Supplementary material for: Mapping the vertical heterogeneity of Greenland’s firn from 2011-2019 using airborne radar and laser altimetry

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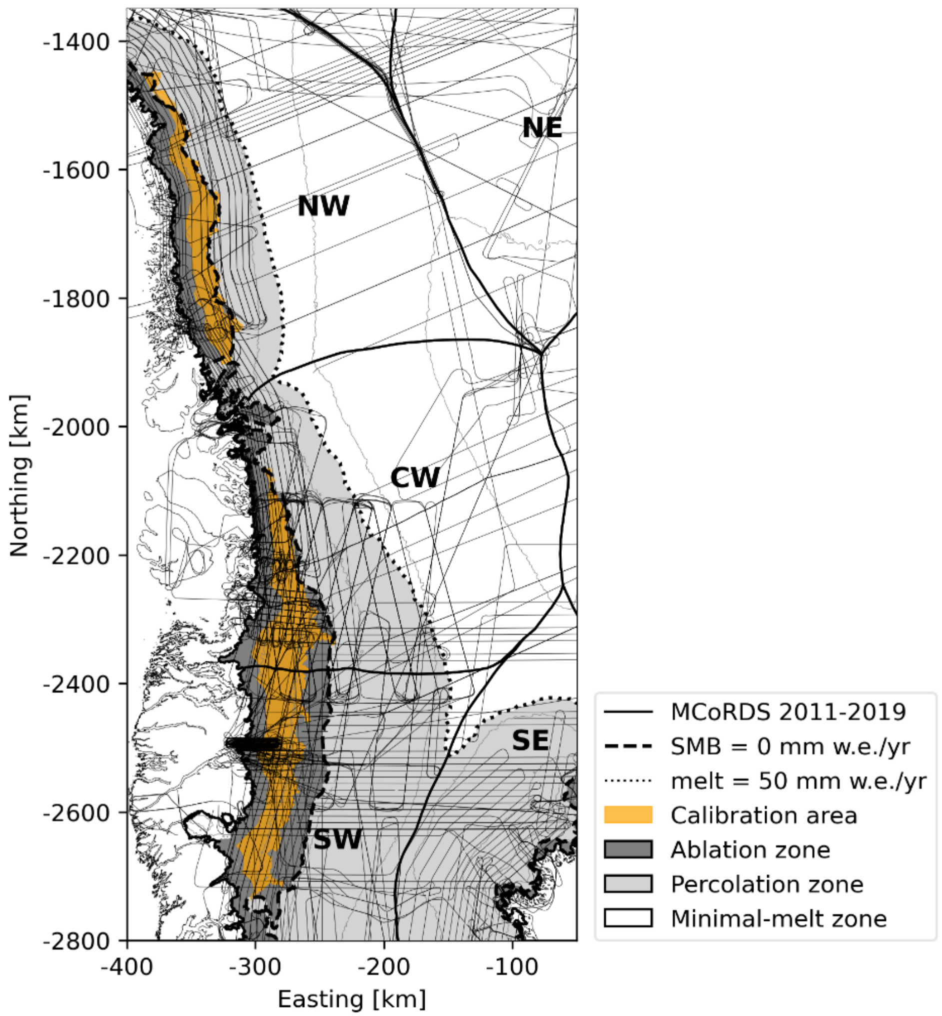

Figure S 1: Map showing the calibration area (orange) used to calibrate the radar peak offsets.

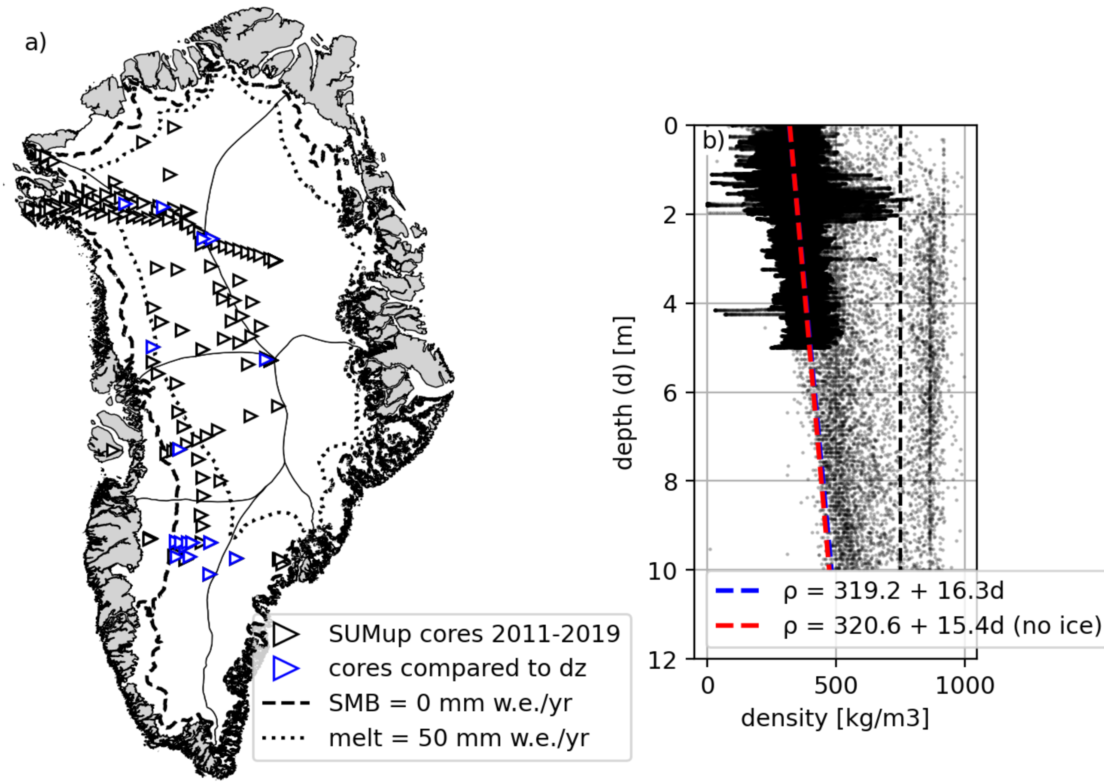

Figure S 2: a) Map of SUMup firn cores collected between 2011-2019 and used to derive the depth-density relationship and compare to the radar peak offsets (blue). b) Firn core density from all cores between 2011-2019, along with the linear regression fits used to generate a first-order depth-density profile for the waveform modelling (red, excluding density values exceeding 750 kg/m^3 to remove the effect of ice layers). Blue regression line includes all density values.

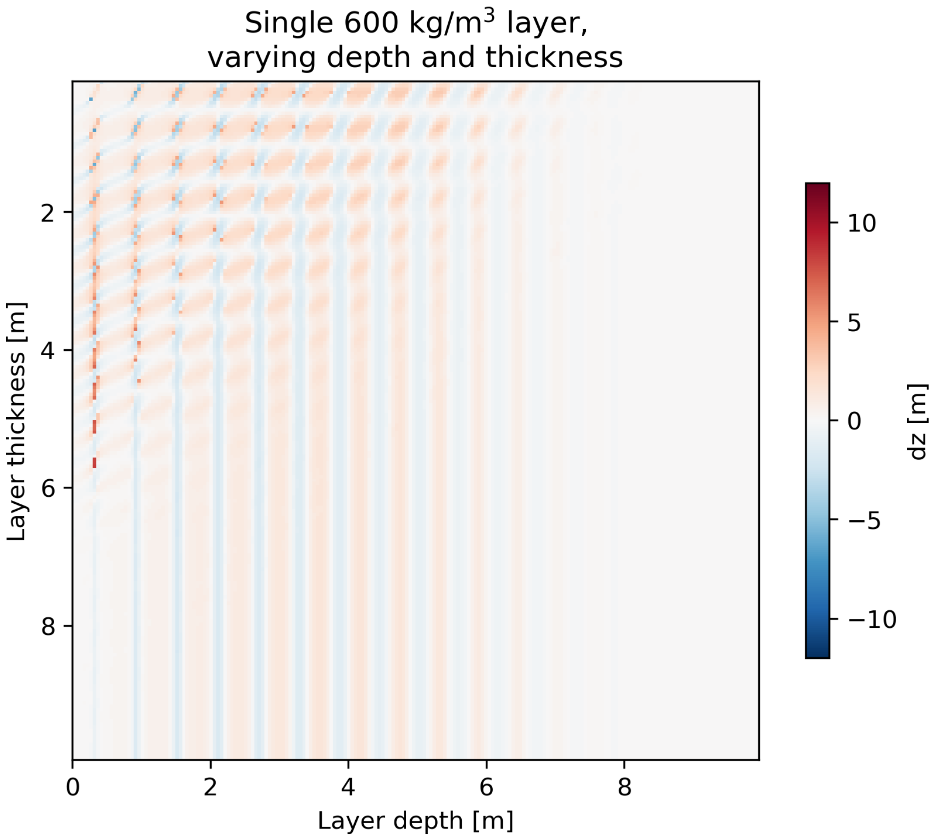

Figure S 3: Surface peak offset (dz) for RadSPy simulated MCoRDS surface returns over firn stratigraphies consisting of a single high density (600 kg/m^3) layer placed at various depths and with different thicknesses.

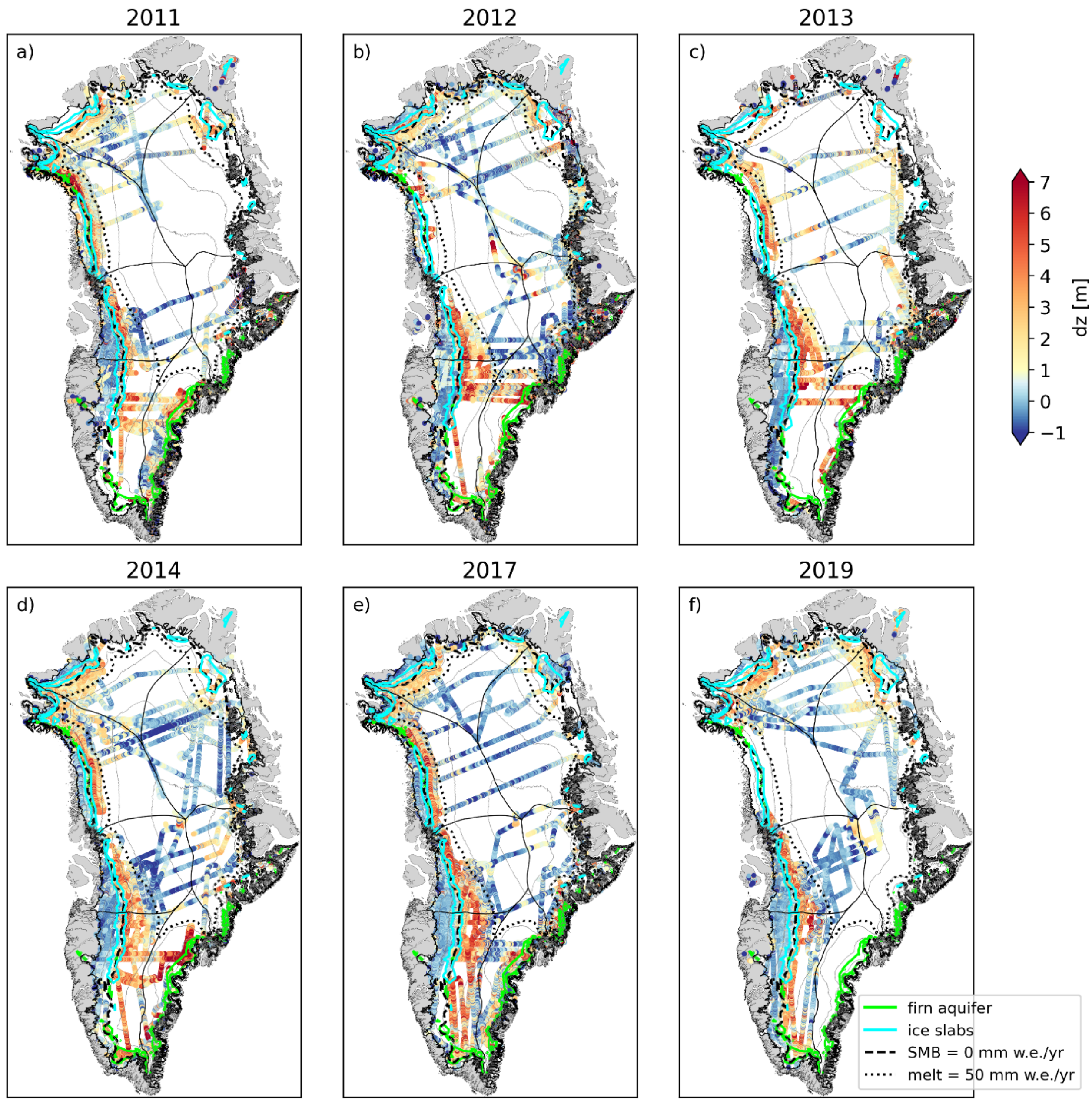

Figure S 4: Maps showing the differential altimetry along profile lines, (non-gridded, but smoothed and subsampled every 1 km along the profile lines) over the GrIS between 2011-2019, along with the extent of ice slabs mapped between 2012-2018) (Jullien et al., 2023) and firn aquifers mapped between 2010-2017 (Brangers et al., 2020; Miège et al., 2016). The dashed black line indicates the boundary between the ablation- and accumulation zones, derived where the mean MAR surface mass balance (SMB) between 2009-2019 equals zero. The dotted black line depicts where the mean MAR derived melt between 2009-2019 equals 50 mm w.e./yr, outlining areas that receive little melting and likely representing the dry-snow facies.

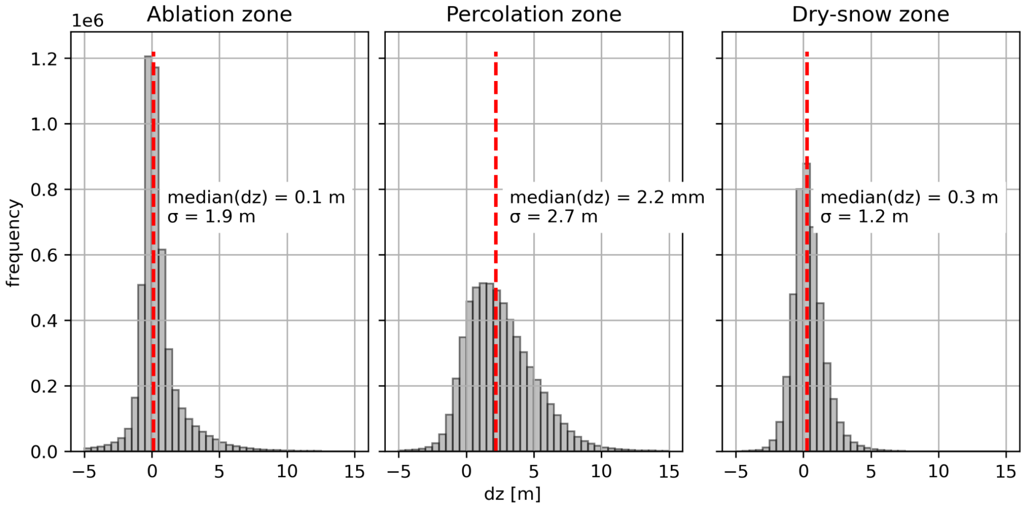

Figure S 5: Distribution of peak offset (*dz*) values from all data between 2011-2019 over the ablation zone (left), percolation zone (centre) and dry-snow zone (right).

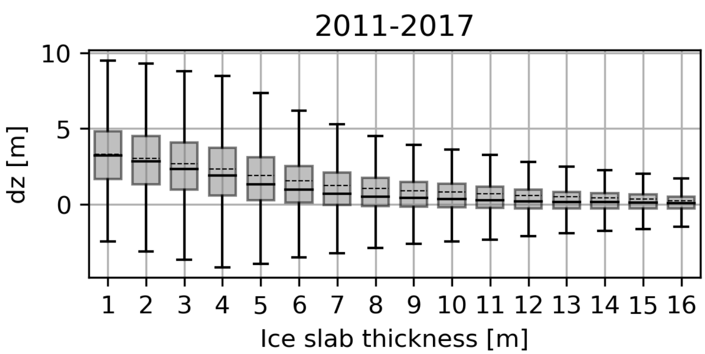

Figure S 6: Correlation of *dz* with ice slab thickness (for the years 2011-2017) derived from (Jullien et al., 2023). The solid and dotted black line represent the mean and median of all observed dz over ice slabs of a given thickness, respectively.

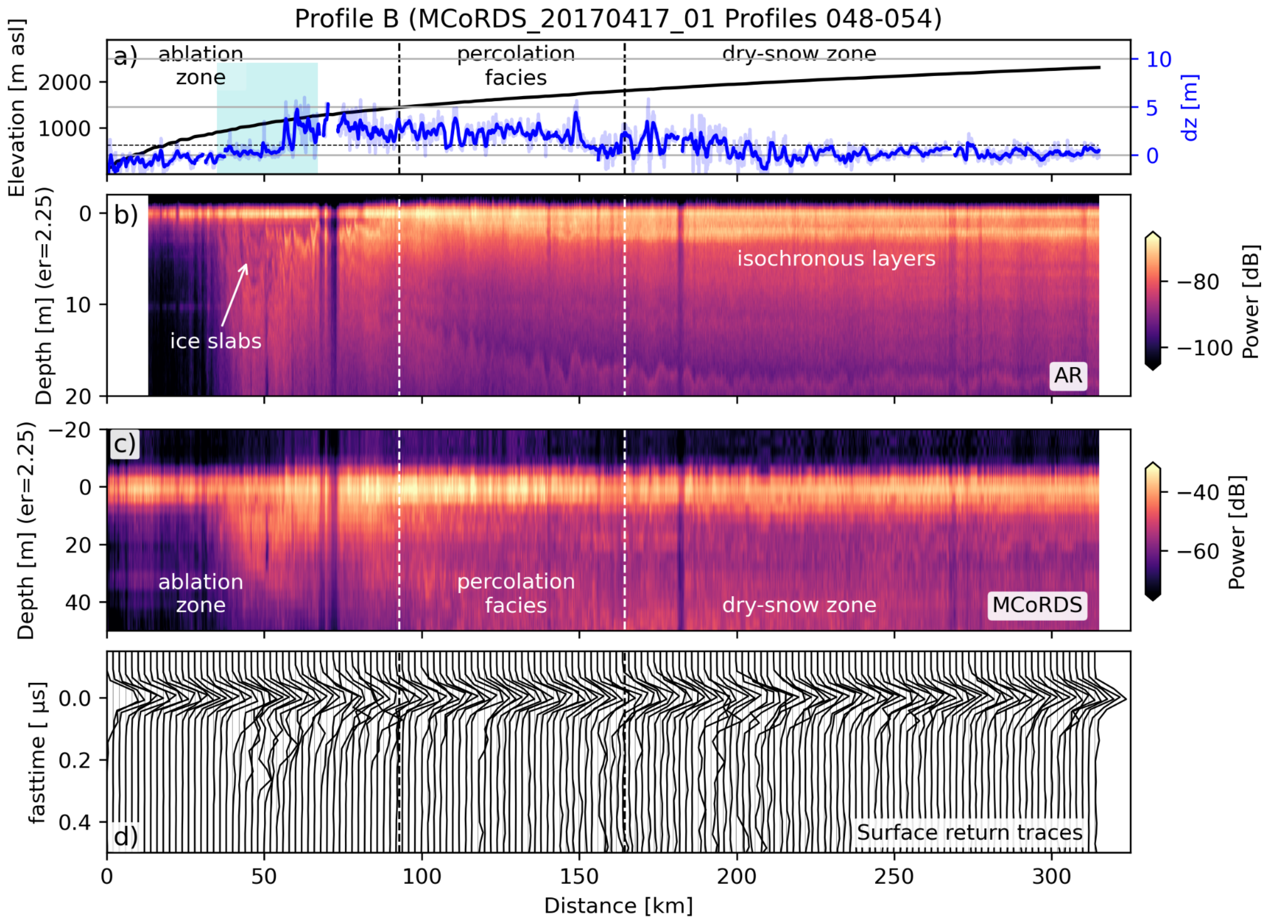

Figure S 7: Radar surface peak offset (*dz*) over OIB CReSIS MCoRDS and Accumulation Radar (AR) profile B in Central West Greenland (see Figure 7e for profile location). a) Ice sheet surface elevation along the profile (black) and *dz* (blue). Vertical dotted black/white lines indicate the firn zone transitions (ablation zone, percolation zone, dry snow zone) derived from MAR, and the blue shaded area marks the location of previously mapped ice slabs (Jullien et al., 2023). b) AR data showing the firn stratigraphy, including ice slabs and isochronous layers of the uppermost 20 m. c) MCoRDS data of the uppermost 50 m in firn/ice. The radargrams have been flattened with respect to the picked surface reflection. d) MCoRDS traces along the profile showing the shape of the surface reflection along the profile. The traces are aligned with respect to the picked surface return, and normalized to the maximum energy.

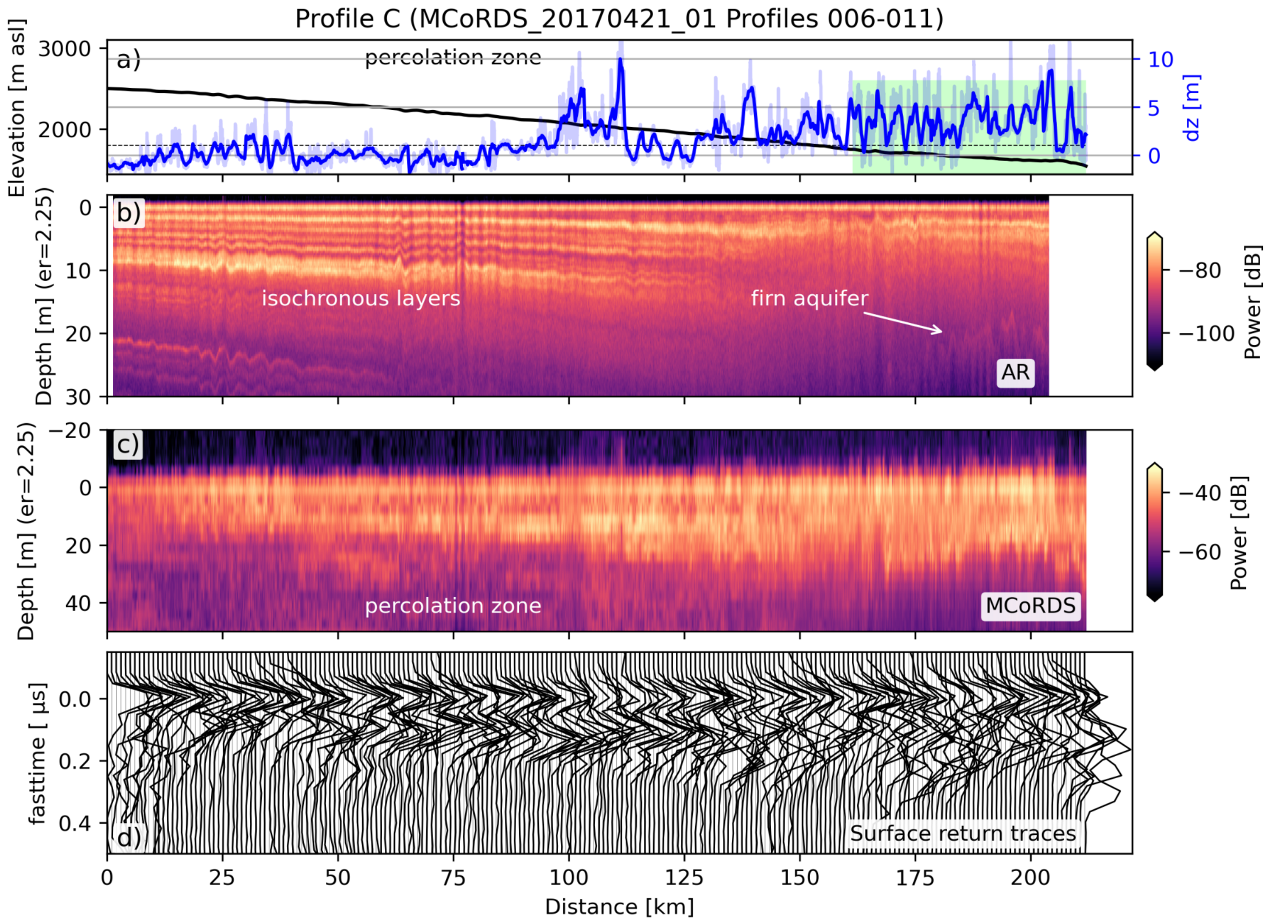

Figure S 8: Radar surface peak offset (*dz*) over OIB CReSIS MCoRDS and Accumulation Radar (AR) profile B in Central West Greenland (see Figure 7e for profile location). a) Ice sheet surface elevation along the profile (black) and dz (blue). Vertical dotted black/white lines indicate the firn zone transitions (ablation zone, percolation zone, dry snow zone) derived from MAR, and the green shaded area marks the location of firn aquifers mapped between 2010-2017 (Brangers et al., 2020; Miège et al., 2016) b) AR data showing the firn stratigraphy, including isochronous layers and a firn aquifer in the uppermost 20 m. c) MCoRDS data of the uppermost 50 m in firn/ice. The radargrams have been flattened with respect to the picked surface reflection. d) MCoRDS traces along the profile showing the shape of the surface reflection along the profile. The traces are aligned with respect to the picked surface return, and normalized to the maximum energy.

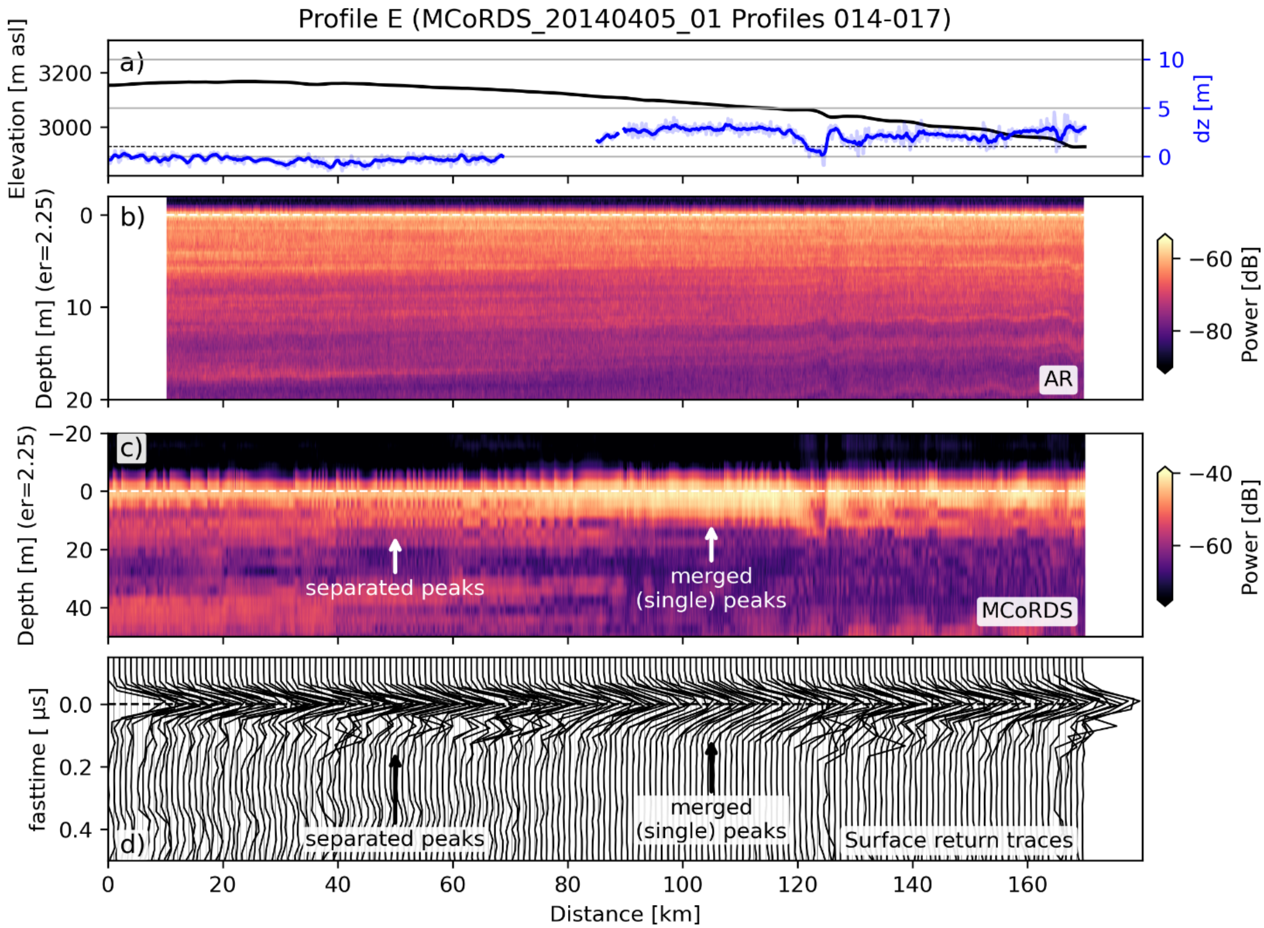

Figure S 9: Radar surface peak offset (*dz*) over OIB CReSIS MCoRDS and Accumulation Radar (AR) profile E over the dz anomaly region near the summit (see Figure 7d for profile location). a) Ice sheet surface elevation (black) and dz (blue) along the profile. b) AR data showing the firn stratigraphy of the uppermost 20 m. c) MCoRDS data of the uppermost 50 m in firn/ice. The radargrams have been flattened with respect to the picked surface reflection. d) MCoRDS traces along the profile showing the shape of the surface reflection along the profile. The traces are aligned with respect to the picked surface reflection, and normalized to the maximum energy.

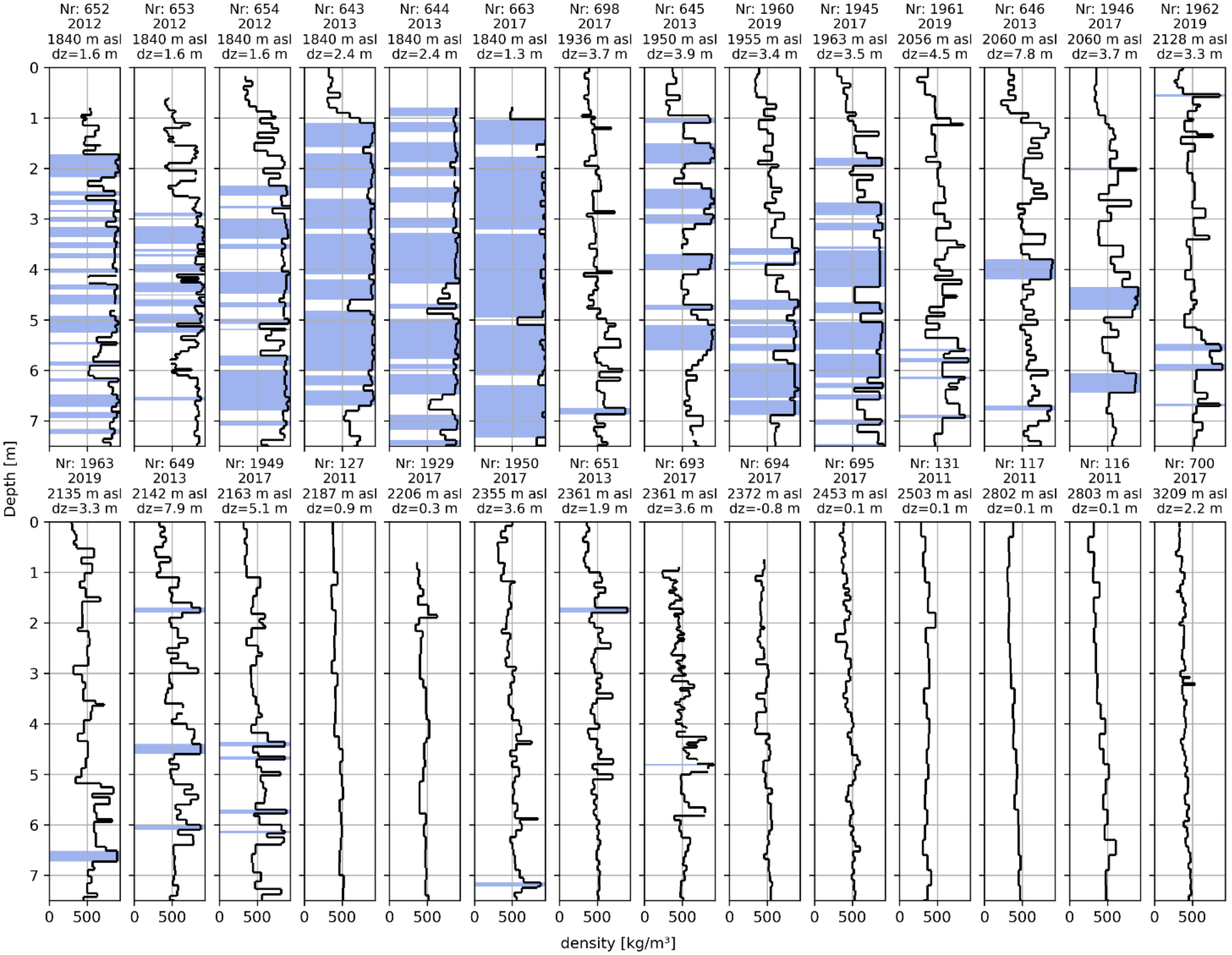

Figure S 10: Firn core stratigraphy of all cores used to compare to the radar peak offsets (*dz*). The cores are ordered (left to right) by elevation. The core number corresponds to the Surface Mass Balance and Snow Depth on Sea Ice Working Group (SUMup) snow density subdataset, Greenland and Antartica, 1952-2019 (Montgomery et al., 2018; Thompson-Munson et al., 2022) core ID number. Blue shaded areas mark ice layers (density >862 kg/m³).

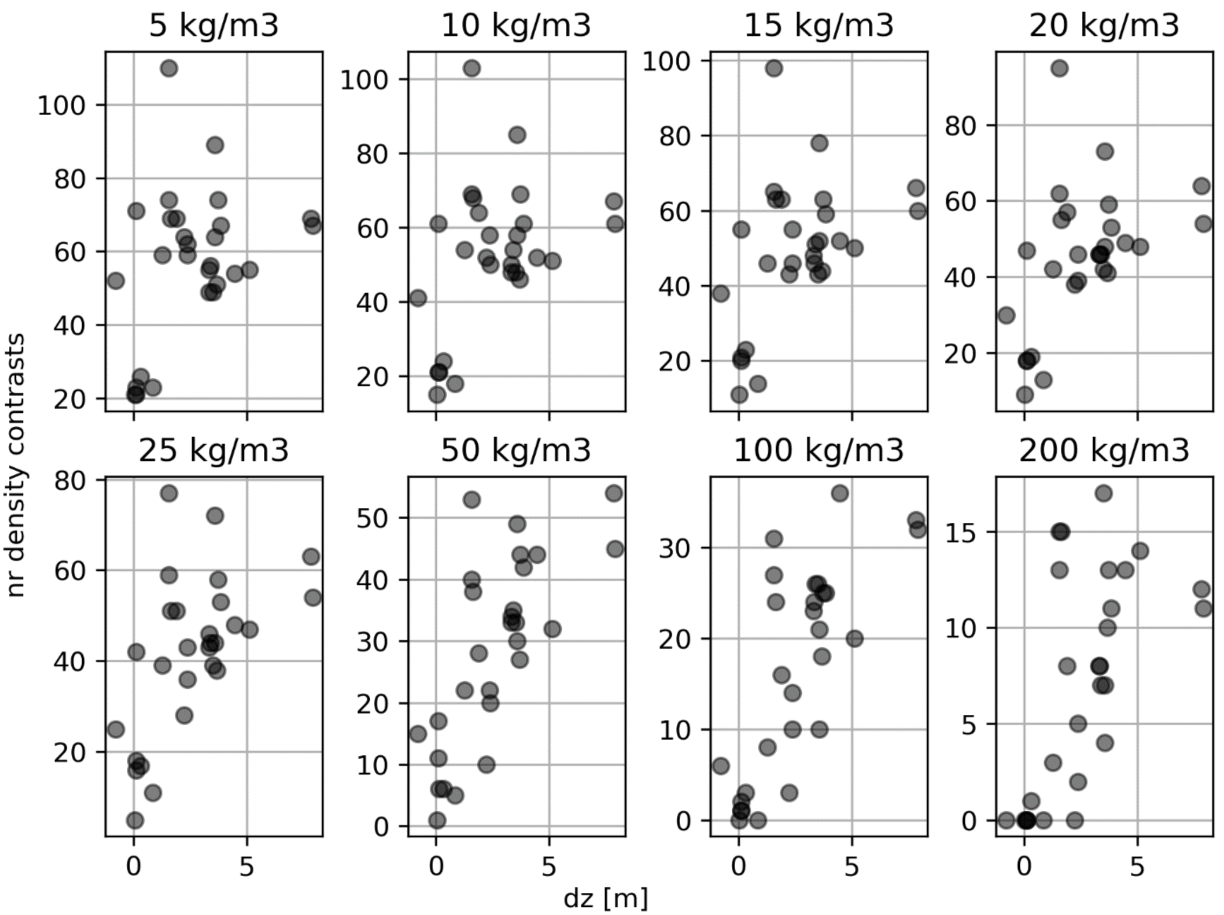

Figure S 11: Radar surface peak offset (*dz*) versus number of density contrasts for minimal thresholds between 5-200 kg/m^3. Note that these are minimal thresholds where all density contrasts above this threshold are included.

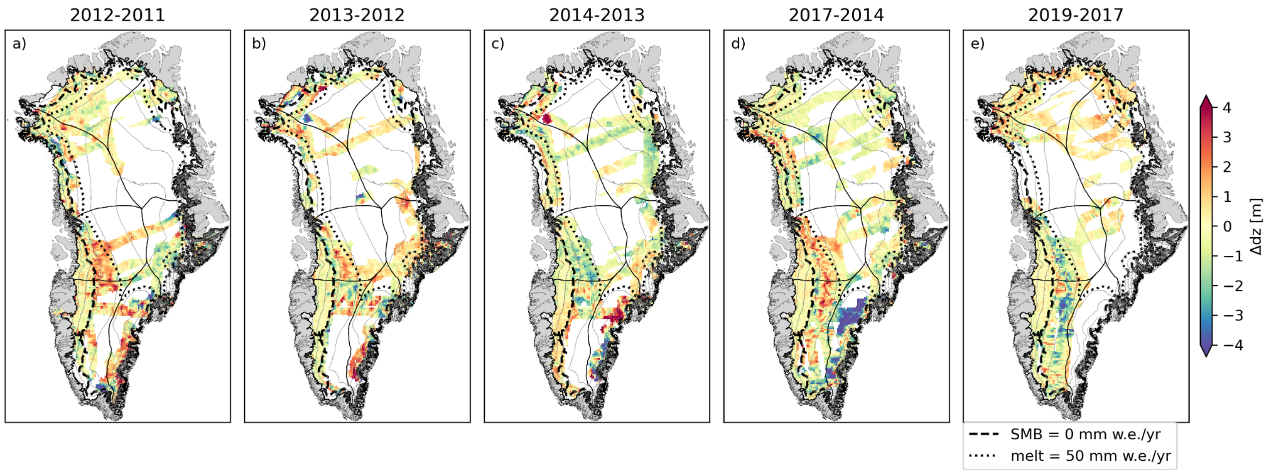

Figure S 12: Difference in *dz* between survey years. The dashed black line indicates the boundary between the ablation- and accumulation zones (derived from MAR SMB), and the dotted black line depicts the dry-snow facies (derived from MAR melt). Thin black lines show elevation contours at a 500 m interval.

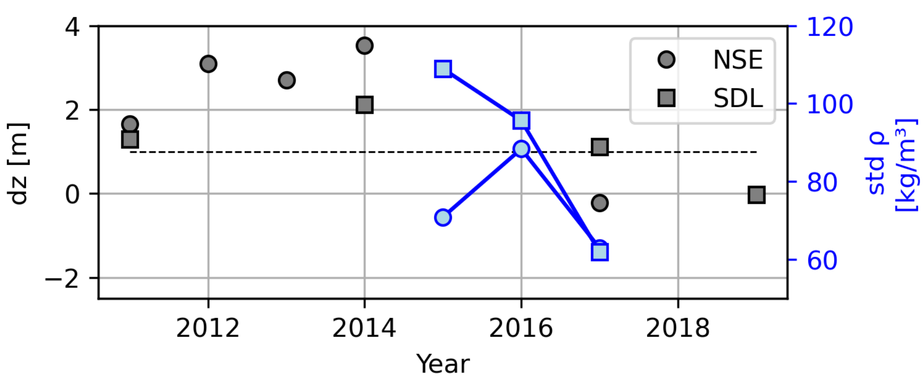

Figure S 13: Change in *dz* (2011-2019) and the standard deviation of firn density (over the top 7.5 m) from cores collected between 2015-2017 at NASA South-East (NSE) and Saddle (SDL). To increase overlap in data points, *dz* values have been taken as the mean from within a 20 km radius of the firn cores. Firn core density profiles are shown in Figure S 14.

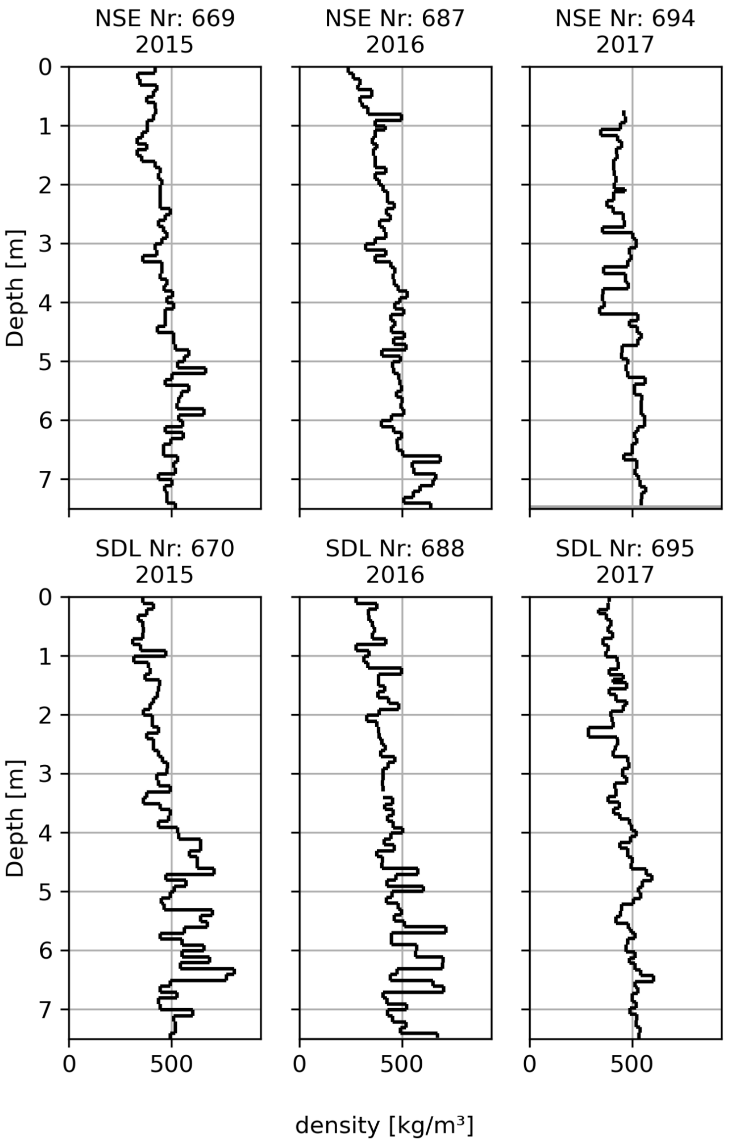

Figure S 14: Firn core stratigraphy at NASA South-East (NSE) and Saddle (SDL) collected between 2015-2017. The core number corresponds to the Surface Mass Balance and Snow Depth on Sea Ice Working Group (SUMup) snow density subdataset, Greenland and Antartica, 1952-2019 (Montgomery et al., 2018; Thompson-Munson et al., 2022) core ID number.

Table S 1: Summary of the MCoRDS radar datasets used to calculate the radar surface peak offset (*dz*), including information on the radar system, the mean radar trace distance, and mean pulse-limited footprint at the ice sheet surface (Dpl), and the median of *dz* over the calibration area used to calibrate the *dz* datasets.

Survey	Radar system	Mean trace distance [m]	Mean Dpl [m]	Median (dz) over calibration area [m]	Datasets excluded
2011_Greenland_P3	MCoRDS 2	13.9	204.5	0.3	20120503_02 20120416_02 20120412_01 20120417_03
2012_Greenland_P3	MCoRDS 2	29.9	215.6	2	
2013_Greenland_P3	MCoRDS 3	25.8	208.5	-4.5	
2014_Greenland_P3	MCoRDS 3	14.9	195.5	-2.1, 3	
2017_Greenland_P3	MCoRDS 3	15.0	201.7	29.1, 6.8	
2019_Greenland_P3	MCoRDS 3	14.9	197.9	3.4	20190405_03 20190415_01 20190410_01