Supplementary Information for

A multi-ice-core, annual-layer counted Greenland ice-core chronology for the last 3800 years: GICC21

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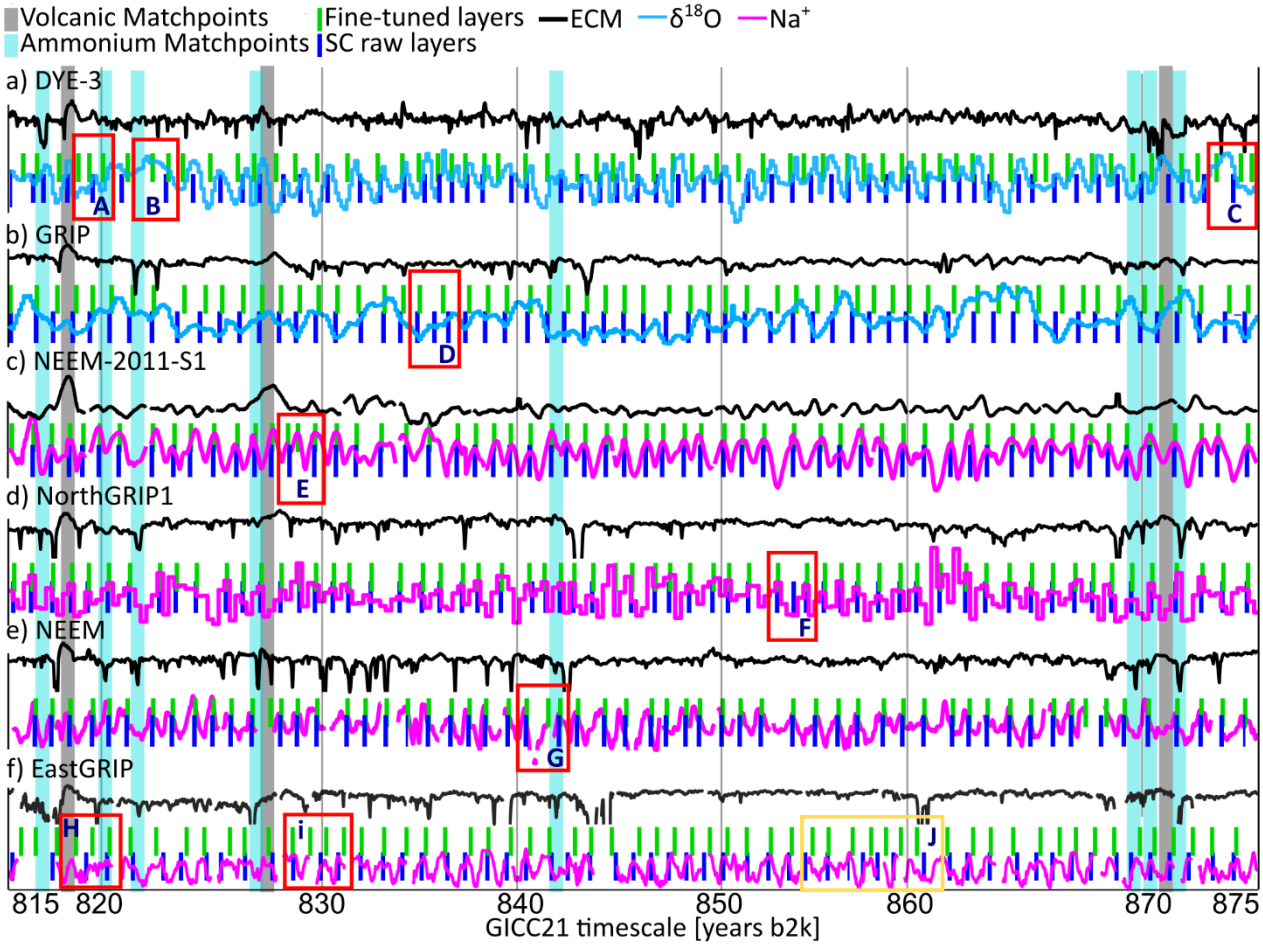

Figure S 1 Example of the fine-tuning decisional process between 815 and 875 years b2k. The units of all data are arbitrary, as they were log-transformed and vertically adjusted to better highlight the layer structure and common matching features. Red and yellow rectangles show some examples of where the observers had to intervene because of discrepancies in the layer count between the ice cores. Rectangles A, B, C: in these cases, DYE-3 needed layer addition because SC did not recognize some small isotope features as annual layers. Rectangle D: a spurious isotope oscillation in GRIP was removed from the raw count. Rectangle E: a dubious feature in the data was solved by comparison to NEEM. Rectangle F: SC counted an extra layer, based on a Ca^{2+}peak (not shown). Rectangle G: SC missed one layer because of the unclear sodium pattern. Rectangle H: An additional layer was inserted because of unclear sodium. Rectangle i: SC did not recognize this annual layer because of the interrupted data. Rectangle J: re-placement of layers did not result in any modification to the count.

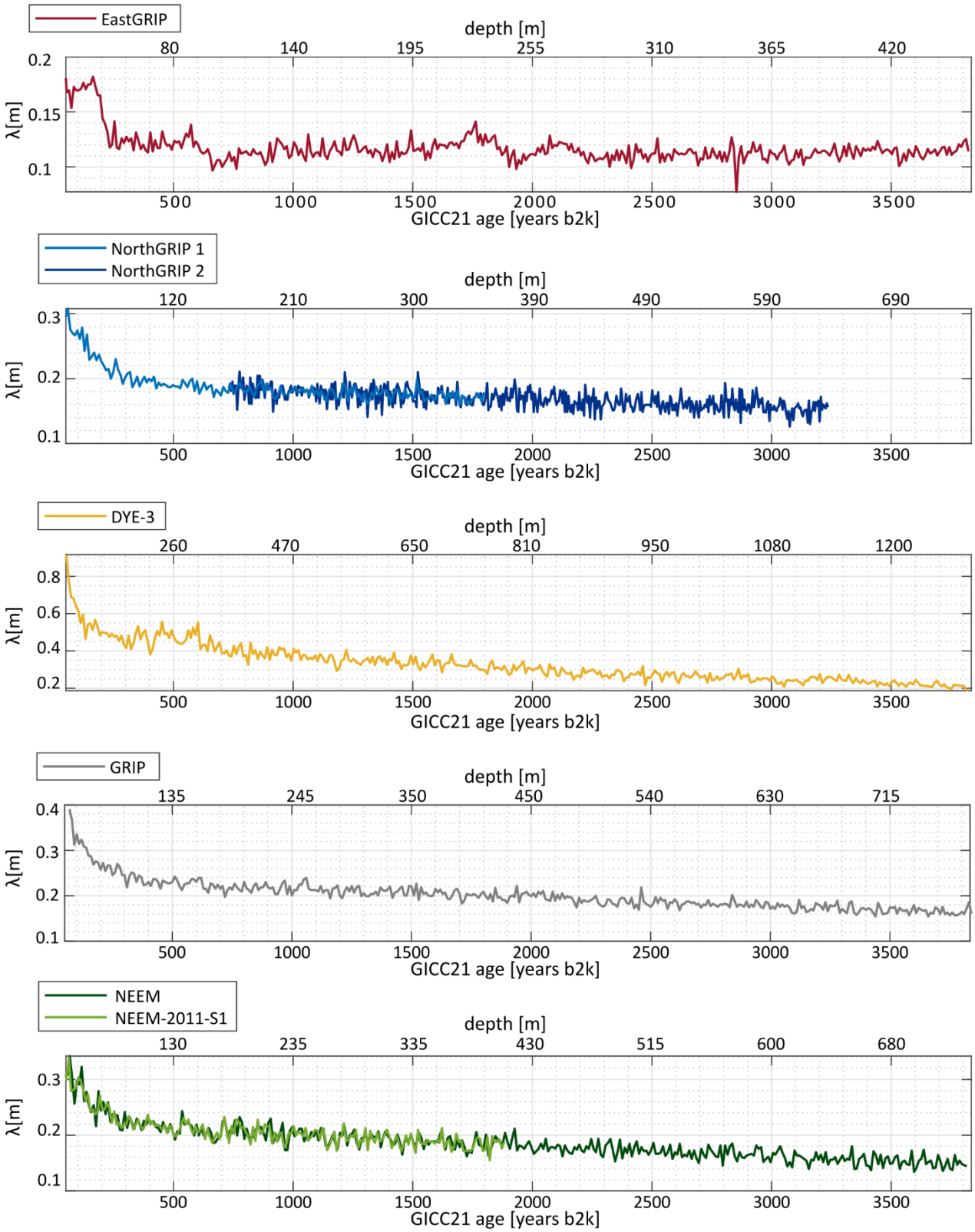

Figure S 2 The layer thickness of all ice cores from the GICC21 timescale, which provides the basis for reconstructing the accumulation rate of Greenlandic ice cores (Andersen, et al., 2006). To retrieve the accumulation from the layer thicknesses, one needs to account for thinning due to flow and to model the firn densification. For DYE-3 and EastGRIP, in particular, upstream effects also need to be accounted for, because of high surface velocities that transported the ice away from its original deposition location (Gerber et al., 2021).

EastGRIP exhibits some thickness fluctuations, not only in the very top, but also around 1700 and 2100 years b2k, that will need to be interpreted in view of the high flow speed this core is subjected to, and the potentially complex deformation history for ice coming from upstream, especially if the ice has crossed the shear margins (Gerber et al., 2021). On average, EastGRIP displays an almost constant layer thickness of about 0.11 m, which is an effect of a balance between layer thinning and increased upstream accumulation. For all other cores, the annual layer thicknesses below the firn zone essentially decrease linearly with depth as expected by simple flow models. We again observe the layer thickness fluctuation of DYE-3 at around 500 years b2k. The layer thickness profiles for closely located ice cores are naturally very similar.

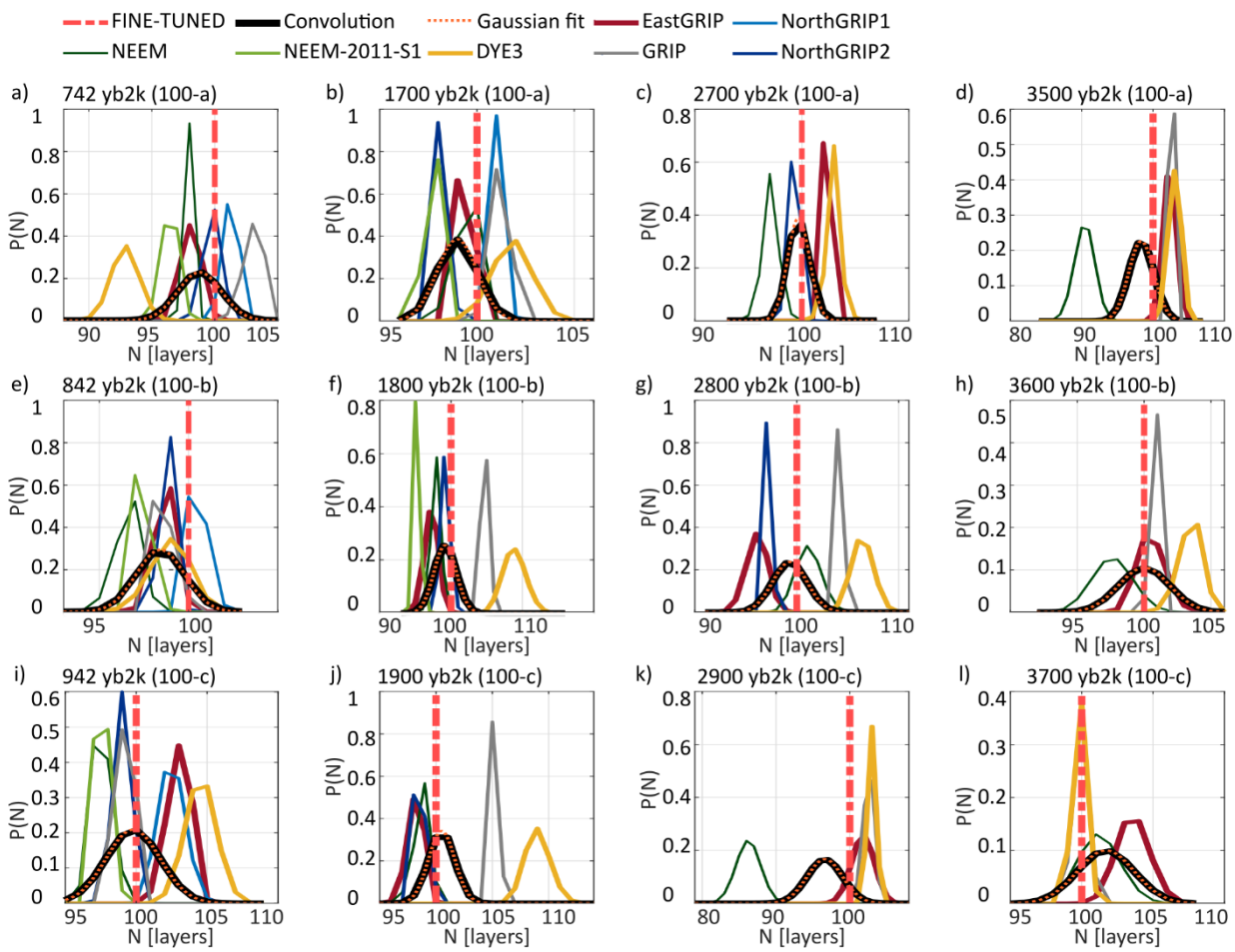

Figure S 3 Single-core probability density functions (pSC) of the number of years counted by SC in 100-year sections. All ice cores were corrected for missing layers in data gaps (see Straticounter Supplement). The fine-tuned result (red line, dashed) is often far off some of the single-core probability distributions. In some cases, we observed a systematic over-count by SC of DYE-3 layers, possibly because of melt layers and mid-year isotopic oscillations. However, most of the single-core SC estimates have fewer annual layers than the fine-tuned result. The convolution of the single-core probabilities (black) was fitted to a gaussian (orange) to obtain the parameters listed in Table 4.

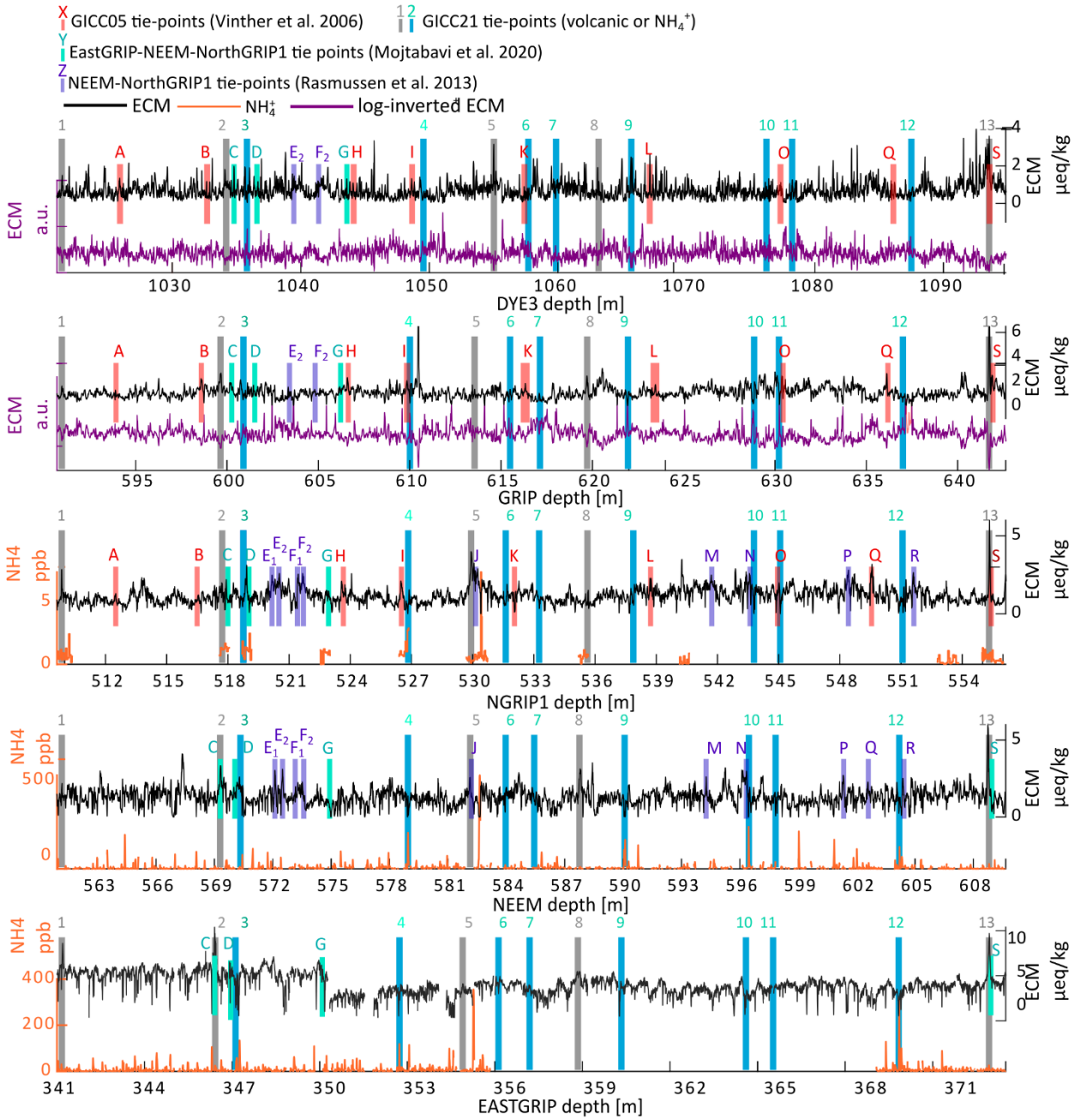

Figure S 4 Example of a matching problem solved in GICC21 between 2800 and 3100 years b2k. Tie-points of GICC05 are indicated by bars with letters, while tie-points of GICC21 are indicated by numbered bars (see figure legend). The relative order between the tie-points of GICC21 and GICC05 confirms the interpretation of the offset-wiggle as a result of volcanic mismatch. For example, tie points C and D are slightly shifted in GRIP and DYE-3, causing the steep offset increase at 2800 years b2k. Tie-point K appears between tie points 6 and 7 for GRIP and NorthGRIP, but is between 5 and 6 for DYE-3, explaining why the offset curve of GRIP is flatter in the area. We observe that the match of DYE-3 is affected by layer thickness fluctuations, causing the placement of tie points no. 4-11 to be shifted to the right, similar to Fig. 7 (in the main text). The problems with EastGRIP and NEEM arise from the match to NorthGRIP1, whose ages result from interpolation from DYE-3 and GRIP, a fact that can be observed by observing the shift of the red and green bars.

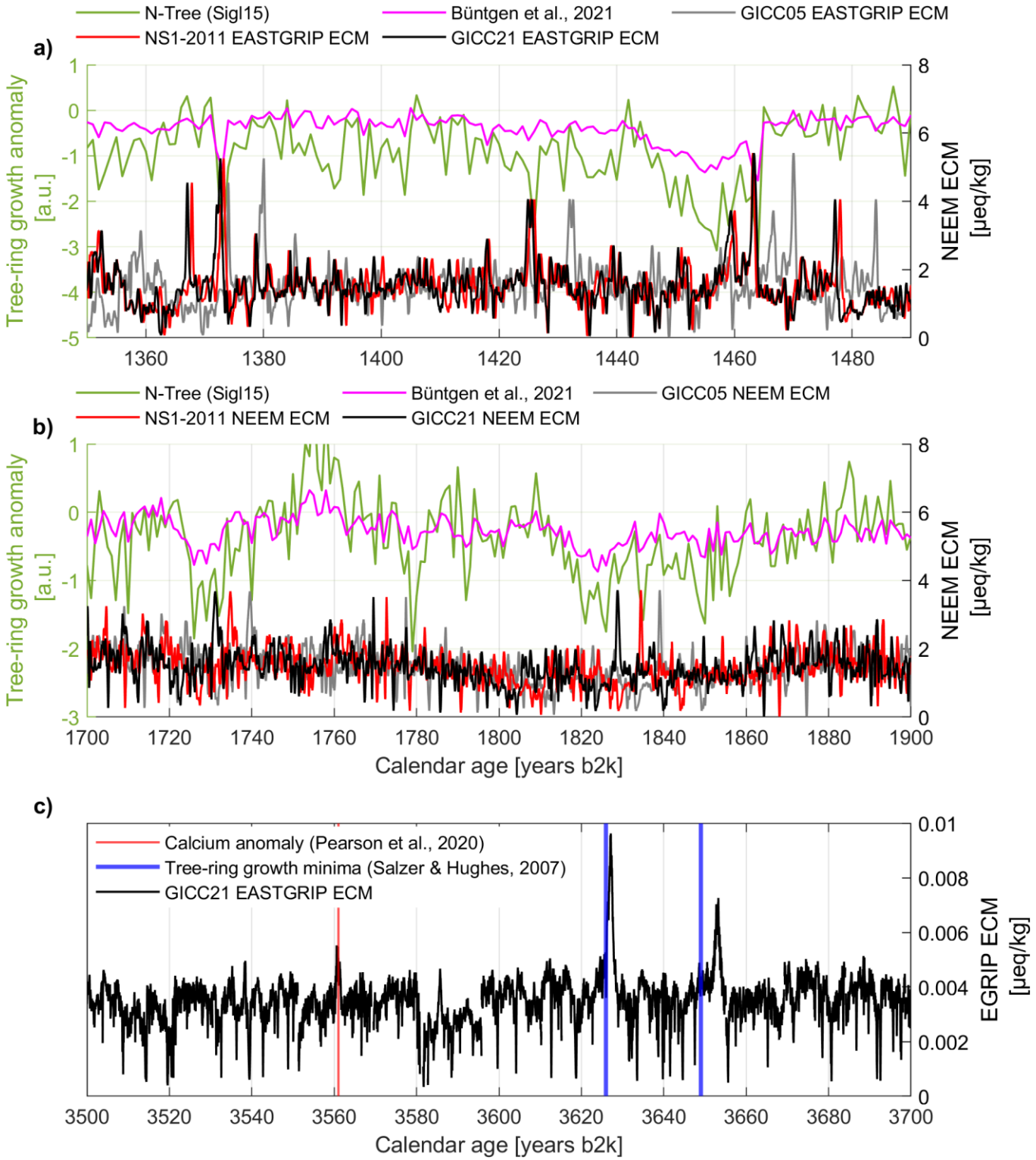

Figure S 5 Comparison of ice-core ECM (NEEM), shifted according to the three compared ice core timescales, to the N-Tree growth-anomaly record provided in Sigl et al. (2015; Sigl15) and to the average temperature reconstruction by Büntgen et al., 2021. (a) Between 1360 and 1480 years b2k, we observed good alignment of the ECM-stack with N-Tree local minima, except for when the ice cores are plotted according to GICC05. This fact links the volcanic eruptions evidenced in the Greenland ice sheet with Northern-Hemisphere post-eruption cooling. (b) In the period 1700-1900, the three timescales do not coincide, as can be observed by the relative delay of the ECM curves. Some clear N-tree minima are observed here, although the GICC21 peaks (black) are not as clearly related to the minima as in panel a. Two ECM peaks

appear somewhat closer to the temperature minima at 1730 and at 1820 years b2k. (c) The ice-core ECM (EastGRIP) compares well to discrete evidence of tree-ring cooling. One example is the calcium anomaly (star) measured by Pearson et al. in a sample from Turkey, speculated to be linked to the eruption of Thera, Santorini. The other two examples are tree-ring growth minima observed in the North American record by Salzer and Hughes.

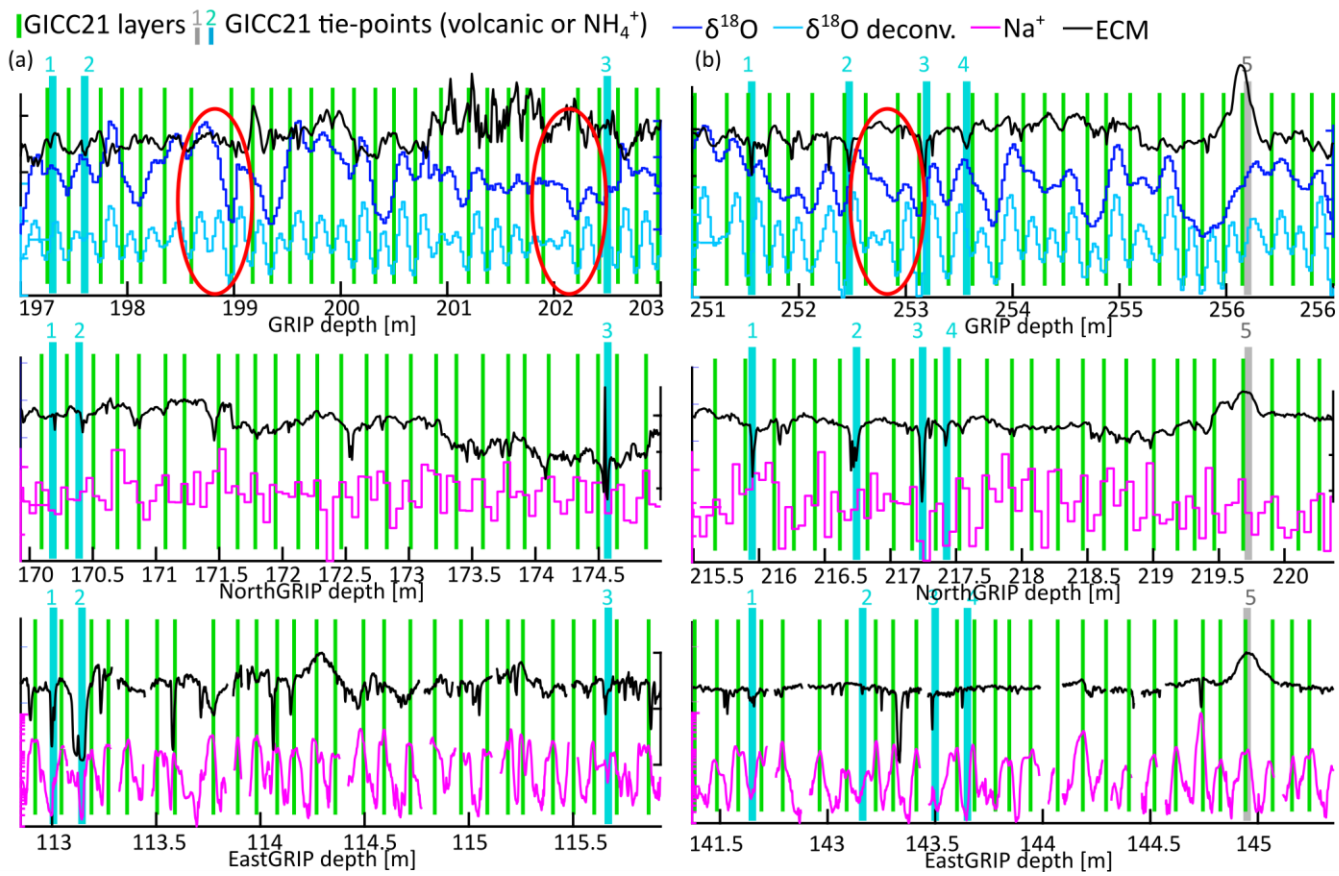

Figure S 6 GRIP spurious layers in deconvoluted $\delta^{18}O$ (red circles). (a) A spurious oscillation possibly caused by a sharp increase of isotopes at 199 m, which produced a deeper-than-average minimum in the deconvoluted series and a double oscillation in the next layer. Comparison to NorthGRIP and EastGRIP was needed to prove that the layer was an artifact. (b) A rather wide, flat isotope layer produces a small oscillation in the deconvoluted signal, which is again solved by comparison to the two other ice cores.

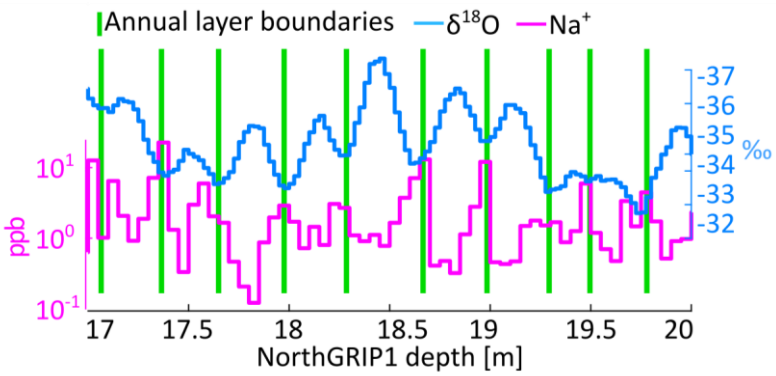

Figure S 7 Section of NorthGRIP1 data close to the surface, where isotope diffusion is not too strong yet. We highlight the equivalence of choosing Na^+ maxima and $\delta^{18}O$ minima as definition for the start of an annual layer.

1. Top-chronology and remarks about the DYE-3 ice core

The DYE-3 ice core is the best ice core to use for directly comparing our results to GICC05, because its well-preserved isotope signal provided the foundation for GICC05 in the last 4000 years. Hence it is important to match it precisely, even for the top 136 m where the ECM is missing. To match the top part of DYE-3, we used two shallow cores, 4B and 18C, drilled respectively 8 km and 36 km upstream of the main drilling site for climate reconstructions (Vinther et al., 2010). Owing to the close distance between the three ice cores , their $\delta^{18}O$ records could be matched by finding common features in the data (Figure S 8). The ECM signal of the two shallow cores was in turn matched to NorthGRIP 1 and GRIP. In this way, DYE-3 has been tied to the timescale for the top 136 m.

Vinther et al. (2010) showed that Greenland ice-core isotope signals correlate well with South West Greenland temperature records, and that the inter-core correlations (e.g. between DYE-3 and GRIP) help assess the quality of the cross-dating of the ice cores. To judge the quality of the new top chronology, we repeated the correlation study of DYE-3 with the South West Greenland (SWG) temperature and with GRIP (Table S 1). The correlation between isotopes of the DYE-3 main core and GRIP improved by $(0.27 - 0.23)/0.23 \approx 17\%$, a promising result that indicates that the matching between DYE-3 and GRIP has improved. Still, the correlation with SWG temperatures is essentially the same as in Vinther et al. (2010). It is reassuring that the new timescale strengthens the link with the SWG temperatures.

	DYE-3 79		DYE-3 4B		DYE-3 18C		GRIP	
	GICC05	GICC21	Vinther et al., 2010	GICC21	Vinther et al., 2010	GICC21	GICC05	GICC21
ρ SWG	0.46	0.47	0.45	0.44	0.35	0.36	0.21	0.20
ρ GRIP	0.23	0.27	0.28	0.31	0.24	0.26		

Table S 1 Correlations (ρ) between $\delta^{18}O$ in the DYE-3 ice cores and the SWG temperatures or the GRIP $\delta^{18}O$ over the last 400 years. The correlation between GRIP and all the DYE-3 ice cores (main core 79 and shallow cores 4B and 18C) have almost all increased with the new GICC21 match. No significant change is observed in the correlation between DYE-3 main core (DYE-3 79) and SWG temperatures, and no significant change is observed in the correlation between the shallow cores and SWG temperatures.

Fine tuning of DYE-3 was made difficult by the ice core's very different characteristics. Upstream surface undulations (Reeh et al., 1985) lead to low-frequency layer thickness fluctuations at depth (main text Fig 6). Further, many layers of DYE-3 show a double isotopic oscillation during the year, a fact made clear during the top match with the shallow cores 4B and 18C. As shown in Figure S 8, the DYE-3 ice core was most affected by over-counting, likely because of mid-year local minima. We speculate that mid-year oscillations in the isotopes of DYE-3 are related to melt layers and to the windy conditions that perhaps cause a redistribution of snow in the area. In cases of doubt about where to place the annual layers, we decided to keep the layer boundaries of the GICC05 timescale where possible without creating annual-layer thickness outliers. Finally, DYE-3 also proved to be the most difficult to match, its ECM record being noisy and not strongly resembling that of the other cores, since it also forms spikes because of the influence of high HNO_3 levels (Clausen et al., 1997).

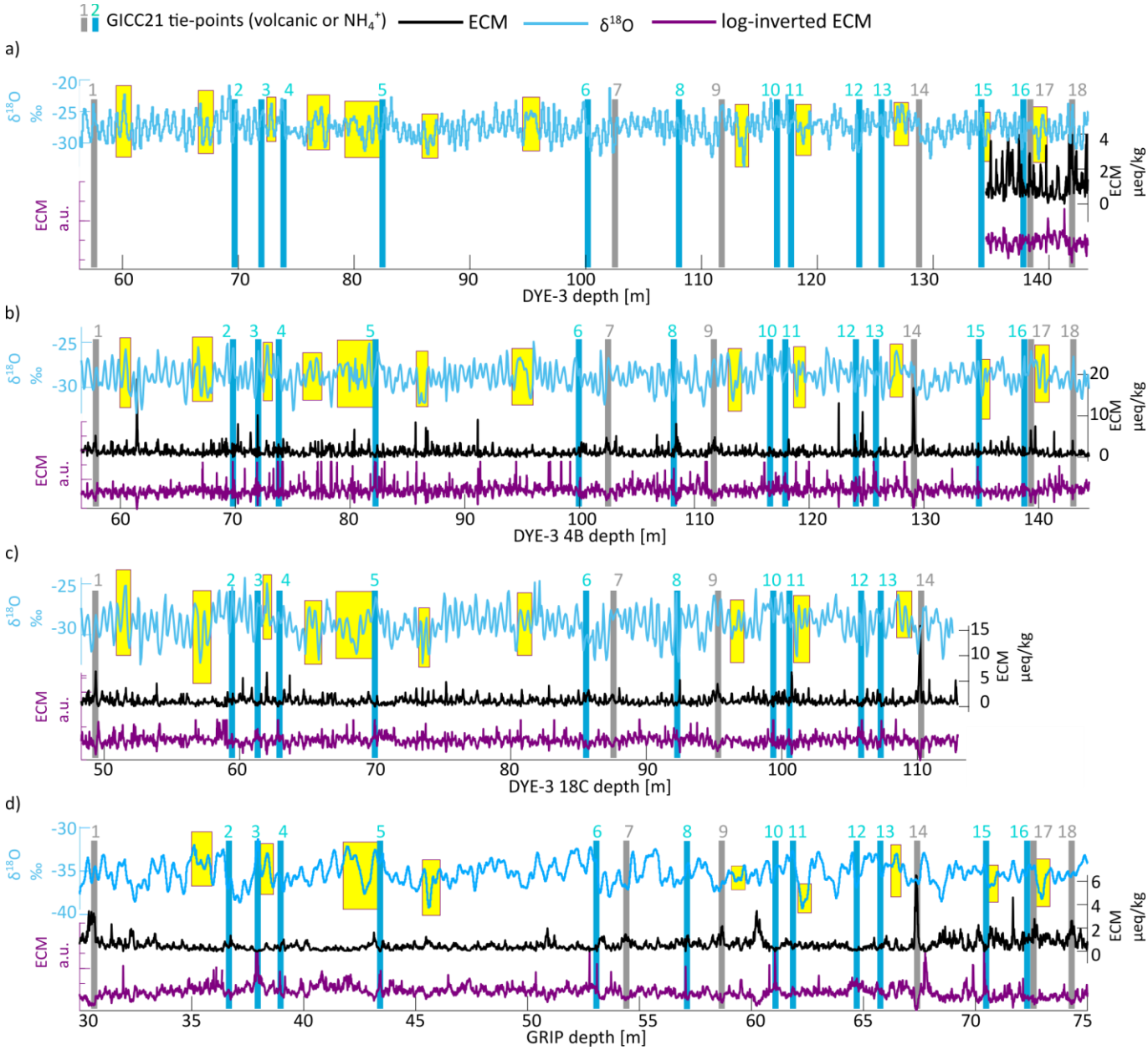

Figure S 8 Matching the top of DYE-3 using the two shallow cores 4B and 18C. Tie-point n.14 is the Laki eruption (1783 CE). Data for 18C covers only until the Laki eruption, while 4B offers a longer overlap with the start of the ECM signal in DYE-3. Yellow patches highlight some of the common features in the isotopic records that were used to match DYE-3 in absence of ECM measurements. Some of the matched features where also visible in GRIP (although GRIP was not used directly for the isotope-based matching). We observed mid-year oscillations in the DYE-3 isotopic signal, visible for example between tie-points no. 13 and 14, a knowledge we applied to interpret DYE-3 layers further on in the chronology.

2. Alternative demonstration of the correlation length

The analysis of Sec. 3.4 (main text) was also performed on sections of 200 and 300 years (numerical results reported in Straticounter Supplement).

To analyze if the uncertainty over centuries are uncorrelated, and hence could be added in quadrature, we evaluated the quantity $\Delta\sigma = \delta t_{i,200}{}^2 - (\delta t_{i,100}{}^2 + \delta t_{i+1,100}{}^2)$, shown in Figure S 9. The meaning of this quantity is that the 200-year deviation from the expected value and the quadrature sum of the 100-year deviation of two adjacent centuries should be

approximately the same if the errors are uncorrelated. The quantity is found to be approximately normally distributed with zero mean (Fig. S9). Consequently, we find this relationship justified for most 200-year intervals.

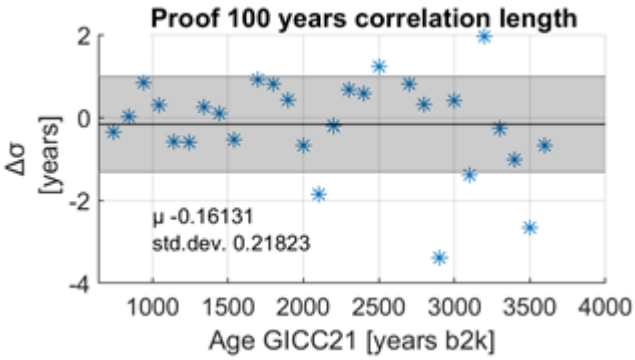

Figure S 9 Comparison of 100- and 200-year deviations to verify the correlation length.

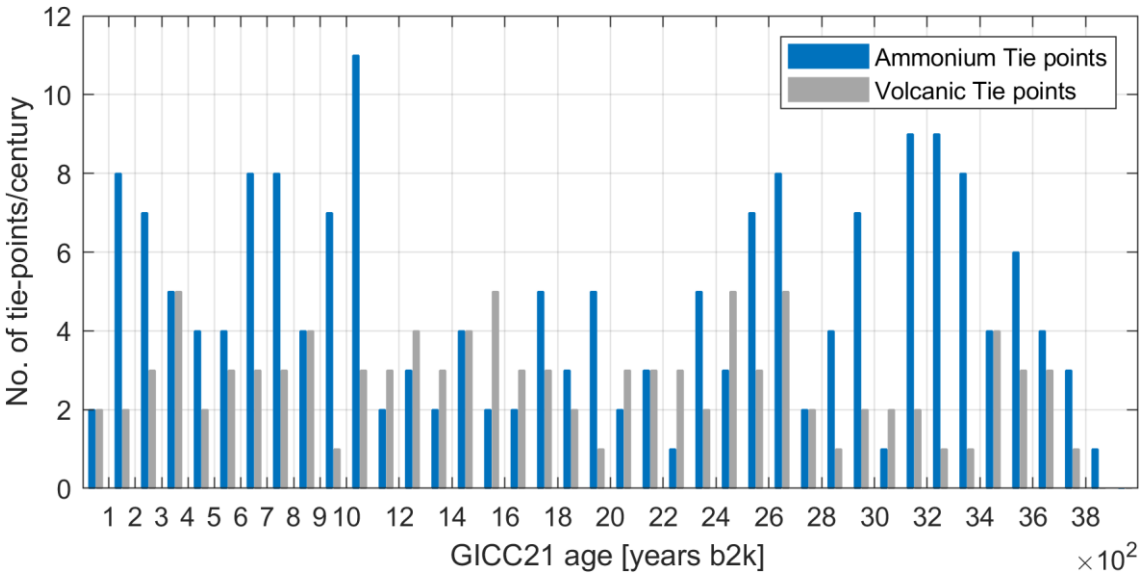

Figure S 10 Number of tie points per century in GICC21. The number of ammonium tie points is largest in the most recent millennium of the time scale, where they were supported by the BC signal of NEEM-2011-S1, and in the period after 2500 years b2k, where ammonium is used to support the volcanic match, especially across intervals with less than 2 volcanic tie-points per century. Generally, ammonium tie points are more because we used patterns instead of single peaks.

References

Andersen, K. K., Svensson, A., Johnsen, S. J., Rasmussen, S. O., Bigler, M., Röthlisberger, R., . . . others. (2006). The Greenland ice core chronology 2005, 15–42 ka. Part 1: constructing the time scale. Quaternary Science Reviews, 25, 3246–3257. https://doi.org/10.1016/j.quascirev.2006.08.002

Büntgen, U., Allen, K., Anchukaitis, K. J., Arseneault, D., Boucher, É., Bräuning, A., ... & Esper, J. (2021). The influence of decision-making in tree ring-based climate reconstructions. Nature communications, 12(1), 1-10. 780 https://doi.org/10.1038/s41467-021-23627-6

Clausen, H. B., Hammer, C. U., Hvidberg, C. S., Dahl-Jensen, D., Steffensen, J. P., Kipfstuhl, J., & Legrand, M. (1997). A comparison of the volcanic records over the past 4000 years from the Greenland Ice Core Project and Dye 3 Greenland ice cores. Journal of Geophysical Research: Oceans, 102(C12), 26707-26723. https://doi.org/10.1029/97JC00587

Gerber, T. A., Hvidberg, C. S., Rasmussen, S. O., Franke, S., Sinnl, G., Grinsted, A., . . . Dahl-Jensen, D. (2021). Upstream flow effects revealed in the EastGRIP ice core using a Monte Carlo inversion of a two-dimensional ice-flow model. The Cryosphere Discussions, 1–32. https://doi.org/10.5194/tc-15-3655-2021

Pearson, C., Salzer, M., Wacker, L., Brewer, P., Sookdeo, A., & Kuniholm, P. (2020). Securing timelines in the ancient Mediterranean using multiproxy annual tree-ring data. Proceedings of the National Academy of Sciences, 117(15), 8410-8415. https://doi.org/10.1073/pnas.1917445117

Reeh, N., Johnsen, S. J., Dahl-Jensen, D., Langway, C. C., Oeschger, H., & Dansgaard, W. (1985). Dating the Dye 3 deep ice core by flow model calculations. Greenland Ice Core: Geophysics, Geochemistry, and the Environment, edited by: Langway, CC, Oeschger, H., and Dansgaard, W., Geophys. Monogr. Series, 33, 57–65. https://doi.org/10.1029/gm033p0057

Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., … Woodruff, T. E. (2015). Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature, 523(7562), 543–549. https://doi.org/10.1038/nature14565

Vinther, B. M., Jones, P. D., Briffa, K. R., Clausen, H. B., Andersen, K. K., Dahl-Jensen, D., & Johnsen, S. J. (2010). Climatic signals in multiple highly resolved stable isotope records from Greenland. Quaternary Science Reviews, 29(3-4), 522-538. https://doi.org/10.1016/j.quascirev.2009.11.002