

SUPPLEMENTARY MATERIAL FOR:

Shallow firn cores 1989 - 2019 in southwest Greenland's percolation zone reveal decreasing density and ice layer thickness after 2012

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Table S1: Core site locations. Refer to Table 1 for information about data collection year and other information.

Core	Latitude (°N)	Longitude (°E)
KAN_U-09-1	67.00025	-47.02130
KAN_U-09-2	67.00025	-47.02130
KAN_U-12-1	67.00025	-47.02130
KAN_U-12-2	67.00025	-47.02138
KAN_U-12-3	66.99825	-47.02083
KAN_U-13-1	67.00025	-47.02263
KAN_U-13-2	66.99837	-47.02213
KAN_U-15	67.00042	-47.02472
KAN_U-16-1	67.00038	-47.02615
KAN_U-16-2	67.00038	-47.02615
KAN_U-17	67.00025	-47.02263
KAN_U-18	67.00000	-47.02900
KAN_U-19	67.00000	-47.03000
Site A-19	66.56000	-47.10600
Site B-19	66.55100	-47.10000
Site C-19	66.55400	-47.06700
Site D-19	66.54700	-47.02400
Core 3-13	66.97795	-46.62850
Core 3-19	66.97800	-46.62800
Site E-19	66.52700	-46.94700
Site F-17	66.52700	-46.88700
Site J-89	66.90000	-46.30000
Site J-17	66.86500	-46.26500
Core 4-13	66.98218	-46.11945
Core 4-19	66.98300	-46.12000
Dye-2-98	66.50000	-46.30000
Dye-2-13-1	66.47758	-46.28472
Dye-2-13-2	66.47260	-46.28298
Dye-2-15	66.47771	-46.28606
Dye-2-16	66.47260	-46.28298
Dye-2-17-1	66.47260	-46.28298
Dye-2-17-2	66.47800	-46.28700
Dye-2-18	66.47800	-46.28700
Dye-2-19	66.47800	-46.28900
Core 7-13	66.98458	-45.75465
Core 7-16	66.98418	-45.75316
Core 7-19-1	66.98500	-45.75400
Core 7-19-2	66.98400	-45.75400
Site G-17	66.53500	-45.95900
Core 8-13	66.98322	-45.04490
Core 8-18	66.98300	-45.04600
EKT-13	66.98528	-44.39360
EKT-15	66.99411	-44.38539
EKT-16	66.98543	-44.39465
EKT-17-1	66.98528	-44.39360
EKT-17-2	66.98500	-44.39500

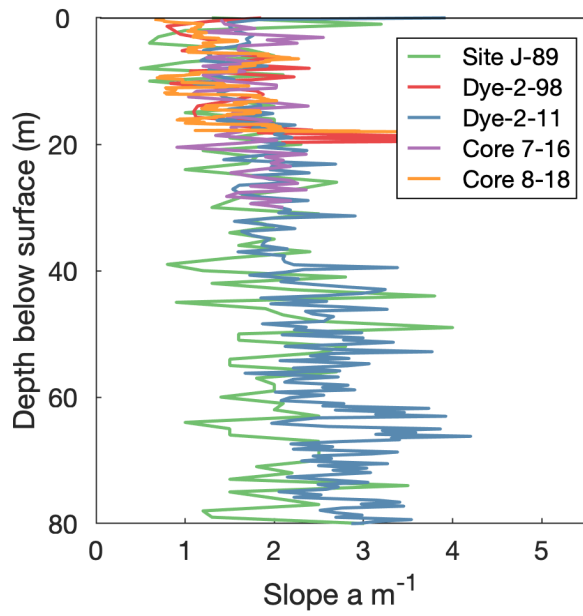


Figure S1. Slope of the depth-age relationship vs. depth. The slope of the depth-age relationship was calculated as the change in age over each measured core segment.

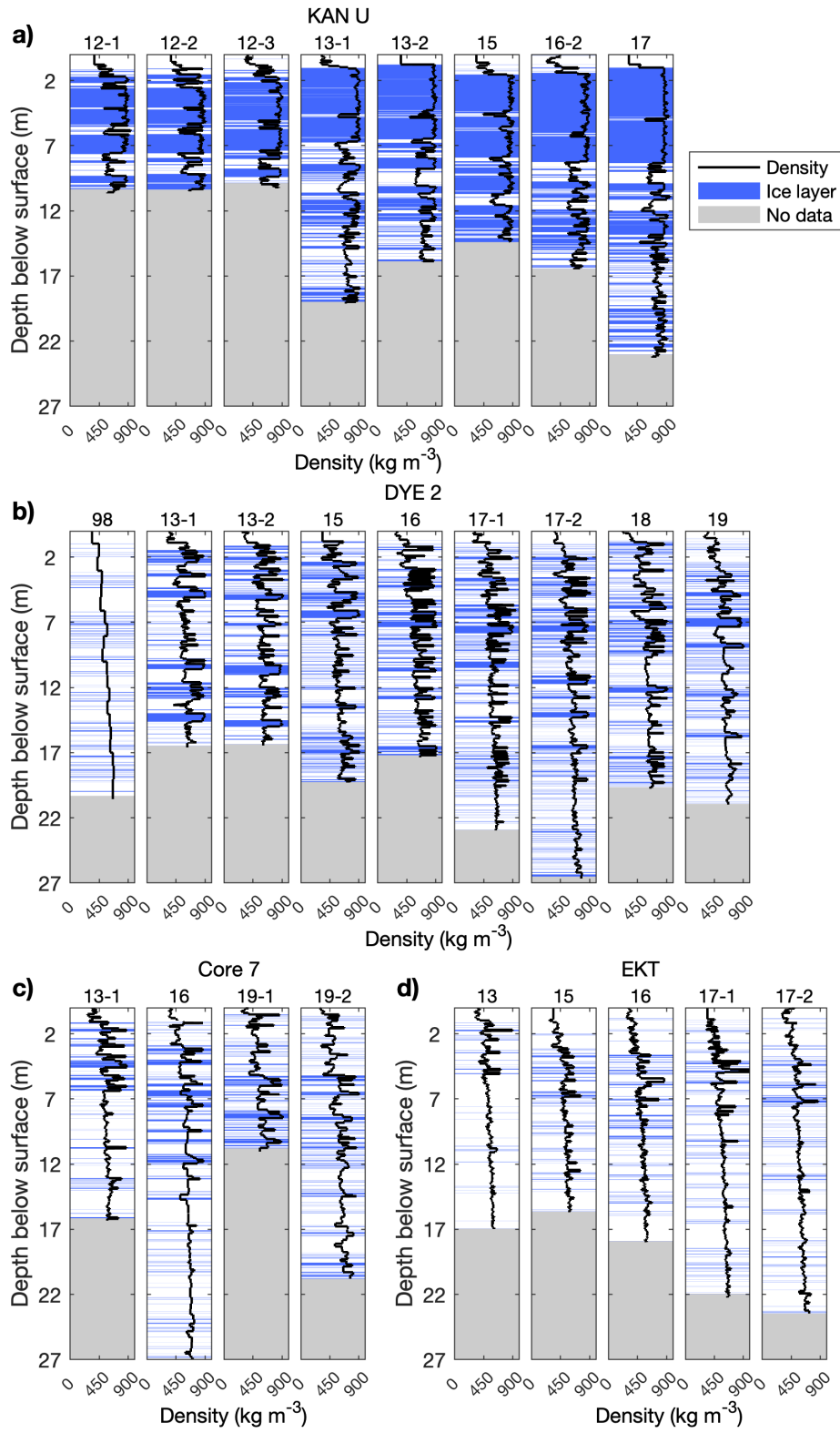


Figure S2. Comparison of all >10 m cores drilled at (a) KAN_U, (b) Dye-2, (c) Core 7, and (d) EKT. The number of top of each core refer to the drilling year followed (if multiple cores available) by the core number.

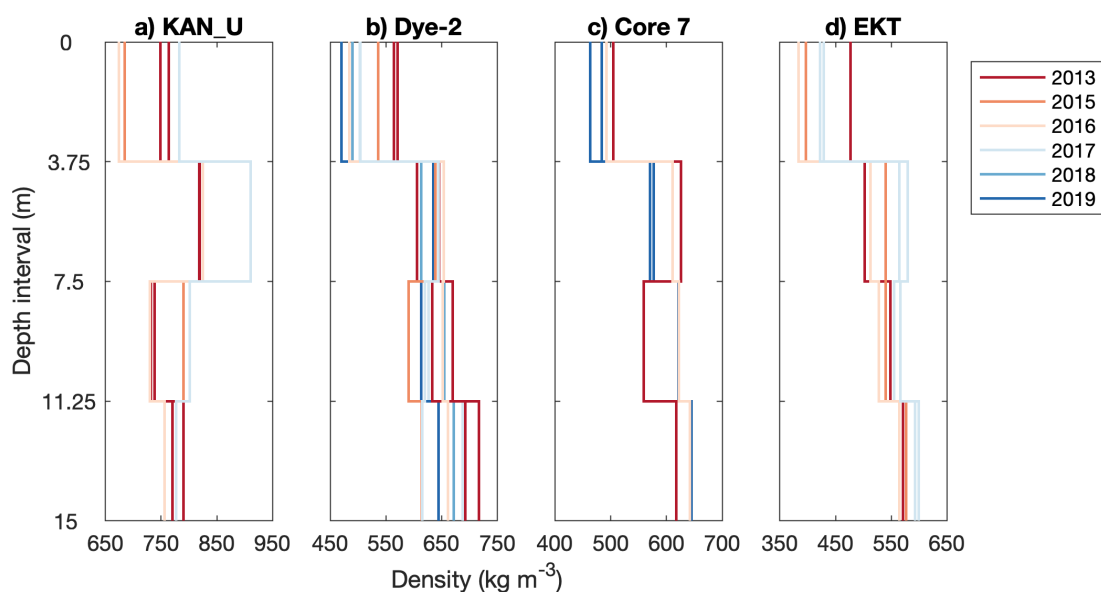


Figure S3. Average density at four depth layers between 2013 and 2019 at (a) KAN_U, (b) Dye-2, (c) Core 7, (d) EKT. These sites are the only places with >15 m cores from three or more years between 2013 and 2019. Note that the x-axes have the same size range, but different absolute values.

Supplementary text

Here we provide further details on core drilling, snow pit analyses and error assessment of the new cores drilled in 2017 - 2019.

Density calculations

An initial assessment of the quality of length measurements was made by comparing three independent estimates of section lengths (by directly measuring section length, by summing core segment lengths, and by differencing successive borehole depth measurements). When the three estimates disagreed by more than 0.1 m, the associated photographs were reviewed, and section lengths corrected accordingly.

To enable density calculations in segments with <100 % intactness, measured weight was increased proportionally, assuming equal density in the missing and intact part of each segment. In some cases, fragmentation of core sections and segments made accurate measurements of diameter and weight impossible. Density corrections were applied where necessary. For firn segments (with or without ice layers) with missing data or unreasonably high densities (i.e., exceeding pure ice density of 917 kg m⁻³), density was calculated as a mean of the two adjacent segments with reasonable densities (applied to 0 – 5.3 % of all segments in each core). Segments with observed densities of less than 70% of the density estimated by the Herron-Langway model (see description in methods section) were

considered unrealistically low and replaced with the average density of the nearest segment above and below that is not pure ice (applied to 0 – 1.1 % of all segments in each core).

For segments consisting entirely of ice with either erroneously high or low densities (outside of the 750 - 917 kg m⁻³ range), or with a missing diameter and weight, measurements were replaced with the mean density of all segments that consisted entirely of ice and were > 90 % intact and thicker than 0.05 m (applied to 0 - 41 % of all segments in each core).

Snow pit analysis

The uppermost portion of the core, which consisted of winter snow, was often fragmented and incomplete due to relatively low densities. Therefore, the core data in this section were replaced with measurements from a snow pit or snow probing within a few meters of each core location. Winter snow density was determined with snow pit surveys at three of the five drill sites in 2017 (Site J, Dye-2, and EKT), all 2018 drill sites (KAN_U, Dye-2, Core 8), and at five of the ten 2019 drill sites (KAN_U, Site C, Site E, Core 3, Core 4, Dye-2). These snow pits were dug to the previous year's snow surface (identified as a harder icy layer overlain by a softer depth hoar). Snow sections were cut out using a Snowmetrics wedge cutter (model RIP 1 with a volume of 0.0001 m³ was used in 2018, and model RIP 2 with a volume of 0.00025 m³ was used in 2017 and 2019). In 2017 and 2018 (all sites but Core 8), snow sections were also cut out with a cylindrical tube (0.001046 m³), and weighed. Deploying the cutter and tube at multiple depths in the walls of each snow pit provided density profiles with 0.1 m and 0.25 m vertical resolution, respectively. Linear scaling was used to match the firn core snow segment depths with the snow pit depths, and the underlying firn column depths were adjusted accordingly (on average by + 0.13 m). Finally, the densities of all winter snow core segments were scaled so that the mean annual winter snow layer density matched the mean snow density determined from the snow pit. Hence, the corrected core data preserve the mean winter snow density as measured in the snow pits and the stratigraphy as measured in the firn cores. At Site F and Site G, without nearby snow pits, avalanche-probe measurements of snow depth replaced the core snow depth, and the underlying firn column was adjusted accordingly. At Site A, B, D, snow pit data from the nearby Site C were used for the winter snow layer corrections.

Uncertainties

Measurement uncertainties were expressed as the best guess of the 95% confidence level, and calculated as follows using cores > 10 m. The density measurement uncertainty for each segment was calculated by error propagation for products

following Taylor (1997) using uncertainties from length measurements (± 0.0025 m), weight (± 0.002 kg), diameter (± 0.002 m), and intactness (± 2 %). The length-weighted averages of density uncertainties for the 19 cores ranged between 2.1-3.2 % . The ice layer thickness uncertainty was estimated to be ± 0.0015 m for each segment. Several ice lenses were broken into multiple segments so that the total uncertainty of those layers exceeded ± 0.0015 m. The mean ice layer thickness uncertainty ranged between 16 - 27 % for the 19 cores. The depth measurement uncertainty was estimated to increase with ± 0.0025 m for each segment, which propagates to a cumulative mean uncertainty ranging from ± 0.21 to ± 0.51 m at the bottom of the cores.

Supplementary References

Taylor JR (1997) *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. 2nd edition.* University Science Books, Sausalito, California