Supplementary Information for

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

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Contents

S1. Supplementary Tables

Table S 1 Information about each ice core's SC run. The preprocessing steps are reported in the Timescale Supplement. A minor modification to the code of SC was made to allow for separate runs on adjacent parts of the data. This was deemed necessary as the layer pattern, layer thickness, and the data availability are not constant throughout each core. Hence, each core was divided into depth intervals which are counted subsequently. The probability information was transferred from one section to the next, however a manual count of 30 layers is needed in each section. It is preferable to count the ice core again as a whole ('whole-run' column) to obtain a more compact probability distribution, which can be done by feeding SC the raw count of the sections. However, the layer boundaries were often sufficiently well-positioned to avoid performing such an additional run.

Ice core	Counted intervals [m]	Comment on whole run
EastGRIP	13-27, 27-61, 61-100, 100-250, 250-300, 300-350, 350-450	Not necessary
NEEM	10 equal sections within [7-194] m, 20 equal sections within [194-750] m	A whole run was performed over [7-194] m;
NEEM-2011-S1	3 equal sections within [6-411] m	Not necessary
GRIP	5-100,100-200,200-300,300-700,700-800	Not necessary
NorthGRIP1	26 equal sections within [9-365] m	A whole run was performed on the entire data.
NorthGRIP2	5 equal sections within [159-526] m	A whole run was performed on the entire data.
DYE-3	A separate layer count for 0-100 (no ECM), 15 equal sections within [100-1600] m	A whole run was produced for the interval [450-1600] m

Table S 2 Manual calibration of the missing layers caused by data gaps and by the SC undercount. Missing layers are manually added based on the layer thickness in the surrounding sections. EastGRIP and NEEM needed the most inserted layers, because small gaps arise as a consequence of the occasional core-quality problems, brittle ice, and trimming of the ice pieces. In other cases, wide data gaps occur due to ice-core breaks. For example, at 300 years after 742, EastGRIP lacked 11 layers, because a total of 1 m of ice was missing. We observe that NorthGRIP2 only needed inserted layers after 2700 years b2k, where the data are becoming scarce and that NEEM is also suffering from increasing data gaps after 3500 years b2k.

Manually inserted gap layers

	Start	EastGRIP			NorthGRIP1			NorthGRIP2			GRIP			NEEM			NEEM-S1-2011			DYE-3		
Section	(yr b2k)	100	200	300	100	200	300	100	200	300	100	200	300	100	200	300	100	200	300	100	200	300

1	a	742	5	6	11	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0
	b	842	1	6		0	0		0	0		0	0		0	0		0	0		0	0	
	c	942	5			0			0			0			0			0			0		
2	a	1700	0	0	1	0			0	0	0	0	0	1	2	2	3	0	0	0	0	0	0
	b	1800		0	1				0	0		0	1		0	1		0			0	0	
	c	1900		1					0			1			1						0		
3	a	2700	4	5	7				9	9	16	0	0	1	1	2	6				0	0	0
	b	2800	1	3					0	7		0	1		1	5					0	0	
	c	2900	2									1			4						0		
4	a	3500	0	0	0							1	1	1	3	11	18				1	1	1
	b	3600	0	0								0	0		8	15					0	0	
	c	3700	0									0			7						0		

S2. Supplementary Figures

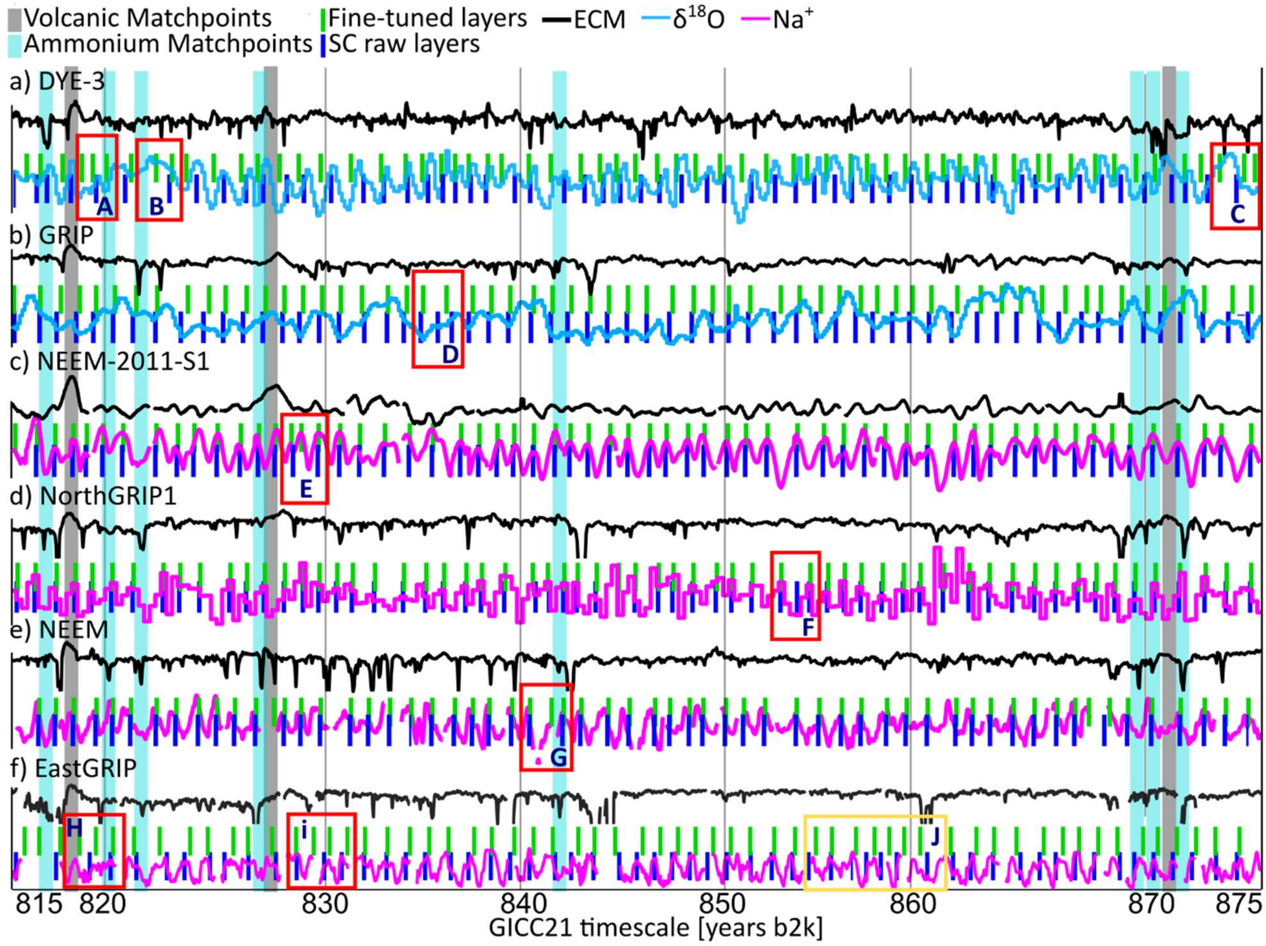

Figure S 1 Example of the fine-tuning decisional process between 815 and 875 years b2k. The units of all data are arbitrary, as they were log-transformed and vertically adjusted to better highlight the layer structure and the common matching features. Red and yellow rectangles show some examples of where 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. Rect H: An additional layer was inserted because of unclear sodium. Rectangle i: SC did not recognize this annual layer because of the interrupted data. Rect J: re-placement of layers did not result in any modification to the count.

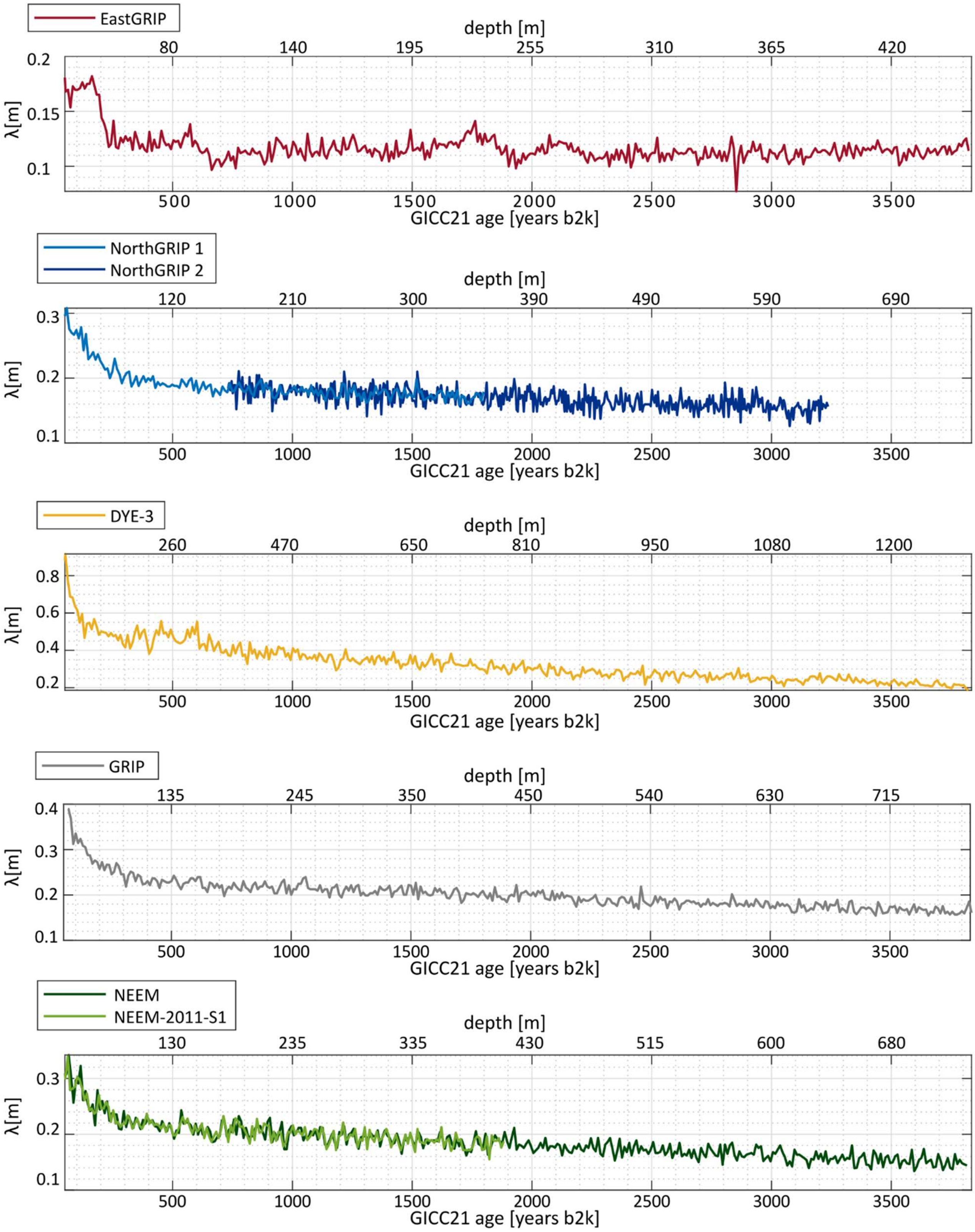

Figure S 2 The layer thickness of all ice cores from the GICC21 timescale, which provides the basis for reconstructing the accumulation rate of Greenlandic ice cores (Andersen, et al., 2006). To retrieve the accumulation, one still needs to account for thinning due to flow and to model the firn densification. 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.

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 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 thinning and increased upstream accumulation, while 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.

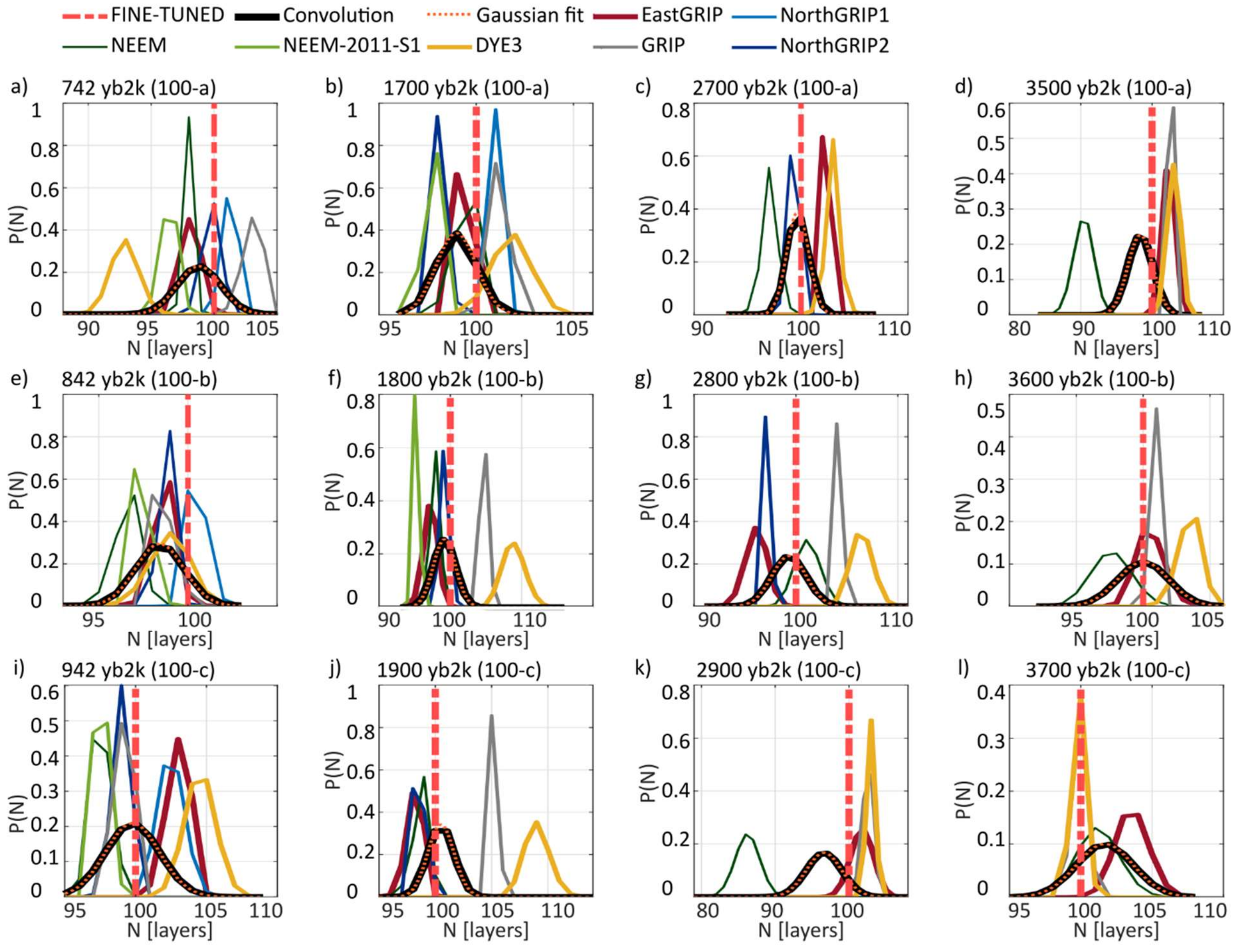

Figure S 3 Single-core probability density functions (pSC) of the number of years counted by SC in 100-year sections. All ice cores were corrected for missing layers in data gaps (Table S 2). The fine-tuned result (red line, dashed) is often far off the single pSC. In some cases, we observed a systematic 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.

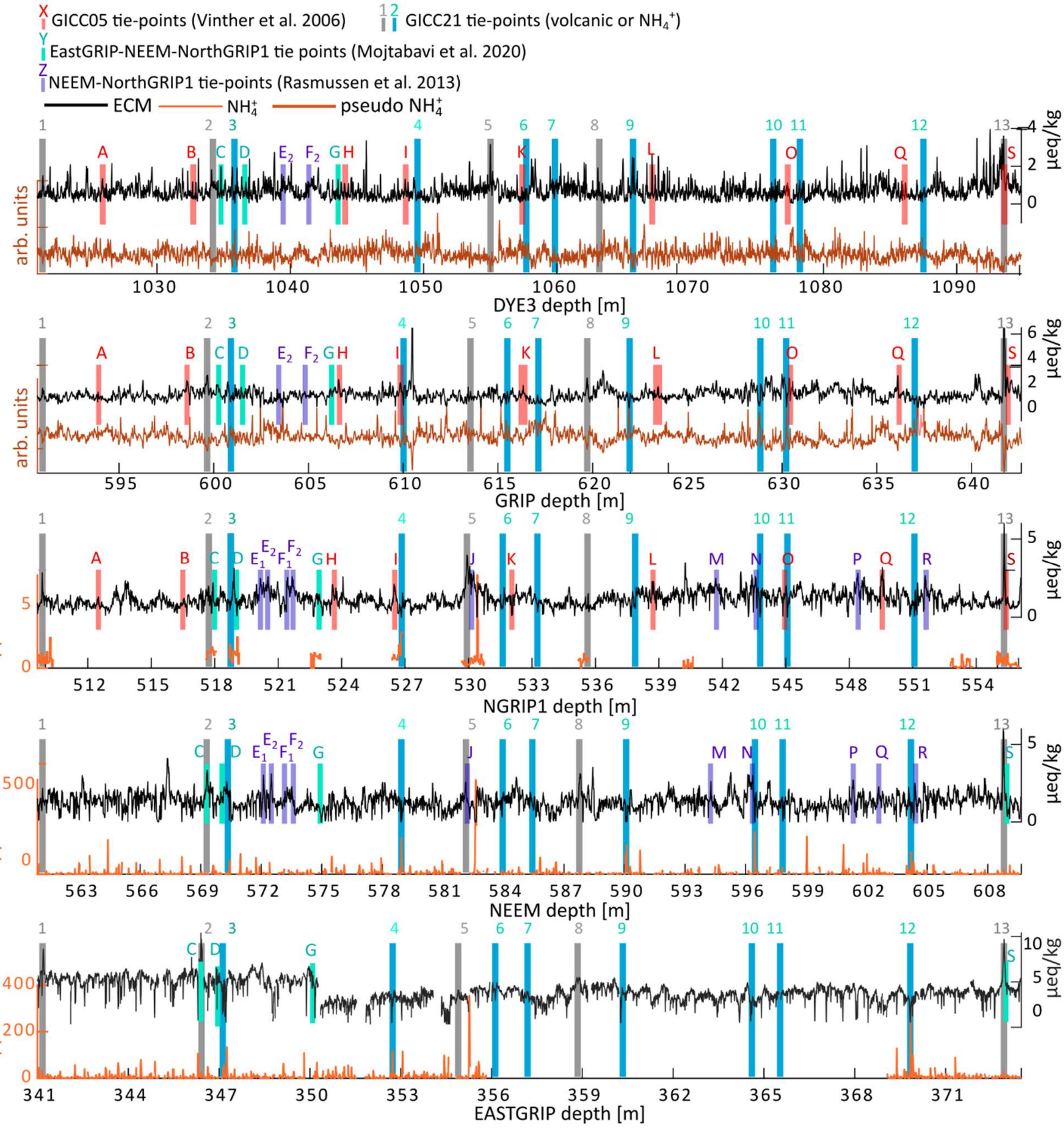

Figure S 4 Example of a matching problem solved in GICC21 between 2800 and 3100 years b2k. Tie-points of GICC05 are indicated by bars with letters, while tie-points of GICC21 are indicated by numbered bars (see figure legend). The relative order between the tie-points of GICC21 and GICC05 confirms the 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.

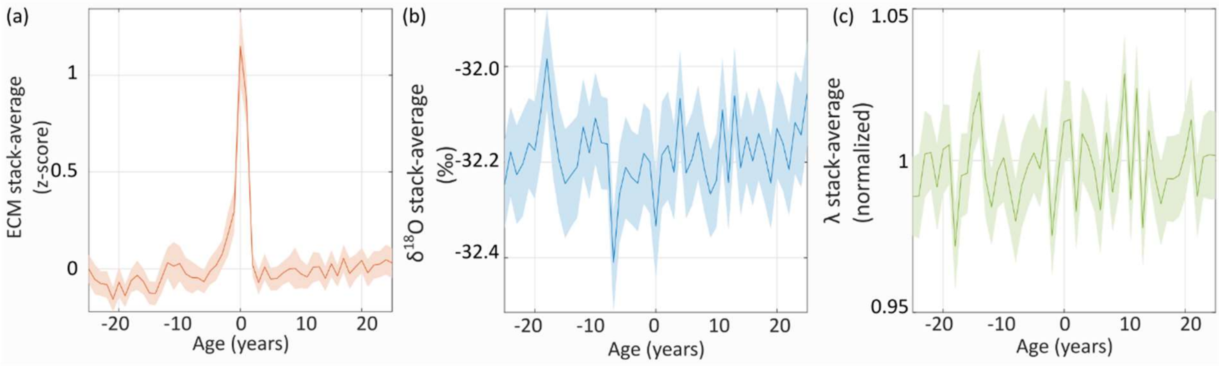

Figure S 5 Signal stack-averages on the GICC05 timescales around 105 eruptions. The average was made around the same eruptions matched in the GICC21 timescale; time is flowing from right to left. Data used for the averages are limited to DYE-3, NorthGRIP, and GRIP, to reproduce the GICC05 data availability and to avoid interpolating GICC05 to annual resolution for the other ice cores. (a) The ECM stack-average is again showing a maximum at 0 years. (b) The $\delta^{18}O$ stack-average does not highlight a significant minimum of more than one year duration. (c) The layer thickness stack-average shows no significant decrease.

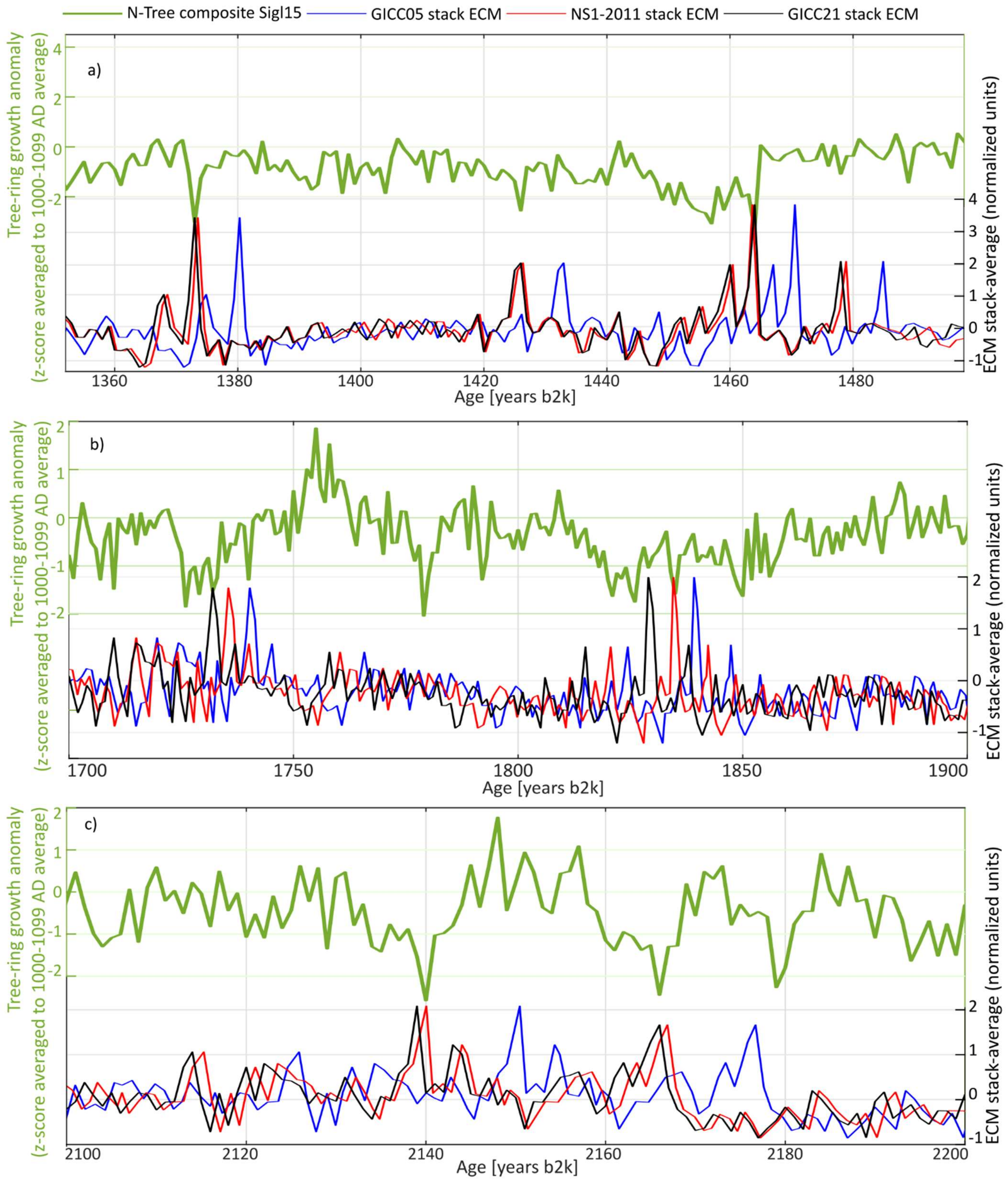

Figure S 6 Comparison of the ice-core ECM stack, shifted according to the three compared ice core timescales, and the N-Tree growth-anomaly record provided in Sigl15. (a) Between 1360 and 1480 years b2k, we observed good alignment of the ECM-stack with N-Tree local minima, except for when the ice cores are plotted according to GICC05. This fact links the 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. No clear N-tree minima are observed here, so that this method does not settle the discrepancy between GICC21 and the other two timescales in this timeframe. (c) The agreement is recovered again between 2100 and 2200 years b2k, although smaller differences between GICC21 and NS1-2011 are observed.

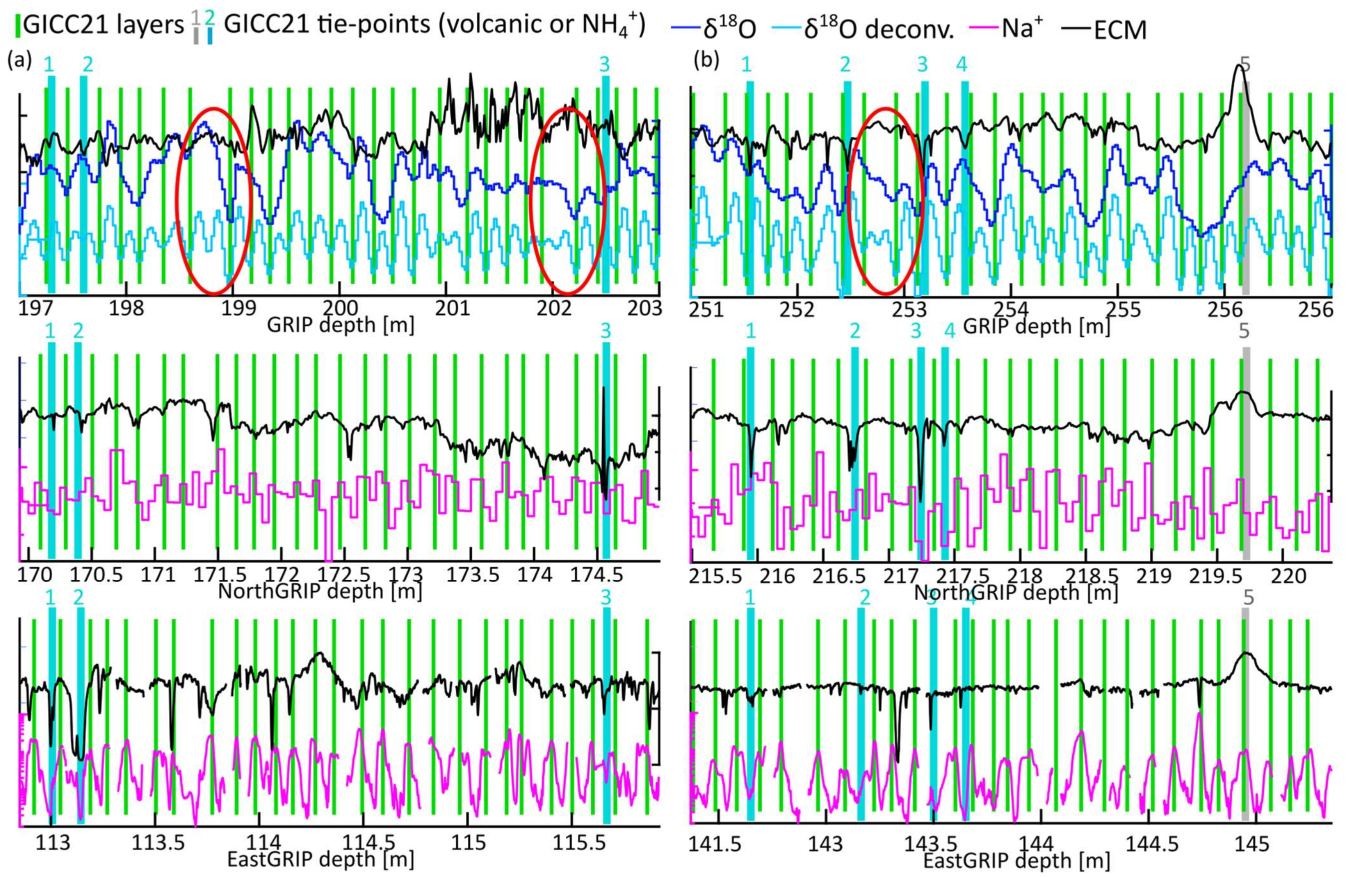

Figure S 7 GRIP spurious layers in deconvoluted $\delta^{18}O$ (red circles). (a) A spurious oscillation possibly caused by a sharp increase of isotopes at 199 m, which produced a deeper-than-average minimum in the deconvoluted series and a double oscillation in the next layer. Comparison to NorthGRIP 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.

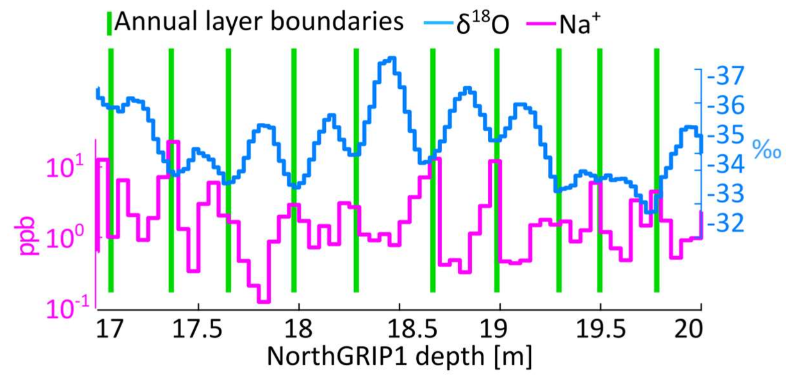

Figure S 8 Section of NorthGRIP1 data close to the surface, where isotope diffusion is not too strong yet. We highlight the equivalence of choosing Na^+ maxima and $\delta^{18}O$ minima as definition for the start of an annual layer.