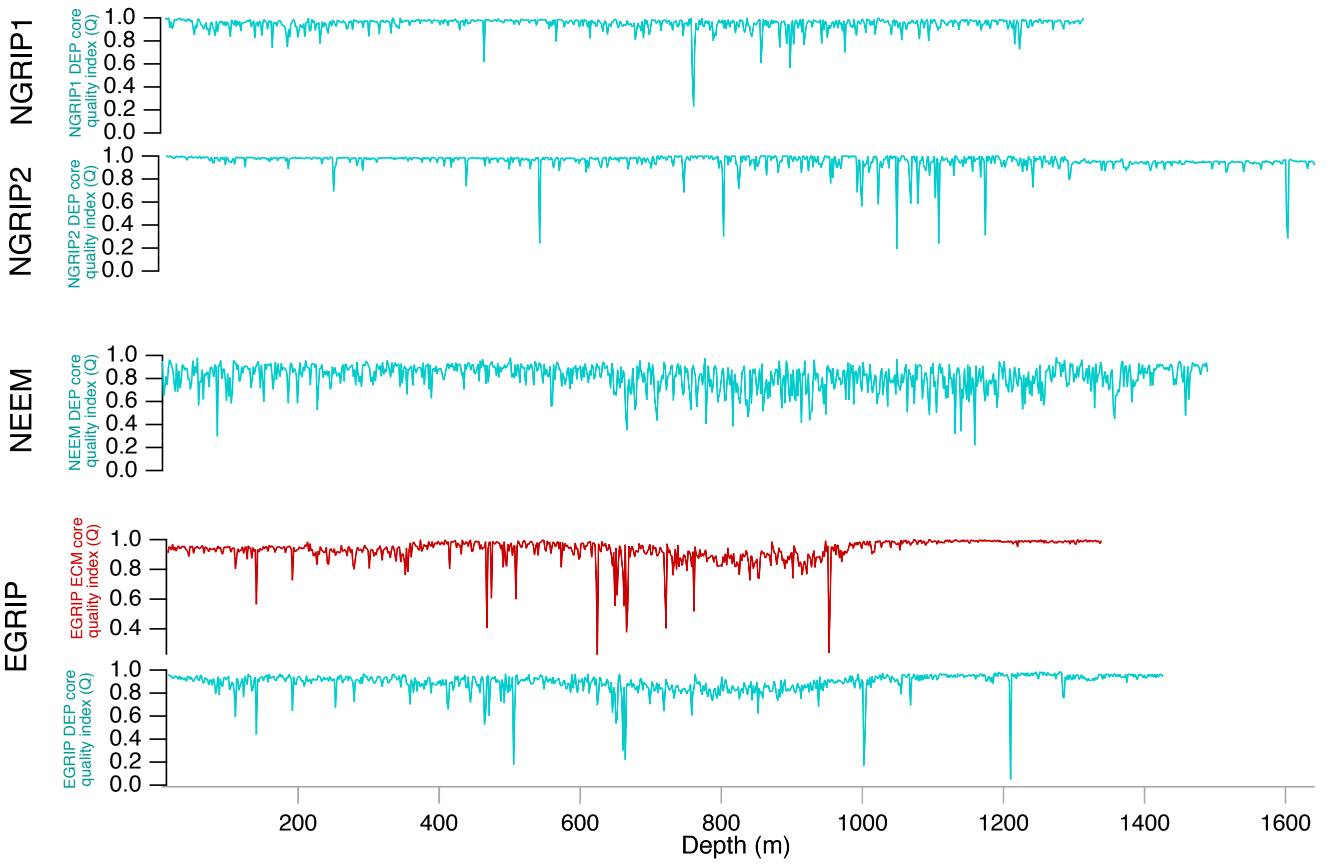

Figure A1. Quality indices for the EGRIP, NGRIP and NEEM ice cores.

Appendix A: Quality index for the NGRIP and NEEM ice cores

For the NEEM and NGRIP ice cores we calculated similar quality indices as provided for EGRIP above. They are presented together in Figure A1.

Appendix B: Calibration and corrections to the DEP data

As a correction in the few percent range we correct the offset, introduced by the changing stray admittance due to the varying cable geometry due to their movement during the measurement, by subtracting the course of free-air measurements from the respective measurement of a core section along the DEP device when processing the data. This is possible as the stray admittance is connected in electric series and is thus additive. This measure reduces coherent noise on the record, which is e.g. important when using the records for spectral analysis.

For the processing of the two NGRIP cores, reproducibility was ensured by laying the cables out to move freely in the same way for all measurements in between two recorded free-air measurements. This was improved for the NEEM and EGRIP processing by placing the cables into cable channels that enforce repeatable deformation.

For the calibration of the DEP device, free-air measurements without ice were recorded frequently, usually at least twice daily before processing started and finished. The slight capacitance and conductance variation on the order of less than 4 fF and 500 pS, thus corresponding to relative permittivity changes of 4 fF/63 fF = 0.06 and conductivity changes of (500 pS)/(63 fF)*(8.8542 pF) = 70 nS, along the DEP device is due to the unavoidable deformation of the cables (Figure 3a) when moving the scanning electrode along the device (Figure 3e)." Compared to the properties of pure glacier ice (ref. to Fig. 4) these variations are in the order of 2% for the permittivity and 5‰ for the conductivity. Additionally, an offset of few nS residual conductance may remain even after performing the correction routines of the LCR meter (inductance L, capacitance C, resistance R) bridge (Figure 3c).

As a further correction in the few percent range, we developed procedures to determine the true absolute free air-capacitance of the DEP capacitor. This is relevant when determining calibrated absolute values of the material properties: permittivity and conductivity. In the original publications (Wilhelms, 1996; Wilhelms et al., 1998) the proper calibration of the device is cross checked by comparison with the theoretical capacitance value of 63.4 fF, where for a precisely adjusted DEP bench, the free air capacitance coincides with in less than 2 fF. These small deviations from the theoretical value might well be due to mechanical tolerances like the electrode length in the range of a few tenths of a mm. However, for a slightly differently adjusted device (e.g. one with slightly more clearance to the core), the deviation from the ideal value of the free air capacitance might be a few fF more. Besides the calibration uncertainty of the LCR meter, it might also include a component of cable stray capacitance, which is not identifiable in the LCR meter's automated correction procedure.

To even proceed from the correction of cable stray admittance variation along the course of the device by simple subtraction towards absolute precision one needs to know the free-air-conductance, which is expected to vanish for the empty device, and the true free-air-capacitance of the capacitor, which needs a special approach as it cannot be measured directly and separately from other interfering capacitances.

In parallel to the NGRIP project, Wilhelms (2000) developed a calibration procedure for a custom DEP device with fixed electrodes, which was optimised for firn studies to establish the DECOMP model (Wilhelms, 2005). For the EGRIP core processing, we transferred the principle of introducing concentric metal tubes to the deep-core DEP bench and upgraded it with a rack to mount to move the tubes of different diameters along with DEP electrodes and record the capacitance along the DEP device. The tube in the electric field increases the capacitance of the arrangement and Wilhelms (2000) derives the theory to calculate the effective relative permittivity of the setup. For the calibration, tubes with radii in approximately 10 mm increments between 0 and 70 mm represented effective permittivity standards ($|\varepsilon|$) between 1 to 4 (Figure B1). The result is a calibration curve which holds for the calculation of a consistent free-air-capacitance for the correction of the DEP measurement of the EGRIP core. The free-air-capacitance is the proportionality factor of the measured capacitance and the effective permittivity, i.e. the slope of the graph in Figure B1. From this analysis one derives the true free-air-capacitance of the deep-core DEP device as adjusted when it was assembled.

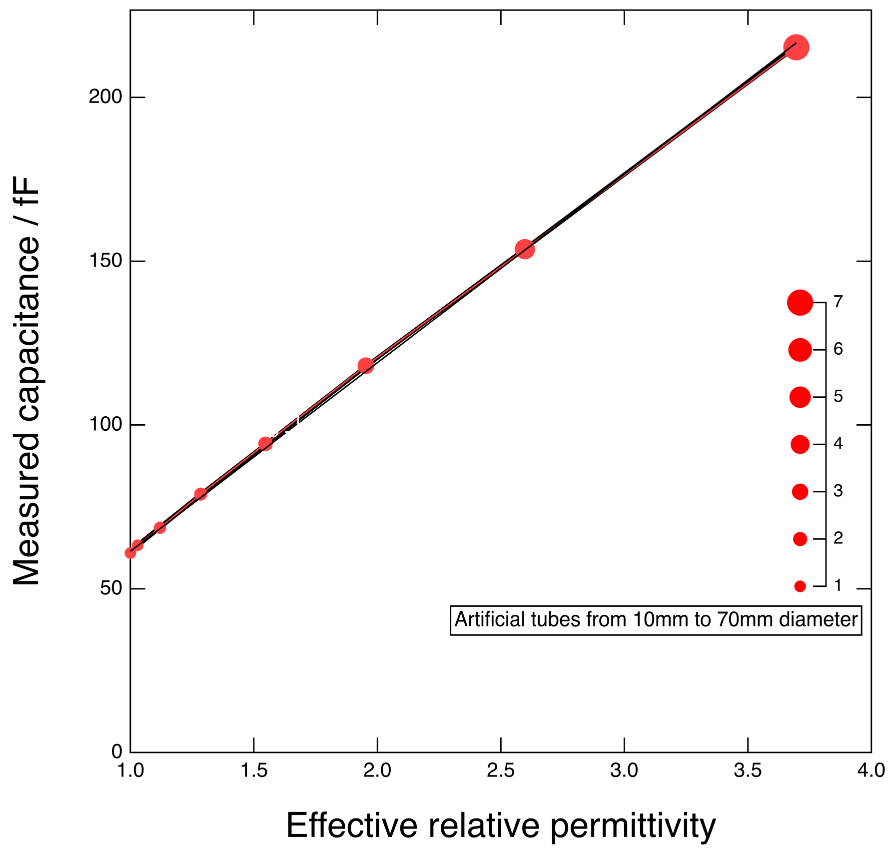

Figure B1. Calibration curve of the measurements with artificial tubes and free-air measurement for DEP device.

Now, we know the true free-air-capacitance (as determined from the just outlined calibration) together with the true (vanishing) conductance for an empty device. The free-air empty capacitor measurements thus determine the (additive) stray conductance and capacitance, which is the difference of the measurement and the reference values. The derived stray conductance and capacitance profile along the course of the DEP device are then subtracted from the actual ice-core measurements. The calculation of both material properties involves a division with the free air-capacitance, where introduction of further errors is minimised by using the precise value from the calibration procedure as outlined above.

Precise permittivity and resultingly precise free air capacitance values mainly make a difference when e.g. computing the wave propagation speed of radar waves while modelling synthetic radargrams (Eisen et al., 2006). For NGRIP and NEEM we did not yet perform the calibration procedure. From assigning the two-way travel time of prominent radar reflectors to volcanic spikes in the core, one can determine the radar wave propagation speed and calculate the ice's permittivity. As the NGRIP and NEEM datasets will also be used for comparison with radar surveys later, we determined the free air capacitance by averaging the measured capacitance over deep core sections and dividing with the expected permittivity of ice of 3.15 ± 0.1 which computes the free air capacitance with 3% relative error, which is only about 2 fF absolute error for the free air capacitance.

To sum up, all material properties' datasets we derived here are only subjected to a few percent absolute error. While the EGRIP record is calibrated independently, for the NGRIP and the NEEM cores the permittivity, as determined from radar wave propagation, was used. The latter is a very minor restriction as this cannot be checked independently, but is not of practical relevance.

Due to the varying temperature in processing area throughout the field seasons, the core was not processed at a consistent temperature and we don't have the temperature readings avail to provide consistently harmonized conductivity data. The missing temperature correction does not affect the use of conductivity peaks for synchronization purposes in between ice cores, which is relevant for the discussion here. When e.g. deriving radar wave absorption coefficients from the presented conductivity record, one would have to be very cautious and have this limitation of the data in mind.

Appendix C: Details on the ECM procedures

The depth scale of the ECM profile was assigned based on the recorded movement of the electrodes interpolated between the logged top and bottom depth of individual ice-core sections. To investigate the quality of the depth assignment, a bag mark position analysis was carried out on the section below the brittle zone in EGRIP, ∼1160–1760 m. Only ice core sections with an undamaged core of 1.65 m length were included in the analysis. Each 1.65 m section contains the equivalent of three 0.55 m bags, and the true depth of the bag interfaces ("bag marks") separating the first and second bags and the second and third bags, respectively, are known. During ECM measurements, these bag marks are logged (just as the break marks), but are not used for the processing. After processing of the ECM signal, the position of logged bag marks were interpolated onto the same depth scale as the processed ECM signal, making it possible to compare the true depth of these marks to their depths in the processed data. The distance in depth between logged and expected positions of individual bag marks were calculated for all sections included in the analysis. It was found that the depth assignment of the bag marks were almost always accurate within 20 mm, with mean distance $\mu = 8.3$ mm and standard deviation $\sigma = 7.9$ mm.

Appendix D: Statistical analysis of the (depth, depth)-match with linear interpolation

Each match point's depth assignment has an uncertainty due to the varying peak form, which is caused by regional deposition differences and short-term accumulation variations. This peak assignment uncertainty dominates the distribution of δ in sections where the EGRIP–NGRIP1/2 depth curve is straight. However, varying conditions at the time and place of the snow deposition or different ice flow pattern between the ice cores cause differently evolving annual layer thickness ratios $r_i = \frac{D_{i+1}-D_i}{d_{i+1}-d_i}$ and recognizable curvature of the (depth, depth)-curve. For the distribution function of δ, we expect a normal distribution of the peak assignment overlaid by a distribution from the curvature of the (depth, depth) curve, in the following referred to as "the refinement".

For further statistical treatment, we bin the δ values. As $\delta \in [-0.42929\mathrm{m}, 0.385968\mathrm{m}]$, we counted the occurrence $N(i)$ of values for the $i = 0 \ldots 20$ intervals $[-(0.525 + i * 0.05)\mathrm{m}, (-0.475 + i * 0.05)\mathrm{m})$ in between -0.525 m and 0.525 m and display the data in the following histogram (ref. Fig. D1). The standard deviation of the counts is $\sigma(N) = \sqrt{N}$. $n = 14$ bins are occupied. The distribution of δ is presented in Fig. D1.

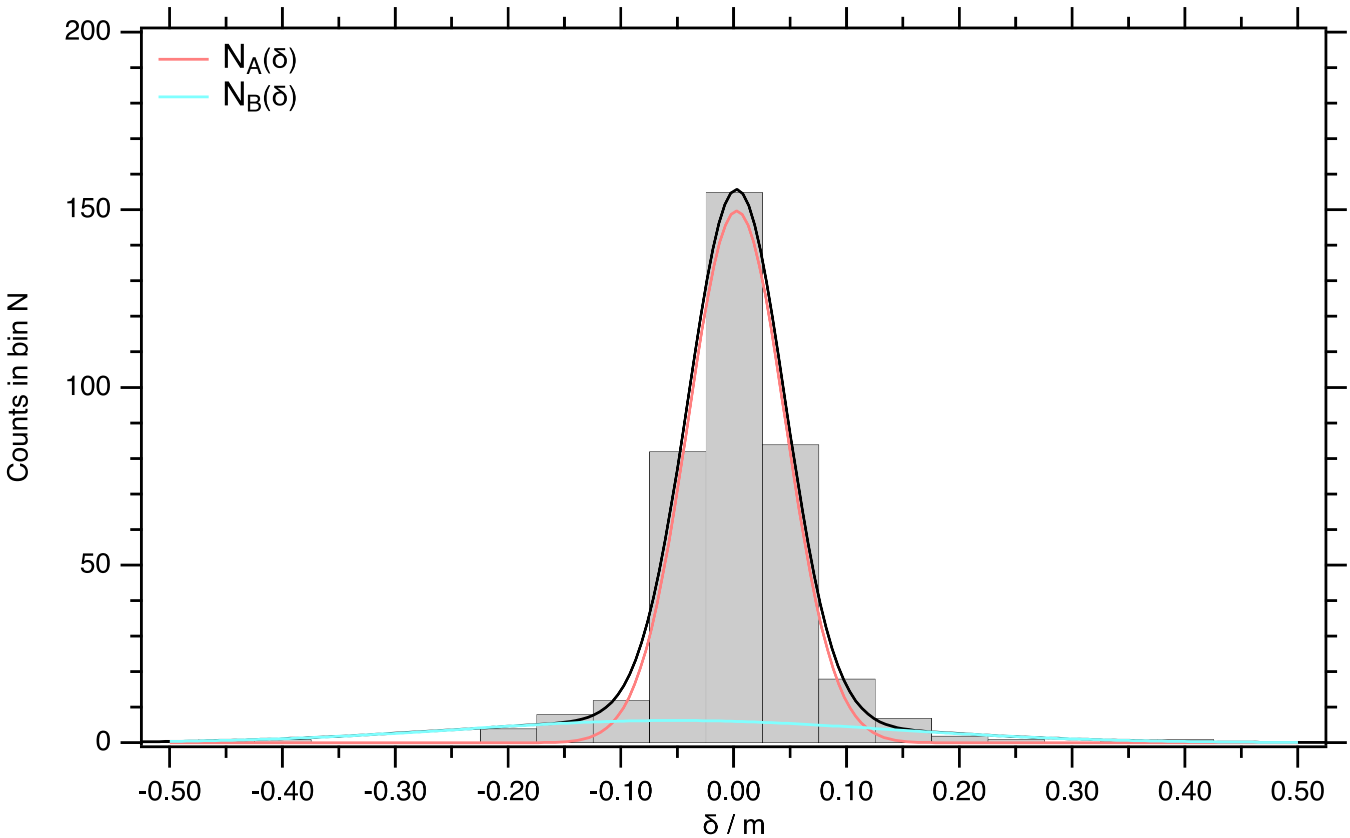

Figure D1. Histogram of the difference data with linear interpolation $\delta_i = (D_{i+1} - D_{i-1})/(d_{i+1} - d_{i-1})(d_i - d_{i-1}) + D_{i-1} - D_i$ for the match points between EGRIP–NGRIP1/2.

The Gaussian normal distribution for the peak assignment in the centre seems to be overlaid by a second Gaussian normal distribution representing the refinement of the depth scale. This is indicated by the quite wide tails of the distribution. Following the just posed assumption, that the refinement distance is statistically normal-distributed $N_B(\delta) = B\exp(-(\delta - \mu_B)^2/\sigma_B^2/2)/\sqrt{2\pi}/\sigma_B$ and that the uncertainty of the peak assignment in smooth intervals is normal-distributed $N_A(\delta) = A\exp(-(\delta - \mu_A)^2/\sigma_A^2/2)/\sqrt{2\pi}/\sigma_A$, we χ^2-fitted the sum $N(\delta) = N_A(\delta) + N_B(\delta)$. The weight of the χ^2 is the counting error $\sigma(N) = \sqrt{N}$. The fit of the $c = 6$ independent parameters converged and yielded a $\chi^2 = 4.7$ for the $f = n - c = 14 - 6 = 8$ degrees of freedom, indicating that the fitted distribution is supported by the data ($\int_{4.7}^{\infty} \chi^2(8) = 0.79$).

The χ^2-fit computes for the peak assignment distribution $N_A(\delta)$ a scaling factor $A = (16 \pm 1)\mathrm{m}$, the shift from the centre $\mu_A = (0.003 \pm 0.003)\mathrm{m}$ and a standard deviation $\sigma_A = (0.043 \pm 0.002)\mathrm{m}$. Similarly for the refinement distance $N_B(\delta)$: $B = (3 \pm 0.7)\mathrm{m}$, $\mu_B = (-0.05 \pm 0.04)\mathrm{m}$ and $\sigma_B = (0.19 \pm 0.04)\mathrm{m}$.

Solving $N_A(\delta_j) = N_B(\delta_j)$ for the roots $\delta_1 = -0.11m$ and $\delta_2 = 0.12m$ defines the inner interval that is dominated by the peak assignment statistics. 349 points are in the interval (δ_1, δ_2) and the direct statistical evaluation confirms $\sigma_A = 0.043m$ (in the main paragraphs of the paper we label this as statistical error for the peak assignment ΔD) and $\mu_A = 0.003$, where the skew (0.06) and the kurtosis (-0.05) are small and support normal distribution $\delta \in (-0.11\mathrm{m}, 0.12\mathrm{m})$. A Shapiro Wilk test confirms normal distribution of the peak assignment errors, as $W = 0.996$ and the corresponding p-Value $p = 0.54$.

As the refinement distance is overlaid by the peak assignment statistics in the centre of the distribution, none of the standard statistics is applicable, but the χ^2-fitted $N_B(\delta_i)$, can be χ^2-tested for the refinement-distance dominated bins. $\chi^2 = 4.0$ over the bins $i = 1, 2, 6, 7, 13, 14, 15, 17, 18$ in the tail that at most are marginally influenced by $N_A(\delta_i)$. The $n = 9$ bins together with initially $c = 3$ fitted parameters computes $f = n - c = 6$ degrees of freedom, which supports the refinement distance being normal distributed ($\int_{4.0}^{\infty} \chi^2(8) = 0.68$).

Appendix E: Statistical analysis of the (depth, depth)-match with cubic spline interpolation

Here, we quantify the difference between using linear interpolation and interpolation by cubic splines, which is a widely used scheme. The latter has the benefit of using smooth curves, such that the (depth, depth) curve and its derivatives are continuous, but as discussed above, several factors may cause the real (depth, depth) curve to be non-differentiable or even discontinuous, and we therefore maintain our practice of linear interpolation between the depths of the match points.

Analog to the definition of δ we define $\Sigma_i = S(D_1, \ldots, \not{D}_i, \ldots, D_n) - S(D_1, \ldots, D_i, \ldots, D_n)$, where $S(D_1, \ldots, D_i, \ldots, D_n)$ is a cubic spline calculated for all match points and $S(D_1, \ldots, \not{D}_i, \ldots, D_n)$ a cubic spline calculated for all but the i-th match point.

Analog to the above analysis with linear interpolation, we expect that each match point's depth assignment has an uncertainty due to the varying peak form, which is caused by regional deposition differences and short-term accumulation variations. This peak assignment uncertainty determines the distribution of Σ in sections where the EGRIP–NGRIP1/2 depth curve is straight and no systematic glaciological differences occur. However, varying accumulation conditions at the time and position of snow deposition or different ice flow patterns influencing the ice cores cause differently evolving annual layer thickness ratios $r_i = \frac{D_{i+1} - D_i}{d_{i+1} - d_i}$ which leads to curvature of the (depth, depth) curve. This curvature may not be captured if there are no match points at the relevant depth, and different interpolation schemes will make different predictions across intervals without match points. For the distribution function of Σ we thus expect two contributions: One from the uncertainty of peak assignment and the other one from the refinement.

For further statistical treatment, we bin the Σ values. As $\Sigma \in [--0.674604\mathrm{m}, 0.364446\mathrm{m}]$, we counted the occurrence $N(i)$ of values for the $i = 1 \ldots 21$ intervals $[-(0.725 + i * 0.05)\mathrm{m}, (-0.675 + i * 0.05)\mathrm{m})$ in between -0.675 m and 0.375 m and display the data in the following histogram (ref. Fig. E1). The standard deviation of the counts is $\sigma(N) = \sqrt{N}$. $n = 17$ bins are occupied. The distribution of Σ is presented in Fig. E1. The weight of the χ^2 is the counting error $\sigma(N) = \sqrt{N}$.

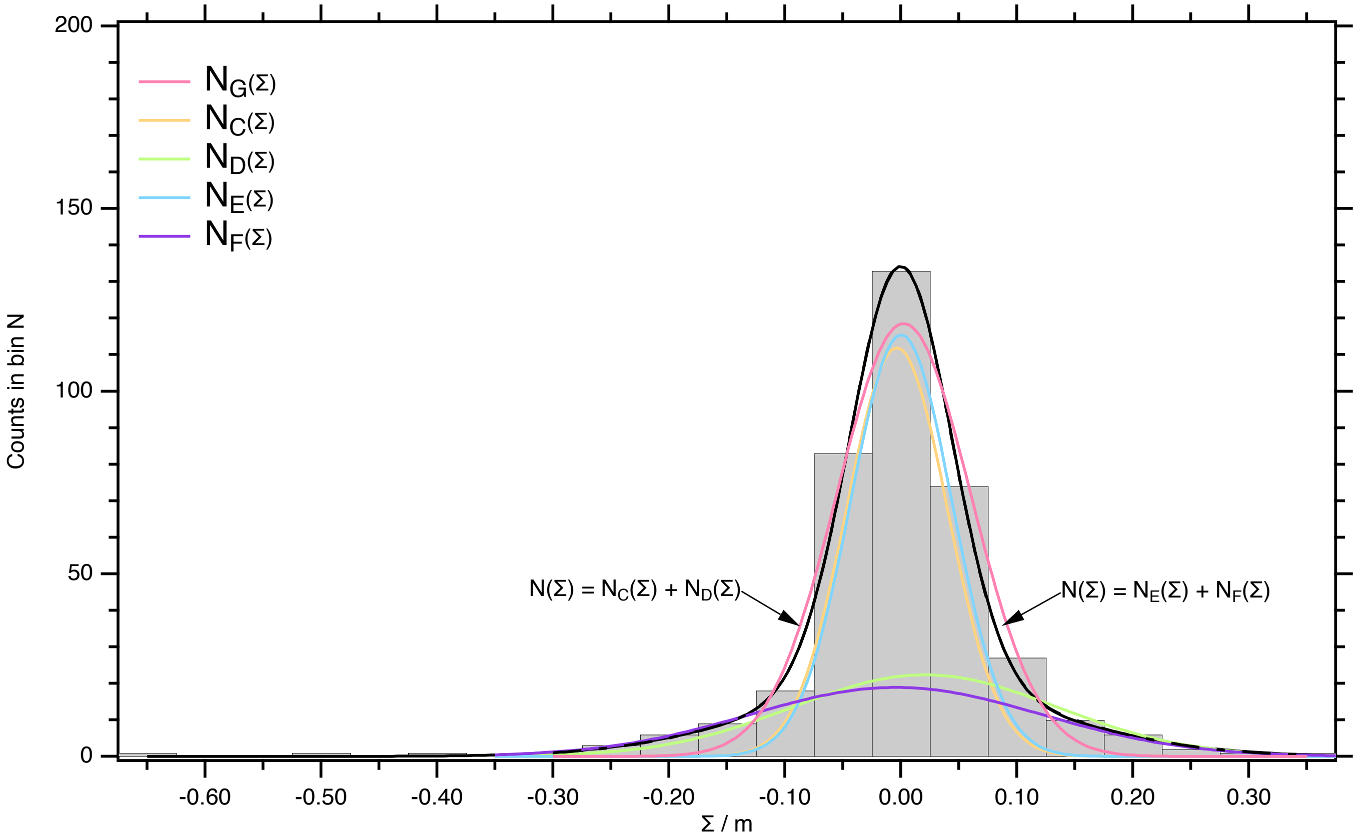

Figure E1. Histogram of the difference data with cubic spline interpolation $\Sigma_i = S(D_1,\ldots,\cancel{D_i},\ldots,D_n) - S(D_1,\ldots,D_i,\ldots,D_n)$ for the match points between EGRIP—NGRIP1/2.

Like for the (depth, depth) differences for the linear interpolation δ, the distribution of Σ appears having too wide tails to match a Gaussian distributions. We support this by trying to fit a single Gaussian normal distribution $N_G(\Sigma) = G\exp(-(\Sigma-\mu_G)^2/\sigma_G^2/2)/\sqrt{2\pi}/\sigma_G$. to the data. Even when treating the 3 values below $\Sigma < 0.325$ as outliers and restricting the fit to the $n = 14$ bins around 0, we minimize $\chi^2 = 30.8$. For the $c = 3$ fitted constants, the degree of freedom is $f = 11$. This indicates that the fitted distribution is not supported by the data ($\int_0^{30.8}\chi^2(11) = 0.99$).The Gaussian normal distribution for the peak assignment in the centre seems – as for the δ – to be overlaid by a second Gaussian normal distribution representing the refinement of the depth scale. Following the just posed assumption that the refinement distance is statistically normal-distributed $N_D(\Sigma)$ and that the uncertainty of the peak assignment in smooth intervals is normal-distributed $N_C(\Sigma)$, we tried to χ^2-fit $N(\Sigma) = N_C(\Sigma) + N_D(\Sigma)$ to the entire dataset with $c = 6$ fitting parameters. For the $n = 17$ bins of the entire dataset Σ we minimised $\chi^2 = 48.7$, which suggests the model does not describe the data (for details refer to Fig. E1, where the figures for a similar treatment as for rejecting $N_G(\Sigma)$ are provided).

By just treating the 3 values (out of 377 in total) below $\Sigma < 0.325$ as outliers, which is justified, when we are mainly interested in assessing the central part of the distribution, which refers to the match-point assignment. Thus, repeating the fit for the bins $i = 8, /ldots, 21$ $(n = 14)$ an labelling the fitted function $N(\Sigma) = N_E(\Sigma) + N_F(\Sigma)$ to clearly distinguish the result from the fit to the entire dataset before, we are able to minimize $\chi^2 = 3.09$ for the $f = n - c = 11$ degrees of freedom, indicating that the fitted distribution is supported by the data ($\int_{3.1}^{\infty} \chi^2(11) = 0.93$).

The χ^2-fit computes for the peak assignment distribution $N_E(\Sigma)$ a scaling factor $E = (12.6 \pm 1.6)\mathrm{m}$, the shift from the centre $\mu_E = (-0.0003 \pm 0.004)\mathrm{m}$ and a standard deviation $\sigma_E = (0.044 \pm 0.004)\mathrm{m}$. Similarly for the refinement distance $N_F(\Sigma)$: $F = (6.0 \pm 1.5)\mathrm{m}$, $\mu_F = (0.004 \pm 0.013)\mathrm{m}$ and $\sigma_F = (0.13 \pm 0.02)\mathrm{m}$.

For the linear interpolation scheme (ref. to Appendix D) the peak assignment contribution ($N_A(\delta)$ dominates the central bins. Only 4% of the counts are attributed to the refinement ($N_B(\delta)$) and we could define the interval where to perform a direct statistical analysis of the δ values for the peak assignment mode from the intersections of $N_A(\delta)$ and $N_B(\delta)$. For the cubic spline interpolation scheme 16% of the counts are contributing to the refinement $N_F(\Sigma)$ in the central bins. Thus the roots $\Sigma_1 = -0.089m$ and $\Sigma_2 = 0.087m$ of $N_E(\Sigma_k) = N_F(\Sigma_k)$ do not define the complete inner interval, where the peak assignment contributes and it does not as clearly dominate the distribution of Σ. The peak assignment and the refinement modes do not separate as clearly as for the linear interpolation, and a Shapiro Wilk test for the (Σ_1, Σ_2) interval fails. When extending the interval to $(-0.16\mathrm{m}, 0.16\mathrm{m})$ – which covers the contributions of the peak assignment mode well –, the direct statistical analysis for the 348 points estimates a standard deviation of $0.056\mathrm{m}$, skew of 0.06 and a kurtosis of 0.21. This suggest a symmetrical distribution that is slightly higher with wider wings, which is consistent with the above observation of the refinement mode being recognizable in interval and the standard deviation is overestimated. A Shapiro Wilk test supports normal distribution in the interval $(-0.16\mathrm{m}, 0.16\mathrm{m})$, as $W = 0.995$ and the corresponding p-Value p=0.38. As we already excluded outliers for the analysis, there is no meaning in the statistical analysis of the refinement distance and we assume Σ as a measure for the systematic deviation when using cubic spline interpolation.

The cubic spline scheme confirms the above observed maximal error of the match points $\Delta D = 0.043\mathrm{m} = \sigma_A \approxeq \sigma_E = 0.044$. When restricting $|\delta|, |\Sigma| \leq 0.375\mathrm{m}$, then both δ and Σ have 3 match points exceeding this threshold and both distributions fit a profile with a standard deviation of $\sigma_F = \sigma_B$ (without 3 outliers) $= 0.13\mathrm{m}$ for the refinement each match point contributes in average. This means that one of the interpolation schemes is not superior to the other, but comparing them illustrates the uncertainty associated with interpolation in between the match points.

Now, we calculate the systematic deviation between linear and cubic spline interpolation from datasets in 0.01 m resolution. ζ_i denotes the maximal absolute difference in the interval between the i-th and (i+1)-th match point, which is a direct measure of systematic differences due to the interpolation schemes.

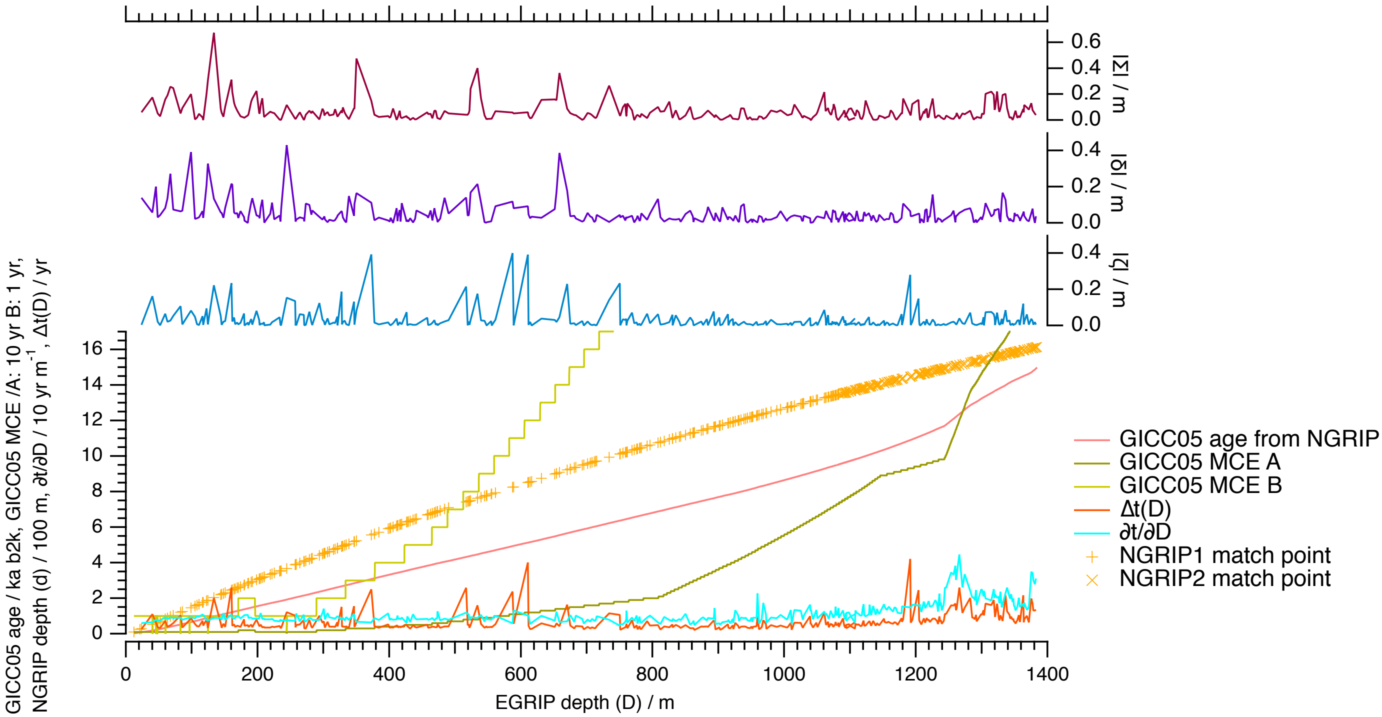

Figure E2. The (EGRIP, NGRIP) match points, (EGRIP-depth, GICC05-time)-scale, the (EGRIP-depth, GICC05-MCE)-curve, $|\delta|$, $|\Sigma|$, $|\zeta|$, $\frac{\partial t_{\mathrm{GICC05}}}{\partial D_{\mathrm{EGRIP}}}$, $\Delta t(D) = |\frac{\partial t}{\partial D}|\sqrt{(\Delta t)^2 + \zeta^2}$

$|\zeta|$ and $|\delta|$ are both less than 0.4 m and exhibit a similar pattern, while $|\Sigma|$ has less in common with both δ and ζ. $|\zeta|$ is a good measure for the interpolation uncertainty along the record as it is the direct comparison of two fundamentally different interpolation approaches (see Figure E2).

For linear interpolation, the statistical error for the computed depth in between two match points is limited by the maximal error of the match points $\Delta D = 0.043\mathrm{m}$ and the error of the interpolated depth D is therefore $\sqrt{(\Delta D)^2 + \zeta^2}$. To propagate the depth error and estimate the additional error of the time match, we start from the highest resolution published GICC05 dating of NGRIP with 2.5 cm and 5 cm depth resolution above and below 349.8 m respectively (Vinther et al., 2006; Rasmussen et al., 2006) and linearly interpolate the EGRIP depth (D) onto the NGRIP depth (d) to get the time scale t(D) for EGRIP. We calculate $\frac{\partial t_{\mathrm{GICC05}}}{\partial D_{\mathrm{EGRIP}}}$ in the high resolution dataset and sample it at the match points.

The matching error related to the timescale transfer $\Delta t(D) = |\frac{\partial t}{\partial D}|\sqrt{(\Delta t)^2 + \zeta^2}$ is maximally about 4 years, exceeds the MCE on two occasions in the uppermost 200 m by 1 year, and becomes increasingly smaller compared to the MCE for increasingly deeper parts of the record (see Figure E2).

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References

Andersen, K. K., Svensson, A., Johnsen, S. J., Rasmussen, S. O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Steffensen, J. P., Dahl-Jensen, D., Vinther, B. M., and Clausen, H. B.: The Greenland Ice Core Chronology 2005, 15–42ka. Part 1: constructing the time scale, Quaternary Science Reviews, 25, 3246 – 3257, https://doi.org/https://doi.org/10.1016/j.quascirev.2006.08.002, http://www.sciencedirect.com/science/article/pii/S0277379106002587, 2006.

Borchardt, G. A., Aruscavage, . J., and Millard, H. T.: Correlation of the Bishop Ash, a Pleistocene marker bed, using instrumental neutron activation analysis, Journal of Sedimentary Research, 42, 301–306, https://doi.org/10.1306/74D72527-2B21-11D7-8648000102C1865D, 1972.

Cook, E., Davies, S. M., Guðmundsdóttir, E. R., Abbott, P. M., and Pearce, N. J. G.: First identification and characterization of Borrobol-type tephra in the Greenland ice cores: new deposits and improved age estimates, Journal of Quaternary Science, 33, 212–224, https://doi.org/10.1002/jqs.3016, https://onlinelibrary.wiley.com/doi/abs/10.1002/jqs.3016, 2018.

Dahl-Jensen, D., Gundestrup, N. S., Miller, H., Watanabe, O., Johnsen, S. J., Steffensen, J. P., Clausen, H. B., Svensson, A., and Larsen, L. B.: The NorthGRIP deep drilling programme, Annals of Glaciology, 35, 1–4, https://doi.org/10.3189/172756402781817275, 2002.

Dahl-Jensen, D., Kirk, M., Koldtoft, I., Popp, T., and P, S. J.: Field season 2019 East GReenland Ice core Project (EGRIP) 2015-2020: Third year of EGRIP deep drilling, https://eastgrip.nbi.ku.dk/documentation/2019/EGRIP2019FieldPlan_1stVersion.pdf, 2019.

Davies, S. M.: Cryptotephras: the revolution in correlation and precision dating, Journal of Quaternary Science, 30, 114–130, https://doi.org/10.1002/jqs.2766, https://onlinelibrary.wiley.com/doi/abs/10.1002/jqs.2766, 2015.

Eisen, O., Wilhelms, F., Steinhage, D., and Schwander, J.: Improved method to determine radio-echo sounding reflector depths from ice-core profiles of permittivity and conductivity, Journal of Glaciology, 52, 299–310, https://doi.org/10.3189/172756506781828674, 2006.

Gfeller, G., Fischer, H., Bigler, M., Schüpbach, S., Leuenberger, D., and Mini, O.: Representativeness and seasonality of major ion records derived from NEEM firn cores, The Cryosphere, 8, 1855–1870, https://doi.org/10.5194/tc-8-1855-2014, https://www.the-cryosphere.net/8/1855/2014/, 2014.

Hammer, C. U.: Acidity of Polar Ice Cores in Relation to Absolute Dating, Past Volcanism, and Radio–Echoes, Journal of Glaciology, 25, 359–372, https://doi.org/10.3189/S0022143000015227, 1980.

Hayward, C.: High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam-induced chemical modification, The Holocene, 22, 119–125, https://doi.org/10.1177/0959683611409777, https://doi.org/10.1177/0959683611409777, 2012.

Jensen, B. J. L., Beaudoin, A. B., Clynne, M. A., Harvey, J., and Vallance, J. W.: A re-examination of the three most prominent Holocene tephra deposits in western Canada: Bridge River, Mount St. Helens Yn and Mazama, Quaternary International, 500, 83 – 95, https://doi.org/https://doi.org/10.1016/j.quaint.2019.03.017, http://www.sciencedirect.com/science/article/pii/S1040618218311911, 2019.

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T., and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, Journal of Glaciology, 56, 415–430, https://doi.org/10.3189/002214310792447734, 2010.

Joughin, I., Smith, B. E., and Howat, I. M.: A complete map of Greenland ice velocity derived from satellite data collected over 20 years, Journal of Glaciology, 64, 1–11, https://doi.org/10.1017/jog.2017.73, 2018.

Karlsson, N. B., Razik, S., Hörhold, M., Winter, A., Steinhage, D., Binder, T., and Eisen, O.: Surface accumulation in Northern Central Greenland during the last 300 years, Annals of Glaciology, p. 1–11, https://doi.org/10.1017/aog.2020.30, 2020.

MacGregor, J. A., Fahnestock, M. A., Catania, G. A., Paden, J. D., Prasad Gogineni, S., Young, S. K., Rybarski, S. C., Mabrey, A. N., Wagman, B. M., and Morlighem, M.: Radiostratigraphy and age structure of the Greenland Ice Sheet, Journal of Geophysical Research: Earth

Surface, 120, 212–241, https://doi.org/10.1002/2014JF003215, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014JF003215, 2015.

Mojtabavi, S., Wilhelms, F., Franke, S., Jansen, D., Steinhage, D., Dahl-Jensen, D., and Eisen, O.: Deep insights to the Greenland ice sheet by linking multichannel ultra-wide-band radar surveys to the latest deep ice cores by synthetic radar modelling. (manuscript in preparation), 2019.

Moore, J. and Paren, J.: A new technique for dielectric logging of Antarctic ice cores, Journal de Physique Colloques, 48, C1–155–C1–160, https://doi.org/10.1051/jphyscol:1987123, https://hal.archives-ouvertes.fr/jpa-00226268, 1987.

Moore, J. C., Wolff, E. W., Clausen, H. B., and Hammer, C. U.: The chemical basis for the electrical stratigraphy of ice, Journal of Geophysical Research: Solid Earth, 97, 1887–1896, https://doi.org/10.1029/91JB02750, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/91JB02750, 1992.

Moore, J. C., Wolff, E. W., Clausen, H. B., Hammer, C. U., Legrand, M. R., and Fuhrer, K.: Electrical response of the Summit-Greenland ice core to ammonium, sulphuric acid, and hydrochloric acid, grl, 21, 565–568, https://doi.org/10.1029/94GL00542, 1994.

Mortensen, A. K., Bigler, M., Grönvold, K., Steffensen, J. P., and Johnsen, S. J.: Volcanic ash layers from the Last Glacial Termination in the NGRIP ice core, Journal of Quaternary Science, 20, 209–219, https://doi.org/10.1002/jqs.908, https://onlinelibrary.wiley.com/doi/abs/10.1002/jqs.908, 2005.

Perkins, M. E., Nash, W. P., Brown, F. H., and Fleck, R. J.: Fallout tuffs of Trapper Creek, Idaho—A record of Miocene explosive volcanism in the Snake River Plain volcanic province, Bulletin of the Geological Society of America, 107, 1484–1506, https://doi.org/10.1130/0016-7606(1995)107<1484:FTOTCI>2.3.CO;2, 1995.

Perkins, M. E., Brown, F. H., Nash, W. P., Williams, S. K., and Mclntosh, W.: Sequence, age, and source of silicic fallout tuffs in middle to late Miocene basins of the northern Basin and Range province, Bulletin of the Geological Society of America, 110, 344–360, https://doi.org/10.1130/0016-7606(1998)110<0344:SAASOS>2.3.CO;2, 1998.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P.: Numerical Recipes in C: The Art of Scientific Computing (2d ed.; Cambridge), Cambridge Univ. Press, 1992.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U.: A new Greenland ice core chronology for the last glacial termination, Journal of Geophysical Research: Atmospheres, 111, https://doi.org/10.1029/2005JD006079, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006079, 2006.

Rasmussen, S. O., Abbott, P. M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Chappellaz, J., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Kipfstuhl, S., Laepple, T., Seierstad, I. K., Severinghaus, J. P., Steffensen, J. P., Stowasser, C., Svensson, A., Vallelonga, P., Vinther, B. M., Wilhelms, F., and Winstrup, M.: A first chronology for the North Greenland Eemian Ice Drilling (NEEM) ice core, Climate of the Past, 9, 2713–2730, https://doi.org/10.5194/cp-9-2713-2013, https://www.clim-past.net/9/2713/2013/, 2013.

Riverman, K. L., Alley, R. B., Anandakrishnan, S., Christianson, K., Holschuh, N. D., Medley, B., Muto, A., and Peters, L. E.: Enhanced Firn Densification in High-Accumulation Shear Margins of the NE Greenland Ice Stream, Journal of Geophysical Research: Earth Surface, 124, 365–382, https://doi.org/10.1029/2017JF004604, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2017JF004604, 2019.

Ruth, U., Wagenbach, D., Steffensen, J. P., and Bigler, M.: Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period, Journal of Geophysical Research: Atmospheres, 108, https://doi.org/10.1029/2002JD002376, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JD002376, 2003.

Seierstad, I. K., Abbott, P. M., Bigler, M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Johnsen, S. J., Pedersen, D. S., Popp, T. J., Rasmussen, S. O., Severinghaus, J. P., Svensson, A., and Vinther, B. M.: Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale δ18O gradients with possible Heinrich event imprint, Quaternary Science Reviews, 106, 29 – 46, https://doi.org/https://doi.org/10.1016/j.quascirev.2014.10.032, http://www.sciencedirect.com/science/article/pii/S027737911400434X, 2014.

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Rasmussen, S. O., Röthlisberger, R., Steffensen, J. P., and Vinther, B. M.: The Greenland Ice Core Chronology 2005, 15–42ka. Part 2: comparison to other records, Quaternary Science Reviews, 25, 3258 – 3267, https://doi.org/https://doi.org/10.1016/j.quascirev.2006.08.003, http://www.sciencedirect.com/science/article/pii/S0277379106002599, 2006.

Svensson, A., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Davies, S. M., Johnsen, S. J., Muscheler, R., Parrenin, F., Rasmussen, S. O., Röthlisberger, R., Seierstad, I., Steffensen, J. P., and Vinther, B. M.: A 60 000 year Greenland stratigraphic ice core chronology, Climate of the Past, 4, 47–57, https://doi.org/10.5194/cp-4-47-2008, https://www.clim-past.net/4/47/2008/, 2008.

Vallelonga, P., Christianson, K., Alley, R. B., Anandakrishnan, S., Christian, J. E. M., Dahl-Jensen, D., Gkinis, V., Holme, C., Jacobel, R. W., Karlsson, N. B., Keisling, B. A., Kipfstuhl, S., Kjær, H. A., Kristensen, M. E. L., Muto, A., Peters, L. E., Popp, T., Riverman, K. L., Svensson, A. M., Tibuleac, C., Vinther, B. M., Weng, Y., and Winstrup, M.: Initial results from geophysical surveys and shallow coring of the Northeast Greenland Ice Stream (NEGIS), The Cryosphere, 8, 1275–1287, https://doi.org/10.5194/tc-8-1275-2014, https://www.the-cryosphere.net/8/1275/2014/, 2014.

Vinther, B. M., Clausen, H. B., Johnsen, S. J., Rasmussen, S. O., Andersen, K. K., Buchardt, S. L., Dahl-Jensen, D., Seierstad, I. K., Siggaard-Andersen, M.-L., Steffensen, J. P., Svensson, A., Olsen, J., and Heinemeier, J.: A synchronized dating of three Greenland ice cores throughout the Holocene, Journal of Geophysical Research: Atmospheres, 111, https://doi.org/10.1029/2005JD006921, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005JD006921, 2006.

Wilhelms, F.: Leitfähigkeits- und Dichtemessung an Eisbohrkernen = Measuring the conductivity and density of ice cores , Berichte zur Polarforschung (Reports on Polar Research), Bremerhaven, Alfred Wegener Institute for Polar and Marine Research, 191 , 224 p. . doi: 10.2312/BzP_0191_1996, 1996.

Wilhelms, F.: Messung dielektrischer Eigenschaften polarer Eiskerne = Measuring the dielectric properties of polar ice cores , Berichte zur Polarforschung (Reports on Polar Research), Bremerhaven, Alfred Wegener Institute for Polar and Marine Research, 367 , 171 p. . doi: 10.2312/BzP_0367_2000, 2000.

Wilhelms, F.: Explaining the dielectric properties of firn as a density-and-conductivity mixed permittivity (DECOMP), Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL022808, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005GL022808, 2005.

Wilhelms, F., Kipfstuhl, J., Miller, H., Heinloth, K., and Firestone, J.: Precise dielectric profiling of ice cores: a new device with improved guarding and its theory, Journal of Glaciology, 44, 171–174, https://doi.org/10.3189/S002214300000246X, 1998.

Winski, D. A., Fudge, T. J., Ferris, D. G., Osterberg, E. C., Fegyveresi, J. M., Cole-Dai, J., Thundercloud, Z., Cox, T. S., Kreutz, K. J., Ortman, N., Buizert, C., Epifanio, J., Brook, E. J., Beaudette, R., Severinghaus, J., Sowers, T., Steig, E. J., Kahle, E. C., Jones, T. R., Morris, V., Aydin, M., Nicewonger, M. R., Casey, K. A., Alley, R. B., Waddington, E. D., Iverson, N. A., Dunbar, N. W., Bay, R. C., Souney, J. M., Sigl, M., and McConnell, J. R.: The SP19 chronology for the South Pole Ice Core – Part 1: volcanic matching and annual layer counting, Climate of the Past, 15, 1793–1808, https://doi.org/10.5194/cp-15-1793-2019, https://www.clim-past.net/15/1793/2019/, 2019.

Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O., and Svensson, A.: Millennial-scale variability during the last glacial: The ice core record, Quaternary Science Reviews, 29, 2828 – 2838, https://doi.org/https://doi.org/10.1016/j.quascirev.2009.10.013, http://www.sciencedirect.com/science/article/pii/S0277379109003588, 2010.