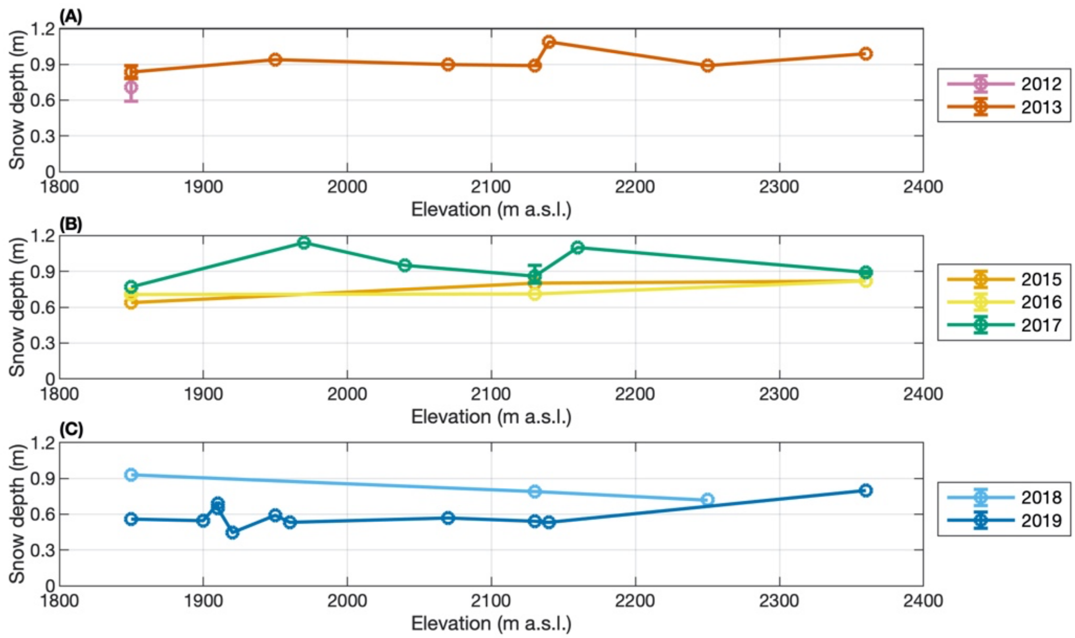
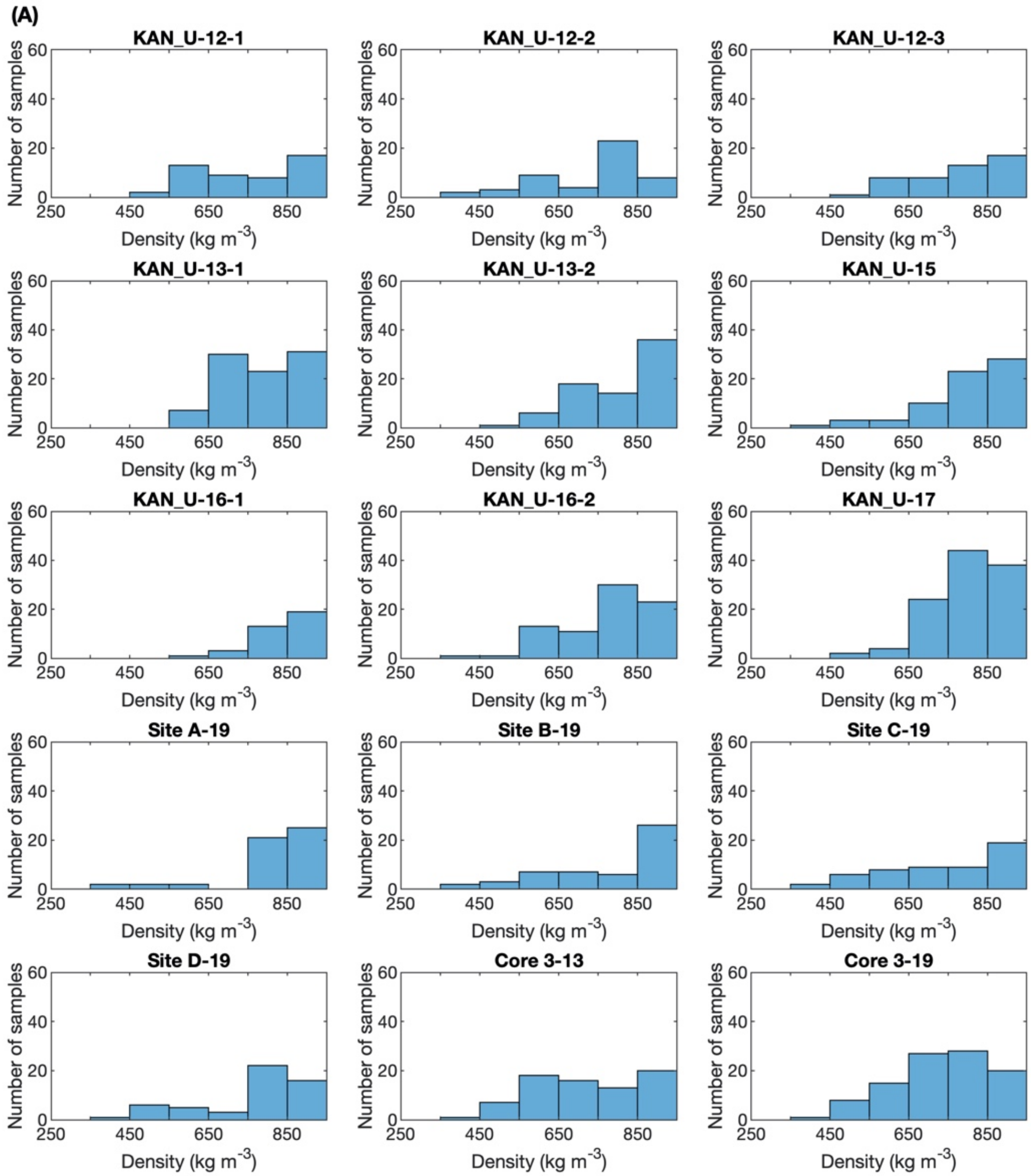
Supplementary Material

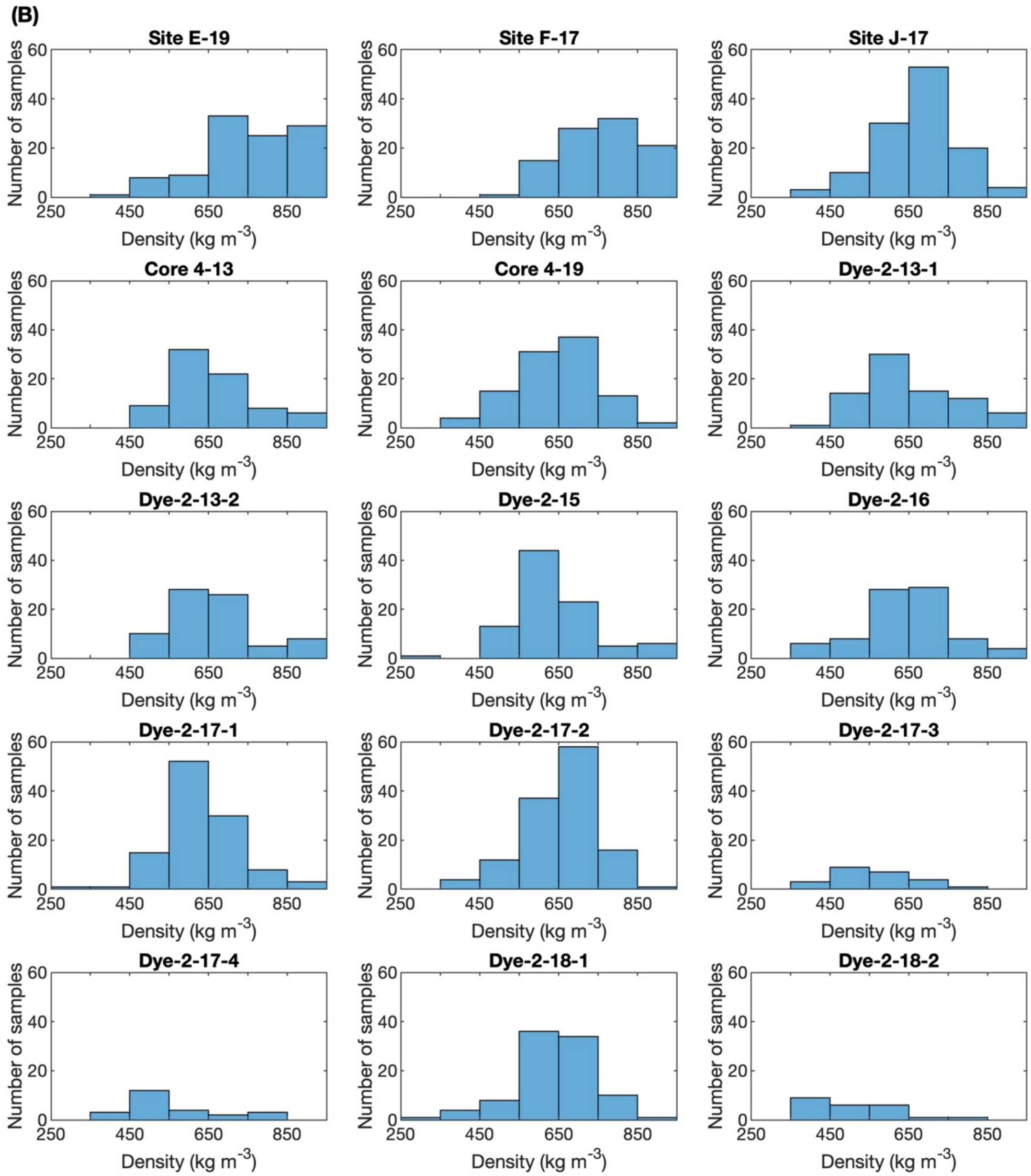
1 Supplementary Figures and Tables

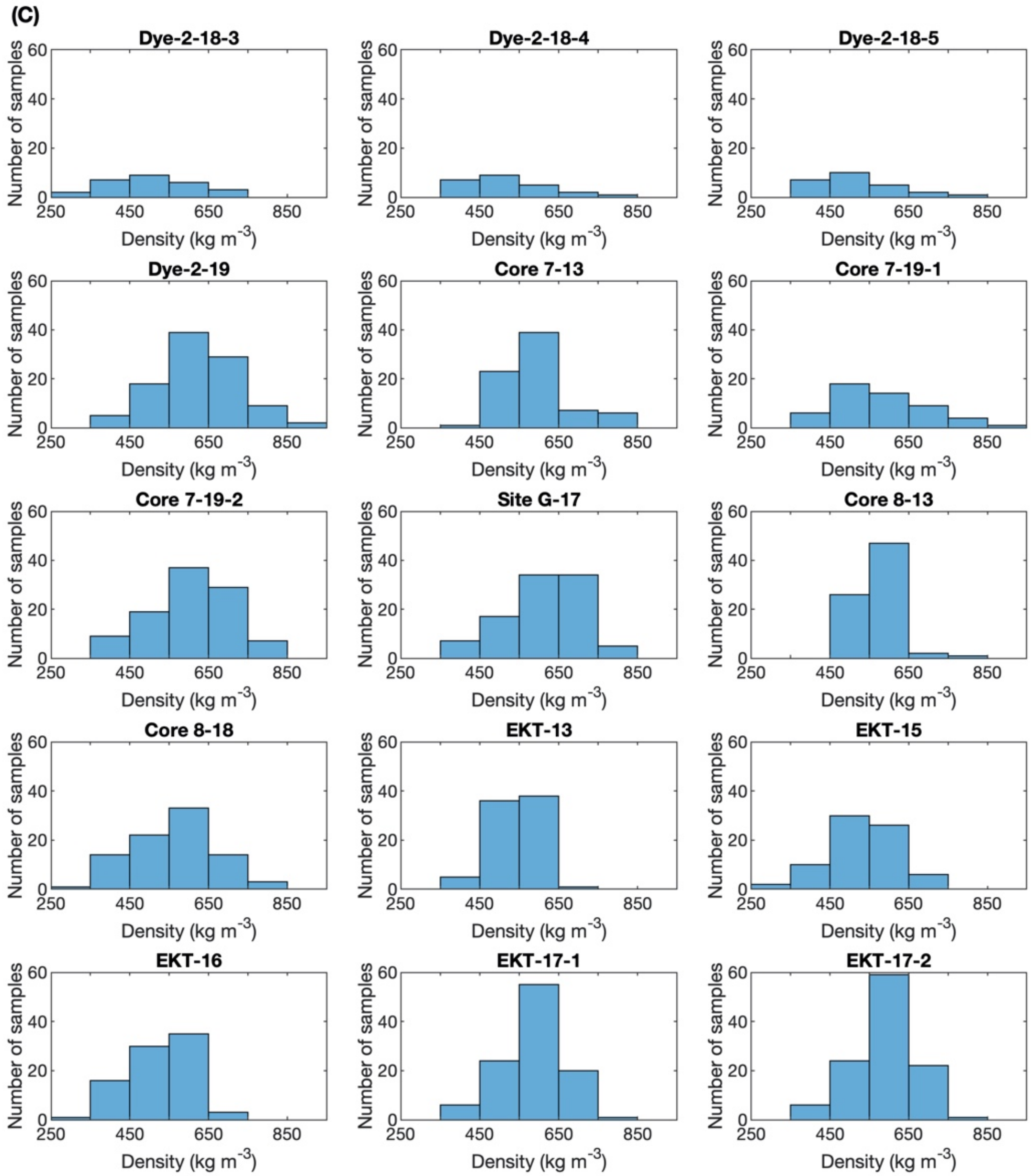
1.1 Supplementary Figures



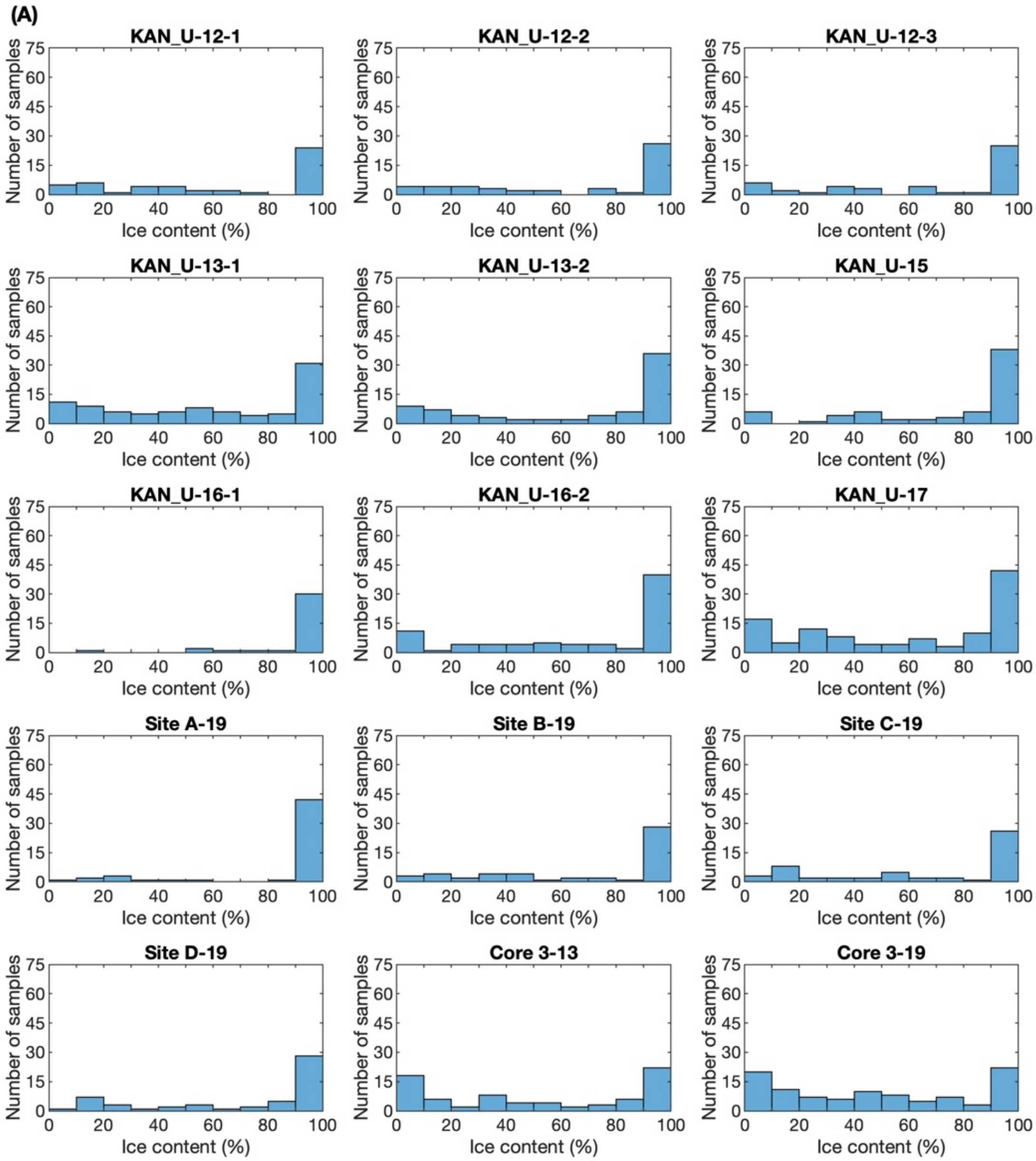
Supplementary Figure S1. Average snow depth measured in April–May at core sites during (**A**) 2012–2013, (**B**) 2015–2017, and (**C**) 2018–2019. The error bars show the ranges of the snow depths when there are multiple measurements. The snow depth averages and ranges were calculated from field measurements (snow depths from the 45 cores and the three additional observations described in the methods section) between late April to late May.


(A)
KAN_U-12-1
KAN_U-12-2
KAN_U-12-3
KAN_U-13-1
KAN_U-13-2
KAN_U-15
KAN_U-16-1
KAN_U-16-2
KAN_U-17
Site A-19
Site B-19
Site C-19
Site D-19
Core 3-13
Core 3-19
Number of samples
Density (kg m-3)
0
20
40
60
250
450
650
850

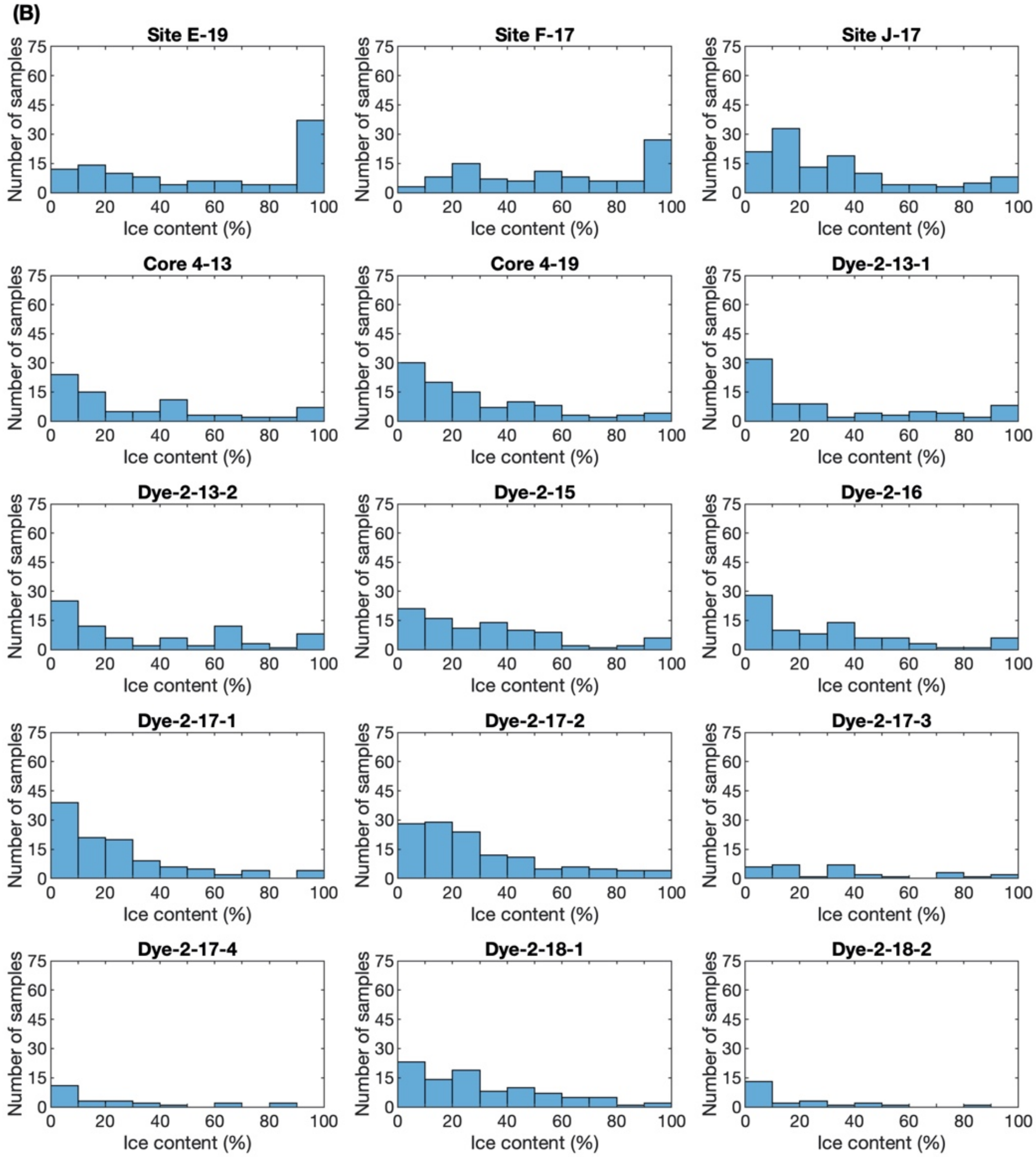

(B)
Site E-19
Site F-17
Site J-17
Core 4-13
Core 4-19
Dye-2-13-1
Dye-2-13-2
Dye-2-15
Dye-2-16
Dye-2-17-1
Dye-2-17-2
Dye-2-17-3
Dye-2-17-4
Dye-2-18-1
Dye-2-18-2
Number of samples
Density (kg m-3)
0
20
40
60
250
450
650
850

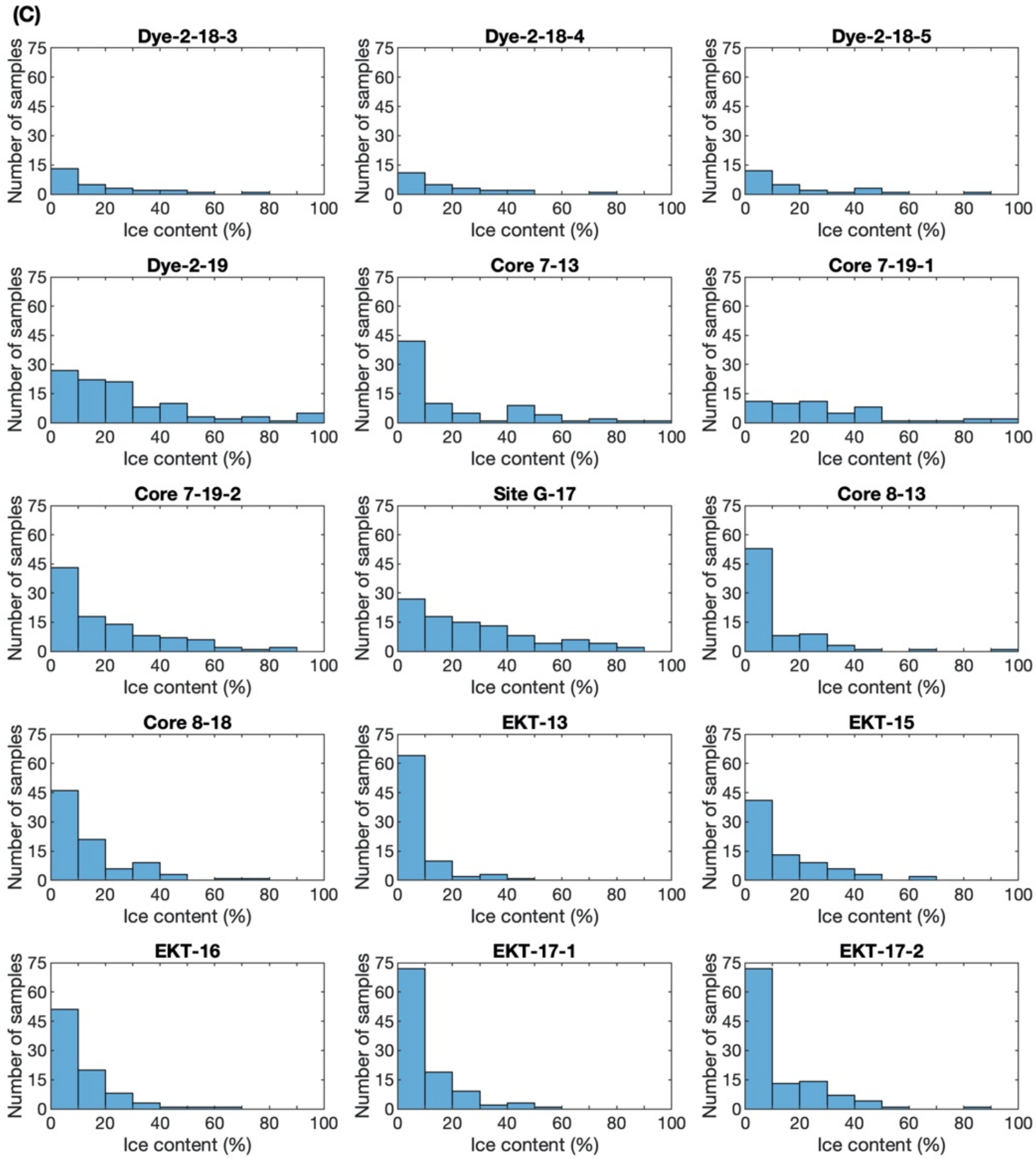


Supplementary Figure S2. Distribution of density data (sampled at every 0.2 m) for all 45 cores (below the winter snow layer). The one-sample Kolmogorov-Smirnov tests show that neither of the 45 density datasets comes from a normal distribution.

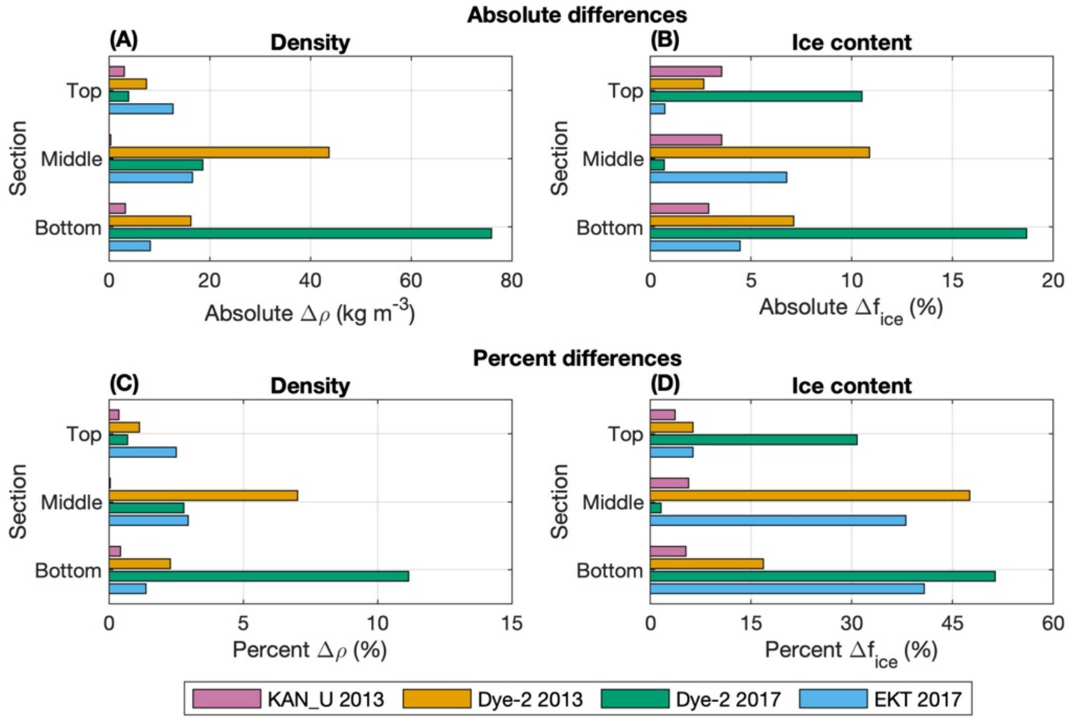

(A)
KAN_U-12-1
KAN_U-12-2
KAN_U-12-3
KAN_U-13-1
KAN_U-13-2
KAN_U-15
KAN_U-16-1
KAN_U-16-2
KAN_U-17
Site A-19
Site B-19
Site C-19
Site D-19
Core 3-13
Core 3-19
Number of samples
Ice content (%)
0
15
30
45
60
75
0
20
40
60
80
100

(B)

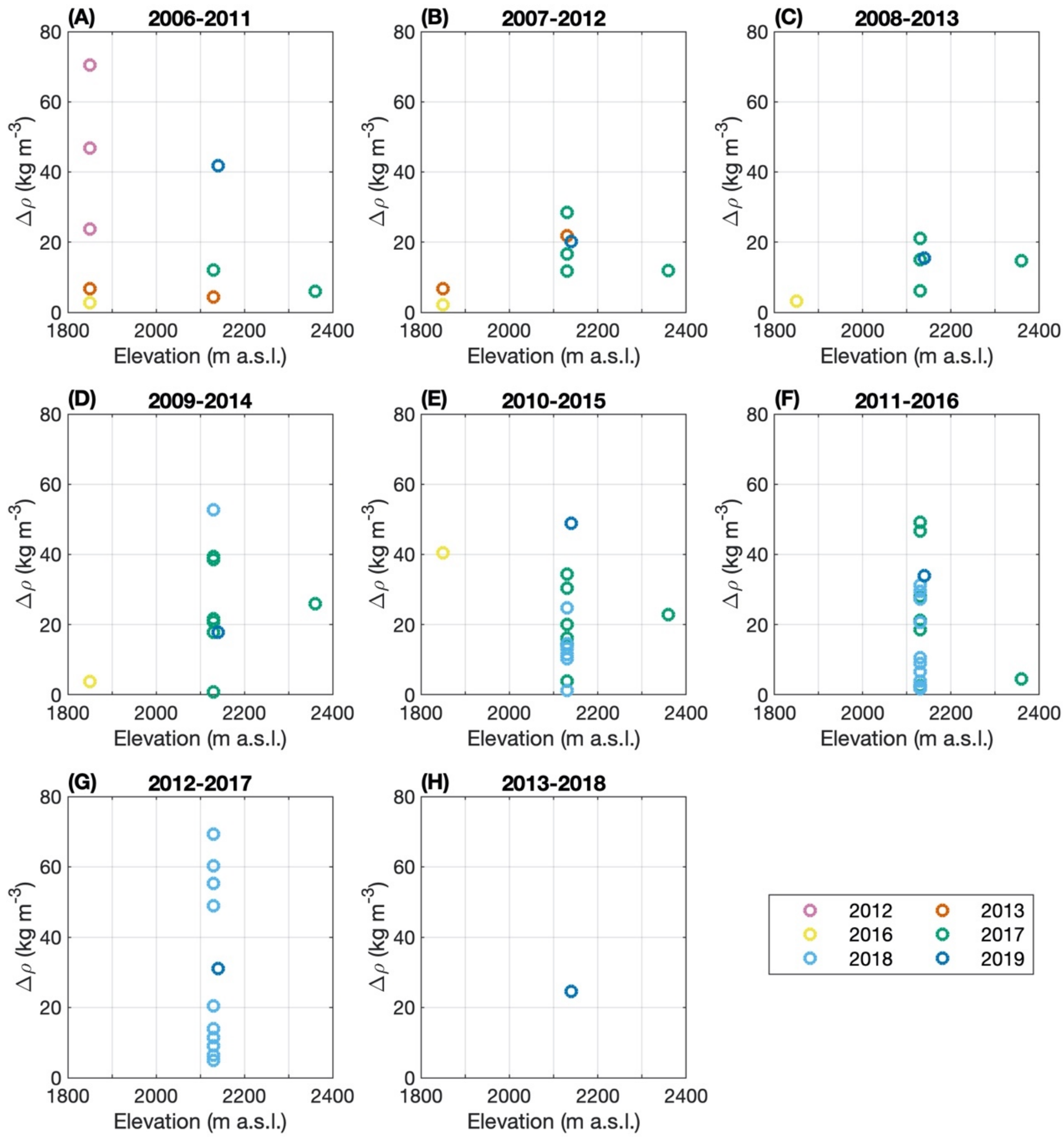

Site E-19
Site F-17
Site J-17
Core 4-13
Core 4-19
Dye-2-13-1
Dye-2-13-2
Dye-2-15
Dye-2-16
Dye-2-17-1
Dye-2-17-2
Dye-2-17-3
Dye-2-17-4
Dye-2-18-1
Dye-2-18-2
Number of samples
Ice content (%)
0
15
30
45
60
75
0
20
40
60
80
100



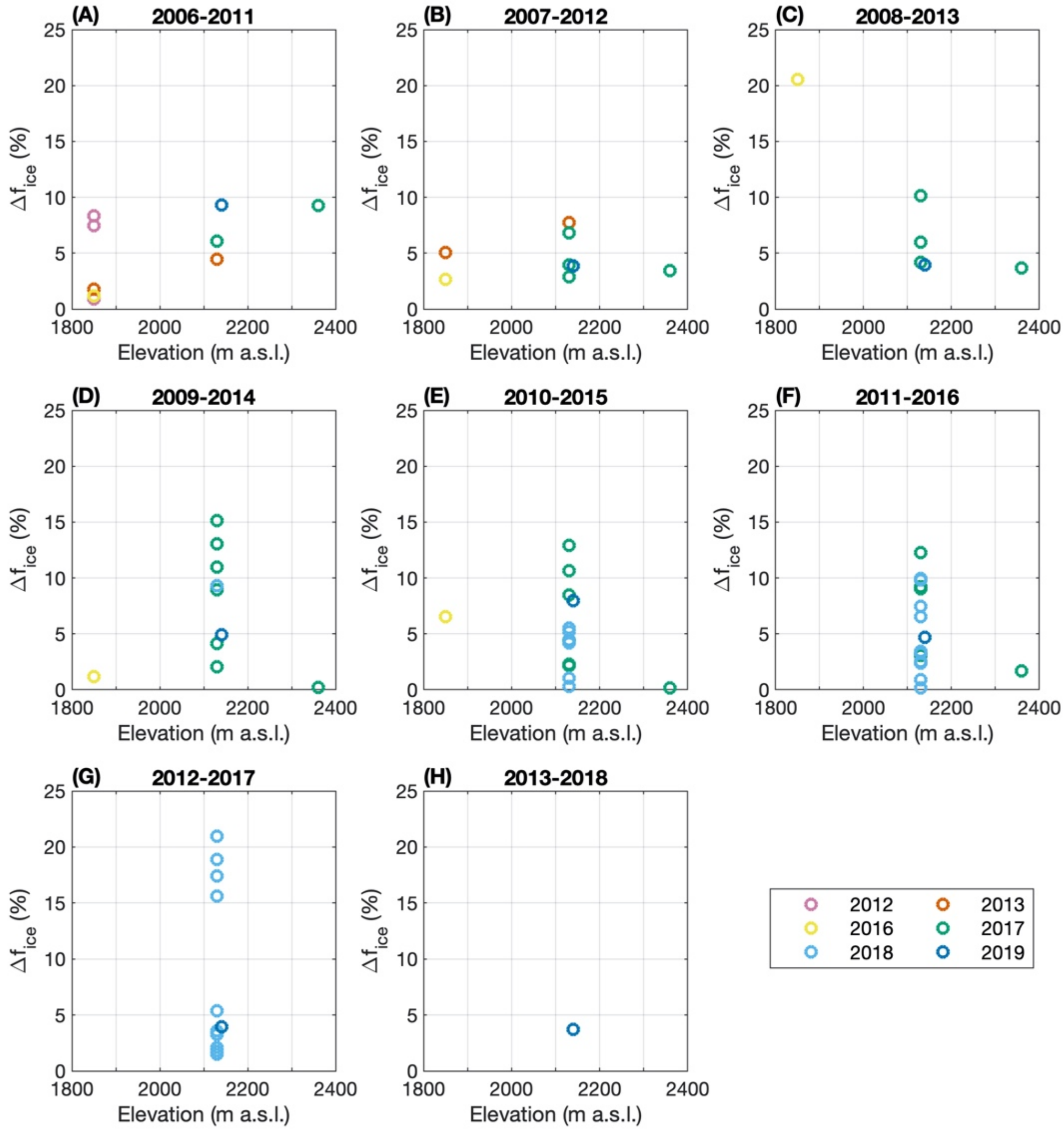
Supplementary Figure S3. Distribution of ice content data (sampled at every 0.2 m) for all 45 cores (below the winter snow layer). The one-sample Kolmogorov-Smirnov tests show that neither of the 45 ice content datasets comes from a normal distribution.



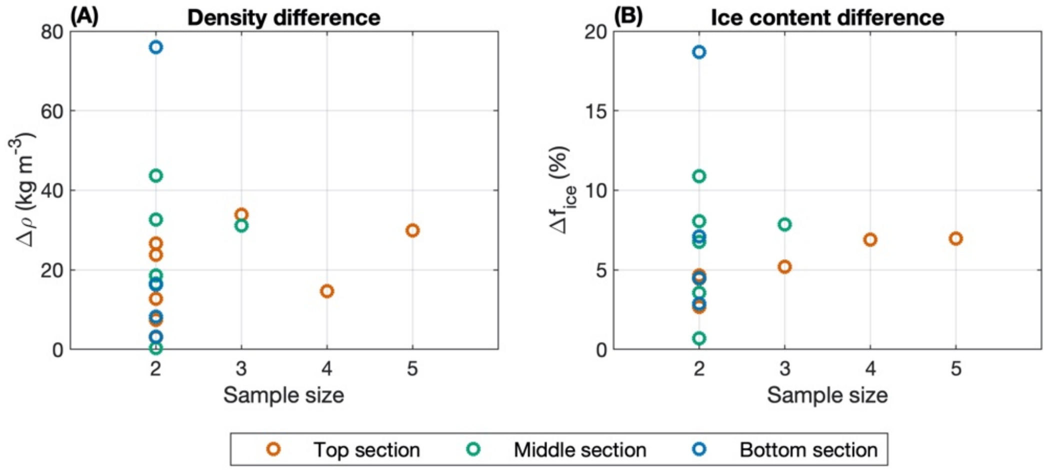
Supplementary Figure S4. Absolute (**A, B**) and percent (**C, D**) differences in mean density (Δρ) and ice content (Δf_{ice}) between four pairs of same site/year cores over three depth sections. The top, middle and bottom sections refer to the 0–4.5 m, 4.5–9 m and 9–13.5 m below the winter snow layer, respectively.



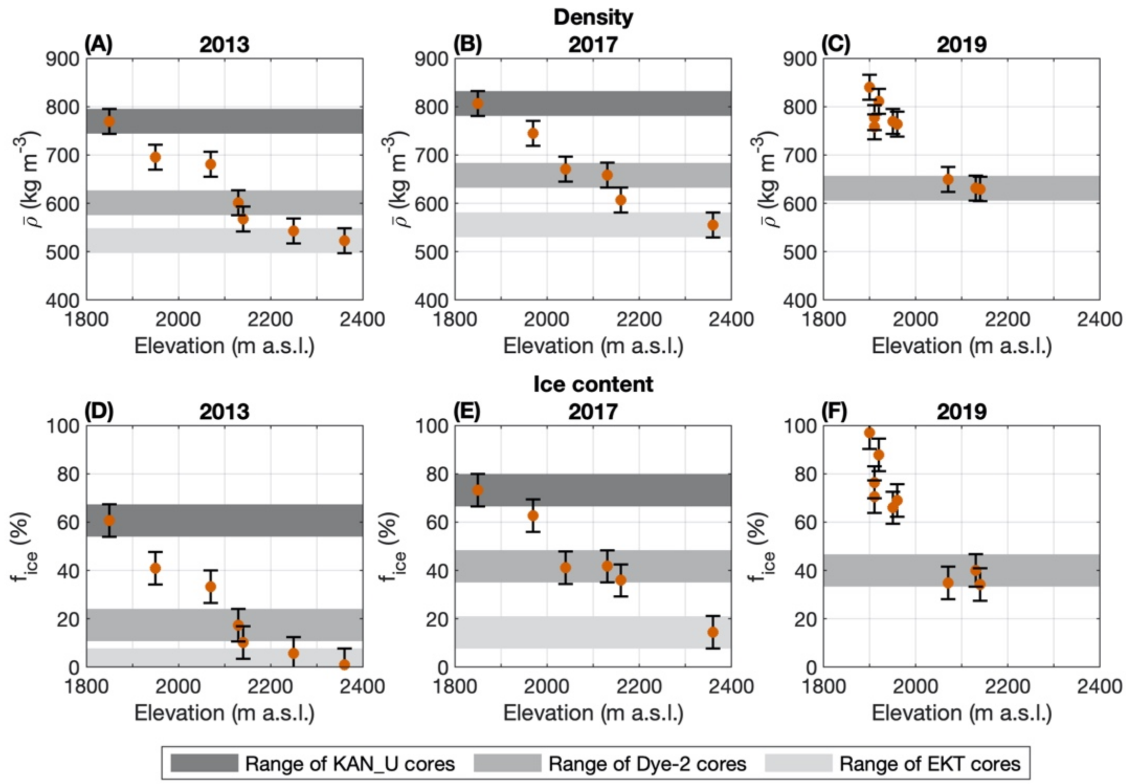
Supplementary Figure S5. Absolute differences in mean density (Δρ) between every same site/year core pair. Each figure shows core density differences calculated using core segments covering the same five years (about 3.36 m long, based on depth-age relationships from Rennermalm et al., 2021a): (**A**) 2006–2011, (**B**) 2007–2012, (**C**) 2008–2013, (**D**) 2009–2014, (**E**) 2010– 2015, (**F**) 2011–2016, (**G**) 2012– 2017, (**H**) 2013–2018. Different colors refer to different core retrieval years.



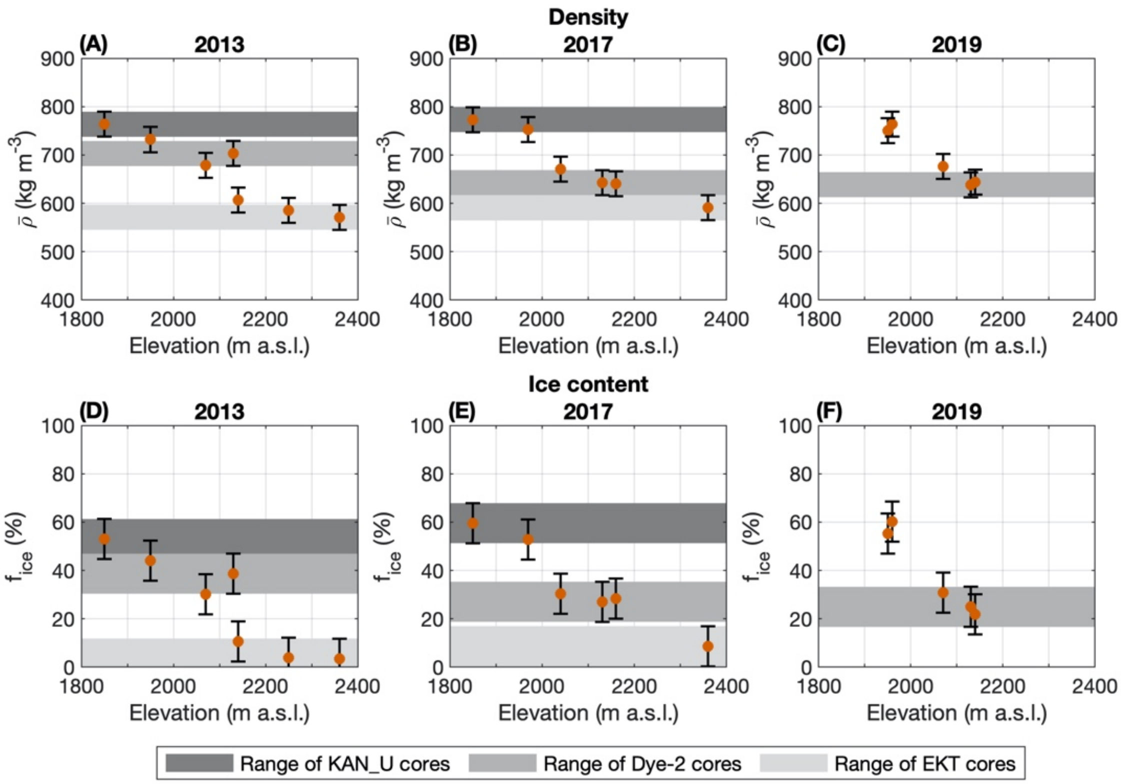
Supplementary Figure S6. Absolute differences in ice content (Δf_{ice}) between every same site/year core pair. Each figure shows core ice content differences calculated using core segments covering the same five years (about 3.36 m long, based on depth-age relationships from Rennermalm et al., 2021a): (**A**) 2006–2011, (**B**) 2007–2012, (**C**) 2008–2013, (**D**) 2009–2014, (**E**) 2010– 2015, (**F**) 2011–2016, (**G**) 2012– 2017, (**H**) 2013–2018. Different colors refer to different core retrieval years.



Supplementary Figure S7. Absolute differences in mean density (Δρ; **A**) and ice content (Δf_{ice}; **B**) between every core pair from the same site and year (i.e., the same group) in three depth sections, compared with the sample size of each group. The top, middle and bottom sections refer to the 0–4.5 m, 4.5–9 m and 9–13.5 m below the winter snow layer, respectively.



Supplementary Figure S8. Core density and ice content over the middle section in 2013 (**A, D**), 2017 (**B, E**) and 2019 (**C, F**). The average density and ice content were presented if there are several cores available at a certain site in a certain year. For the error bar (local variability), we used the average absolute difference of density and ice content in the middle section shown in **Figures 7A, B** (26 kg m^{-3} and 7%). The ranges (density/ice content ± local variability) of KAN_U, Dye-2 and EKT were marked in different gray shades. The middle section refers to the 4.5–9 m below the winter snow layer.



Supplementary Figure S9. Core density and ice content over the bottom section in 2013 (**A, D**), 2017 (**B, E**) and 2019 (**C, F**). The average density and ice content were presented if there are several cores available at a certain site in a certain year. For the error bar (local variability), we used the average absolute difference of density and ice content in the bottom section shown in **Figures 7A, B** (26 kg m^{-3} and 8%). The ranges (density/ice content ± local variability) of KAN_U, Dye-2 and EKT were marked in different gray shades. The bottom section refers to the 9–13.5 m below the winter snow layer.

1.2 Supplementary Tables

Supplementary Table S1. Firn cores used in this study. The elevation was extracted from the ArcticDEM 1 km v3.0 product by the Polar Geospatial Center (Porter et al., 2018) adjusted using the EGM2008 geoid offset (Pavlis et al., 2012). Data source refers to 1) Machguth et al. (2016), 2) MacFerrin et al. (2019), 3) Vandecrux et al. (2019), and 4) Rennermalm et al. (2021a). Same site/year cores are marked in bold. Cores denoted by asterisk in the data source column were not presented in the source publications but included in the accompanying datasets.

Core	Year	Date	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Core length (m)	Segment length (μ ± δ) (m)	Data source
KAN_U-12-1	2012	1 May	67.00025	-47.02130	1850	10.7	0.09 ± 0.07	1
KAN_U-12-2	2012	1 May	67.00025	-47.02138	1850	10.5	0.07 ± 0.05	1
KAN_U-12-3	2012	1 May	66.99825	-47.02083	1850	10.3	0.09 ± 0.03	1
KAN_U-13-1	2013	27 Apr	67.00025	-47.02263	1850	19.1	0.11 ± 0.03	1
KAN_U-13-2	2013	28 Apr	66.99837	-47.02213	1850	15.9	0.11 ± 0.06	1
KAN_U-15	2015	5 May	67.00042	-47.02472	1850	14.4	0.11 ± 0.05	2
KAN_U-16-1	2016	26 Apr	67.00038	-47.02615	1850	8.0	0.10 ± 0.02	2
KAN_U-16-2	2016	28 Apr	67.00038	-47.02615	1850	16.5	0.10 ± 0.02	2
KAN_U-17	2017	28 Apr	67.00025	-47.02263	1850	23.3	0.11 ± 0.05	2
Site A-19	2019	23 May	66.56002	-47.10570	1900	11.1	0.09 ± 0.06	4
Site B-19	2019	26 May	66.55124	-47.09964	1910	10.9	0.12 ± 0.07	4
Site C-19	2019	27 May	66.55383	-47.06741	1910	11.3	0.09 ± 0.07	4
Site D-19	2019	28 May	66.54686	-47.02390	1920	11.2	0.09 ± 0.06	4
Core 3-13	2013	30 Apr	66.97795	-46.62850	1950	16.0	0.10 ± 0.02	1
Core 3-19	2019	7–8 May	66.97809	-46.62807	1950	20.5	0.12 ± 0.07	4
Site E-19	2019	21 May	66.52671	-46.94749	1960	21.6	0.13 ± 0.07	4
Site F-17	2017	15 May	66.52740	-46.88664	1970	20.6	0.14 ± 0.08	4
Site J-17	2017	28 Apr–1 May	66.86495	-46.26514	2040	25.0	0.14 ± 0.04	4
Core 4-13	2013	3 May	66.98218	-46.11945	2070	16.3	0.10 ± 0.02	1
Core 4-19	2019	3–4 May	66.98287	-46.11959	2070	21.0	0.16 ± 0.09	4
Dye-2-13-1	2013	5 May	66.47758	-46.28472	2130	16.6	0.10 ± 0.04	1
Dye-2-13-2	2013	5 May	66.47260	-46.28298	2130	16.5	0.10 ± 0.02	1
Dye-2-15	2015	21 May	66.47771	-46.28606	2130	19.3	0.11 ± 0.05	3

Dye-2-16	2016	6 May	66.47260	-46.28298	2130	17.4	0.10 ± 0.04	3
Dye-2-17-1	2017	11 May	66.47260	-46.28298	2130	23.0	0.09 ± 0.04	3
Dye-2-17-2	2017	13–14 May	66.47804	-46.28713	2130	26.7	0.13 ± 0.06	4
Dye-2-17-3	2017	11 May	66.47260	-46.28298	2130	7.0	0.05 ± 0.01	3
Dye-2-17-4	2017	12 May	66.47260	-46.28298	2130	5.8	0.05 ± 0.01	3
Dye-2-18-1	2018	9–11 May	66.47787	-46.28674	2130	19.8	0.12 ± 0.06	4
Dye-2-18-2	2018	18 May	66.47807	-46.28720	2130	5.4	0.12 ± 0.05	4*
Dye-2-18-3	2018	18 May	66.47807	-46.28716	2130	6.4	0.14 ± 0.06	4*
Dye-2-18-4	2018	18 May	66.47802	-46.28690	2130	5.7	0.12 ± 0.06	4*
Dye-2-18-5	2018	18 May	66.47799	-46.28674	2130	6.0	0.12 ± 0.06	4*
Dye-2-19	2019	19–20 May	66.47805	-46.28870	2130	21.0	0.16 ± 0.07	4
Core 7-13	2013	15 May	66.98458	-45.75465	2140	16.4	0.10 ± 0.02	1
Core 7-19-1	2019	6 May	66.98480	-45.75423	2140	11.0	0.13 ± 0.07	4
Core 7-19-2	2019	9 May	66.98444	-45.75443	2140	20.8	0.17 ± 0.07	4
Site G-17	2017	16 May	66.53512	-45.95919	2160	20.5	0.14 ± 0.05	4
Core 8-13	2013	13 May	66.98322	-45.04490	2250	16.3	0.11 ± 0.03	1
Core 8-18	2018	19–20 May	66.98269	-45.04649	2250	18.2	0.19 ± 0.13	4
EKT-13	2013	19 May	66.98528	-44.39360	2360	17.0	0.11 ± 0.03	1
EKT-15	2015	9 May	66.99411	-44.38539	2360	15.7	0.11 ± 0.07	3
EKT-16	2016	2 May	66.98543	-44.39465	2360	18.0	0.10 ± 0.01	3
EKT-17-1	2017	2 May	66.98528	-44.39360	2360	22.2	0.09 ± 0.06	3
EKT-17-2	2017	8 May	66.98541	-44.39508	2360	23.5	0.13 ± 0.04	4

Supplementary Table S2. The Mann-Whitney *U*-test analysis result difference when using two different sampling intervals. The Mann-Whitney *U*-test analysis in Section 3.4 (conducting the *U*-tests for all core pairs from the same year in the three depth sections) was performed for different sampling intervals ranging from 0.1–0.3 m. For example, for the top section (top 0–4.5 m below the winter snow layer), we conducted the Mann-Whitney *U*-tests to examine the density similarity of all 153 pairs of cores from the same year using sampling intervals of 0.1 m and 0.2 m, respectively. The number of core pairs whose densities do not have equal medians (i.e., the null hypothesis is rejected, and the h-index is 1) is 98 and 91, respectively, which gives a *U*-test analysis result difference of 7.1%. A positive difference indicates that the first interval leads to more different *U*-test results than the second interval, while a negative difference suggests that the first interval leads to more similar results. Only selected comparisons are shown here.

Sampling intervals (m)	The Mann-Whitney *U*-test analysis result difference (%)					
	Top section 0–4.5 m		Middle section 4.5–9 m		Bottom section 9–13.5 m	
	Density	Ice content	Density	Ice content	Density	Ice content
0.1 vs 0.2	7.1	13.5	6.9	6.8	6.6	7.3
0.15 vs 0.2	4.2	10.0	4.7	5.7	5.0	3.8
0.25 vs 0.2	-3.3	1.1	1.2	-2.4	-1.8	0.0
0.3 vs 0.2	-8.8	1.1	0.0	-6.1	-7.0	-13.7

Notes:

As discussed in Section 2.3, the sampling interval has an impact on the Mann-Whitney *U*-test. The smaller the sampling interval (i.e., the higher the sampling frequency), the more likely that the null hypothesis is rejected (i.e., the two cores do not have equal medians). On the contrary, the larger the sampling interval, the more likely the null hypothesis cannot be rejected. An appropriate sampling interval should be neither too small to enhance unrealistic heterogeneity, nor too large to fail to capture the local variability. Based on the core segment lengths (mean ± std. dev. = 0.11 ± 0.05 m), the sampling interval should not be smaller than ~0.1 m. In addition, a wide sampling interval (e.g., > 0.3 m) provides limited samples and is likely to smooth out the local variability. Therefore, we determined that sampling intervals ranging between 0.1–0.3 m are generally suitable for our cores.

We repeated the Mann-Whitney *U*-test analyses in Section 3.4 (conducting the *U*-tests for all core pairs from the same year in the three depth sections) using different sampling intervals between 0.1–0.3 m. A difference of 0.01 m in the sampling interval produces a result difference (absolute) ranging from 0.0–12.2%, with an average of 2.7%. Compared to 0.2 m, using a sampling interval of 0.1 m leads to a result difference of 6.6–13.5%; using a sampling interval of 0.3 m leads to a result difference of -13.7–1.1%. The sensitivity test shows that the Mann-Whitney *U*-tests results do not vary much when using different intervals between 0.1–0.3 m. For our study, we decided to use 0.2 m as the sampling interval.

Supplementary Table S3. Absolute and percent differences in mean density between pairs of cores from the same site and year in three depth sections.

Same site/year core pair		Depth below the snow-firn interface					
		Top section 0–4.5 m		Middle section 4.5–9 m		Bottom section 9–13.5 m	
Core 1	Core 2	Absolute difference (kg m^{-3})	Percent difference (%)	Absolute difference (kg m^{-3})	Percent difference (%)	Absolute difference (kg m^{-3})	Percent difference (%)
KAN_U-12-1	KAN_U-12-2	40	5	17	2	–	–
KAN_U-12-1	KAN_U-12-3	11	1	47	6	–	–
KAN_U-12-2	KAN_U-12-3	51	7	29	4	–	–
KAN_U-13-1	KAN_U-13-2	3	0	0	0	3	0
KAN_U-16-1	KAN_U-16-2	27	3	–	–	–	–
Dye-2-13-1	Dye-2-13-2	7	1	44	7	16	2
Dye-2-17-1	Dye-2-17-2	4	1	19	3	76	11
Dye-2-17-1	Dye-2-17-3	4	1	–	–	–	–
Dye-2-17-1	Dye-2-17-4	24	4	–	–	–	–
Dye-2-17-2	Dye-2-17-3	0	0	–	–	–	–
Dye-2-17-2	Dye-2-17-4	28	5	–	–	–	–
Dye-2-17-3	Dye-2-17-4	28	5	–	–	–	–
Dye-2-18-1	Dye-2-18-2	52	9	–	–	–	–
Dye-2-18-1	Dye-2-18-3	73	13	–	–	–	–
Dye-2-18-1	Dye-2-18-4	51	9	–	–	–	–
Dye-2-18-1	Dye-2-18-5	56	10	–	–	–	–
Dye-2-18-2	Dye-2-18-3	20	4	–	–	–	–
Dye-2-18-2	Dye-2-18-4	1	0	–	–	–	–
Dye-2-18-2	Dye-2-18-5	4	1	–	–	–	–
Dye-2-18-3	Dye-2-18-4	21	4	–	–	–	–
Dye-2-18-3	Dye-2-18-5	17	3	–	–	–	–
Dye-2-18-4	Dye-2-18-5	4	1	–	–	–	–
Core 7-19-1	Core 7-19-2	24	5	33	5	–	–
EKT-17-1	EKT-17-2	13	3	17	3	8	1

Supplementary Table S4. Absolute and percent differences in ice content between pairs of cores from the same site and year in three depth sections.

Same site/year core pair		Depth below the snow-firn interface					
		Top section 0–4.5 m		Middle section 4.5–9 m		Bottom section 9–13.5 m	
Core 1	Core 2	Absolute difference (%)	Percent difference (%)	Absolute difference (%)	Percent difference (%)	Absolute difference (%)	Percent difference (%)
KAN_U-12-1	KAN_U-12-2	8	10	8	13	–	–
KAN_U-12-1	KAN_U-12-3	1	1	12	17	–	–
KAN_U-12-2	KAN_U-12-3	7	9	4	5	–	–
KAN_U-13-1	KAN_U-13-2	4	4	4	6	3	5
KAN_U-16-1	KAN_U-16-2	5	5	–	–	–	–
Dye-2-13-1	Dye-2-13-2	3	6	11	48	7	17
Dye-2-17-1	Dye-2-17-2	11	31	1	2	19	51
Dye-2-17-1	Dye-2-17-3	10	29	–	–	–	–
Dye-2-17-1	Dye-2-17-4	0	0	–	–	–	–
Dye-2-17-2	Dye-2-17-3	1	3	–	–	–	–
Dye-2-17-2	Dye-2-17-4	11	31	–	–	–	–
Dye-2-17-3	Dye-2-17-4	10	29	–	–	–	–
Dye-2-18-1	Dye-2-18-2	13	43	–	–	–	–
Dye-2-18-1	Dye-2-18-3	15	52	–	–	–	–
Dye-2-18-1	Dye-2-18-4	15	50	–	–	–	–
Dye-2-18-1	Dye-2-18-5	11	37	–	–	–	–
Dye-2-18-2	Dye-2-18-3	3	16	–	–	–	–
Dye-2-18-2	Dye-2-18-4	2	13	–	–	–	–
Dye-2-18-2	Dye-2-18-5	2	9	–	–	–	–
Dye-2-18-3	Dye-2-18-4	0	3	–	–	–	–
Dye-2-18-3	Dye-2-18-5	4	23	–	–	–	–
Dye-2-18-4	Dye-2-18-5	4	21	–	–	–	–
Core 7-19-1	Core 7-19-2	4	29	8	21	–	–
EKT-17-1	EKT-17-2	1	6	7	38	4	41