

Greenland Ice Sheet Ice Slab Expansion and Thickening

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Key Points:

- Ice slabs were already present in the early 2000s in southwest, central-west and north Greenland.
- Ice slabs expanded inland from 2002 to 2018 and thickened by top-down accretion and by accretion on their undersides.
- Near-surface ice layers support subsequent ice slab development.

Abstract

We use airborne accumulation radar data acquired over the Greenland Ice Sheet between 2002 and 2018 to identify changes in ice slab extent and thickness. We show that ice slabs several metres thick were already present at least as early as 2002. Between 2012 and 2018, they expanded 13,400-17,600 km² inland, or by 37-44%. Our results document that the extremely warm summer of 2012 produced near-surface ice layers at higher elevations, enabling ice slabs to develop in locations with only moderate melting in the following summers. With repeated flights over a transect in southwest Greenland, we show that ice slabs can thicken from above and on their undersides. Moderate melting primarily thickens ice slabs by top-down accretion, while large melting events can also trigger ice accretion below the slabs.

Plain Language Summary

Above the equilibrium line elevation, seasonal snow is not entirely removed by summer melting. As a result, firn - an interannual layer made of old snow and refrozen meltwater - builds up. Firn holds the potential to buffer sea level rise by trapping liquid water within its pore space. However, surface melting has increased in recent decades, making large quantities of water available to percolate into the firn where it refreezes, eventually creating metres-thick ice slabs that hinder future percolation. We mapped ice slabs in the subsurface firn (0-20m depth) by using airborne radar surveys and show that they have expanded inland and thickened from 2002 to 2018. Once formed, ice slabs continue to thicken, even under moderate melt conditions. Recent increases in the ice sheet's visible runoff area match well with the expansion of ice slabs, so we conclude that ice slabs will be an important control on the future runoff area of the ice sheet.

1 Introduction

In the 1990s, the mass balance of the Greenland Ice Sheet (GrIS) was close to equilibrium, but has been negative for the last two decades (The IMBIE Team, 2020). Iceberg calving rates increased (King et al., 2020; Rignot et al., 2008; The IMBIE Team, 2020) and the surface mass balance (SMB) has decreased as a result of increasing melt and runoff (Enderlin et al., 2014; Fettweis et al., 2017; The IMBIE Team, 2020; van den Broeke et al., 2016). Furthermore, extremely warm summers such as in 2010, 2012, 2016 and 2019 (Mikkelsen et al., 2016;

44 Tedesco et al., 2011, 2013; Tedesco & Fettweis, 2020) triggered unprecedented surface melt
45 rates at high elevations (Hall et al., 2013; Nghiem et al., 2012) and exceptionally high volumes
46 of runoff (Mikkelsen et al., 2016; van Angelen et al., 2014).

47 Recent increases in surface melting have densified the subsurface firn (Machguth et al., 2016;
48 Mikkelsen et al., 2016; van Angelen et al., 2014). Firn is found above the equilibrium line and
49 consists of interannual snowpack, the density of which increases by compaction through burial
50 but also due to percolation and refreezing of surface meltwater (Braithwaite et al., 1994; Brown
51 et al., 2011; Pfeffer & Humphrey, 1998). Firn has the potential to trap and store meltwater within
52 its pore space, thereby buffering the GrIS contribution to sea level rise (Harper et al., 2012;
53 Pfeffer et al., 1991).

54 In the percolation zone, where surface melt rates are substantial but usually do not deplete the
55 seasonal snow completely, the fate of meltwater varies mainly with annual snowfall. Where
56 snowfall rates are high ($\sim 1000 \pm 400$ mm w.e. per year), mostly in southeast and south
57 Greenland, liquid water percolates to a depth where it forms perennial firn aquifers (Forster et
58 al., 2014; Miège et al., 2016; Miller et al., 2022). Conversely, in regions where accumulation
59 rates are lower and which have recently experienced significant melting, ice slabs several metres
60 thick can form – mostly along the west, north and northeast of the GrIS (MacFerrin et al., 2019;
61 Miller et al., 2022). In these regions, increased meltwater percolation during several successive
62 summers fused centimeters-scale ice lenses into increasingly contiguous ice layers tens of
63 centimeters thick and eventually metres-thick slabs, thereby decreasing the firn's permeability
64 (de la Peña et al., 2015; Vandecrux et al., 2019). Ice slabs form an aquitard, preventing most
65 subsequent meltwater from reaching the relict pore space below (MacFerrin et al., 2019;
66 Machguth et al., 2016).

67 Ice slabs favour the development of surface streams in the high percolation zone (Machguth et
68 al., 2016; Mikkelsen et al., 2016; Tedstone & Machguth, 2022). The area of the ice sheet drained
69 by surface rivers increased by 29% between 1985 and 2020, corresponding strongly with the
70 locations of ice slabs mapped previously and suggesting that 5-10% of recent ice-sheet-wide
71 mass losses originated from these newly densified parts of the accumulation zone (Tedstone &
72 Machguth, 2022). This underlines that it is essential to understand firn densification and ice slab

development for inclusion in ice sheet mass balance models that are used for projections of future ice sheet runoff (de la Peña et al., 2015). Despite their emerging importance to future runoff magnitude, ice slabs have only been mapped over a short time period: with accumulation radar from 2010 to 2014 (MacFerrin et al., 2019), and through a proxy approach with satellite microwave radiometry from 2015 to 2019 (Miller et al., 2022). Here we investigate changes in the extent and thickness of ice slabs using airborne radar observations acquired during spring-time campaigns between 2002 and 2018.

2 Data and Methods

To map ice layer and slab locations in 2002-03 we used data collected by 600-900 MHz accumulation radar (Kanagaratnam et al., 2004; Lewis, 2010). To examine changing ice content during 2010-18, we used the 550-900 MHz accumulation radar (Carl et al., 2011; CReSIS, 2021; Rodriguez-Morales et al., 2010) ; the 2010-14 data that we processed are identical to those used by MacFerrin et al. (2019).

Data acquired during 2002-03 were detrended in the logarithmic domain by the provider, so they have virtually no radiometric information (J. Paden, personal communication 2020). This means they are only useful for layer tracking. Nevertheless, the radiometric variability of the signal is large enough to enable manual ice identification (Text S1). For radargrams acquired between 2010 and 2018, we developed a semi-automated approach based on MacFerrin et al. (2019) (Text S2). In brief, to prepare the radargrams we picked the ice sheet surface, corrected for the roll of the aircraft, removed the impact of varying atmospheric conditions by subtracting the average surface signal strength, and applied a correction for depth attenuation.

We aimed to detect changes sub-surface ice thickness through time. MacFerrin et al. (2019) used a normalised threshold to detect ice content, but we found that this yielded strong differences between co-located radargrams over successive years (Text S2). Instead, we examined a range of radar signal strengths extracted from a “reference” radargram as thresholds to discriminate between porous firn and ice content in the uppermost 20 m. To determine the appropriate range of radar signal strengths, we first manually digitised ice content in the reference radargram based on comparison with in-situ ground penetrating radar measurements and firn cores acquired by MacFerrin et al. (2019) (Fig. S3). Next, we used our reference radargram to determine the signal

return strength given by (a) ice content versus (b) porous firn. The signal distributions of ice content and porous firn partially overlap (Fig. S4). Following a sensitivity analysis (Text S2), we chose lower and upper signal strength thresholds which correspond to the minimum and maximum likely ice content, respectively. The producer's accuracy (overall accuracy) in detecting ice content is 53% (86%) at the lower threshold and 73% (88%) at the higher threshold (Tables S1, S2). For each radargram we also estimated the likelihood of ice content presence between the lower and upper thresholds when ice is first detected. Thus, 100% ice likelihood corresponds to detection at the lower threshold, while 50% corresponds to detection mid-way between the lower and upper thresholds. Finally, following MacFerrin et al., (2019), we identify ice slabs where radar-detected ice content is at least 1 m thick, and consider them to have a maximum accumulation radar-detected thickness of 16 m. We use the term 'ice layers' to refer to ice content less than ~1 m thick.

As a proxy for surface melting, we calculated Positive Degree Hour sum using a similar approach to degree-day modelling (Hock, 2003), using in-situ 2 m air temperature measurements from 2009 to 2017 at the automatic weather station KAN_U (Fausto et al., 2021). We summed every positive 1-hour average temperature (i.e. above 0°C) for each year.

3 Results

3.1 Ice slab expansion from 2002 to 2018

Ice layers and slabs were present in 2002-03 (Fig. 1, 2a), up to several meters thick in SW Greenland (Fig. 1a,c-d). Although the observations are relatively sparse (Fig. S7a), they were also identified in the CW, in the vicinity of Sermeq Kujalleq's (Jakobshavn Isbrae) high percolation zone. Ice layers and slabs were identified in the NO but not in the NW nor the NE, although spatial coverage was limited in the latter regions.

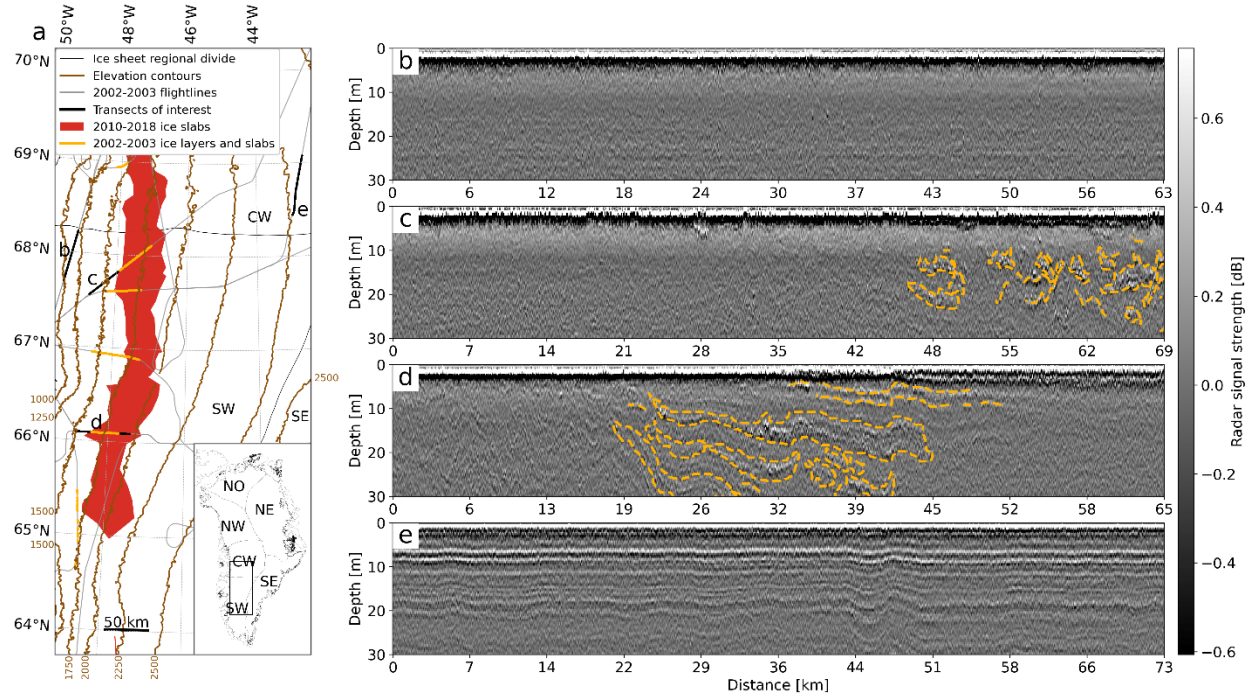


Figure 1. Ice layers and slabs in central and southwest Greenland in 2002-2003. (a) Regional zoom of radargram locations. Radargrams with ice layers/slabs identification overlaid (orange dashed lines) acquired from the (b) ablation zone (c-d) percolation zone and (e) dry snow zone.

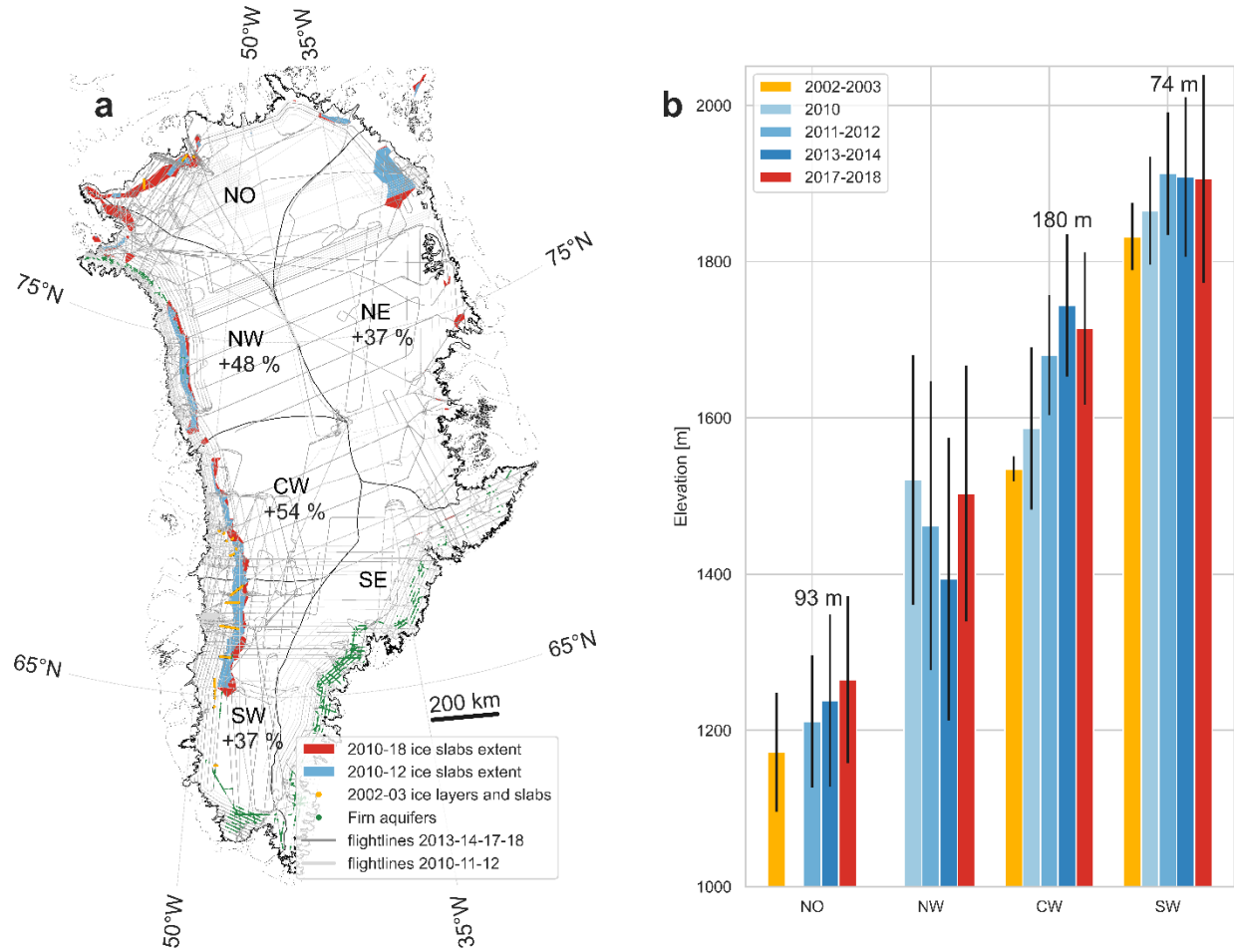


Figure 2. Ice slab extent from 2002 to 2018. (a) Ice layers and slabs in 2002-03 (orange), ice slab extent in 2010-12 (blue) and 2010-18 (red), firm aquifers in 2010-2014 (Miège et al., 2016) (green). Ice slab extents are derived from multiple flight lines (Fig. S8). Flight lines used for identification of 2010-2018 ice slabs (light grey: 2010-12, dark grey: 2013-18). Percentages indicate the upglacier expansion of ice slab extent in 2017-2018 with respect to 2010-12. (b) Maximum ice slab elevation (coloured bars) \pm 1 standard deviation (black bars) in each region. Numbers indicate the change in maximum ice slab elevation between 2002-03 and 2017-18. Elevations are above WGS84 ellipsoid. Maximum elevation changes in the NE, are omitted, as well as extent change in the NO and north of the NW as there was insufficient overlap in flight lines between the different periods (Fig. S7a-e).

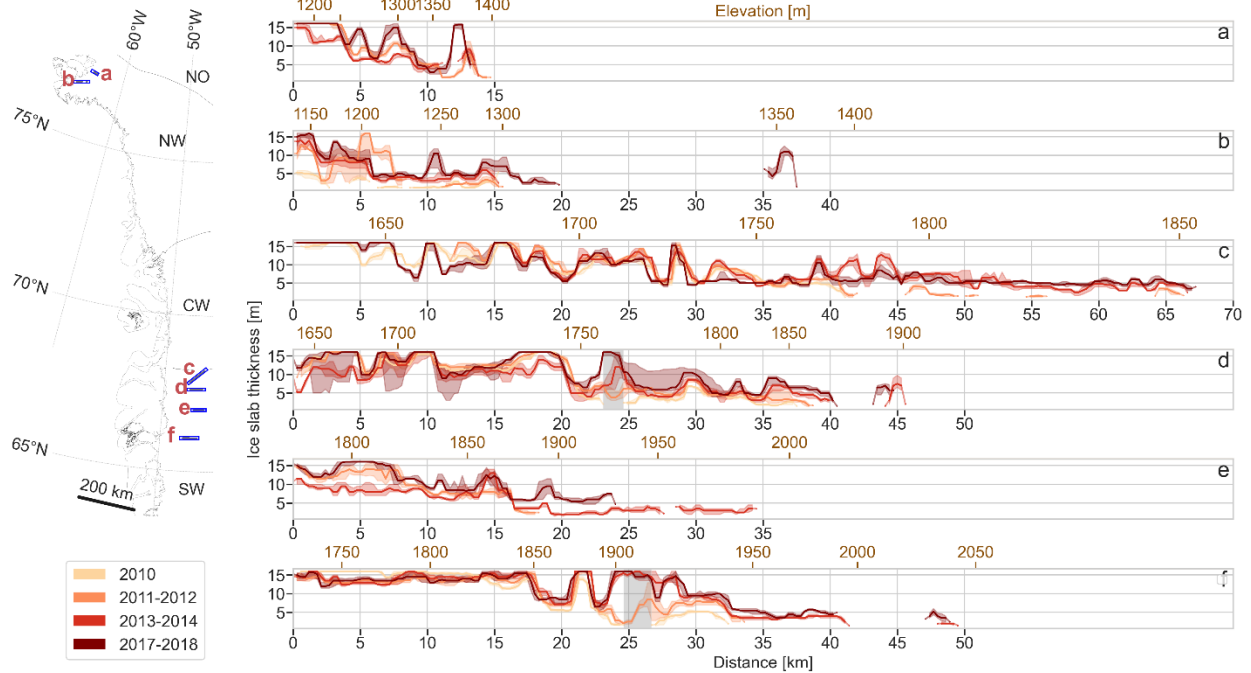
Considering the extents of our slab retrievals (Figs. 2a, S8), ice slabs occupied over 60,400-73,500 km^2 (low-high bounds) in 2018, consistent with 2015-2019 ice slabs retrievals extending over 76,000 km^2 using satellite microwave radiometry by Miller et al., (2022). Except in the southern part of SW Greenland, we did not identify any entirely new ice slabs in either 2002-03 or 2017-18 compared to the 2010-14 mapping performed by MacFerrin et al., (2019) (Fig. S8).

We examined inland expansion between 2010-12 and 2017-18 (Fig. 2a). We use 2010-12 because there is good spatial coverage in 2011-12 supported by complementary coverage in 2010 (Fig. S7b-e). We estimate that the ice slab area increased from 2010-12 to 2017-18 by 37% in the NE and the SW, 48% in the NW, and 54% in the CW. We also calculated the maximum ice slab elevation in each period by picking the maximum elevation in 10 km-wide boxes, then calculating the median value in each region. This showed that the increase in area was driven by ice slab expansion to higher elevations throughout the west coast (Figs. 2b, S8), in agreement with the upslope expansion of ice slabs identified by Miller et al., (2022).

3.2 Ice slab thickening

The accumulation radar used between 2010 and 2018 has a vertical resolution of 65 cm in snow and firn (Rodriguez-Morales et al., 2014), enabling the examination of changes in ice slab thickness along repeated radar survey lines. We focus on six transects which had repeated radar surveys within tens to hundreds of metres of each other (Fig. 3) and differentiate between three stages of ice slab change between 2010 and 2018: (i) initiation (i.e. appearance of a ~meter-thick slab), (ii) development (i.e. significant thickening of existing ice slab) and (iii) well-developed (i.e. already at least 10 m thick) (Text S3, Fig. S5). Ice content increased between 2010 and 2018 along all the transects. While there were no major thickness changes where well-developed ice slabs were already present in 2010 (e.g. Fig. 3f from 0 to 23 km), we observed development of thinner ice slabs. On transect A, ice content at 11-13 km increased by 13.5 m between 2011-12 and 2017-18. On transect B, the slab at 8-15 km thickened from less than 2 m in 2010 to roughly 5 m by 2017-18.

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171 **Figure 3.** Ice slab thickness over time. Ice thickness derived from our upper ice content detection
 172 threshold (quantile 0.79). For each transect, the data were aggregated from the start of the
 173 transect into 300 m bins, smoothed with a 900 m rolling median. Median in bold, interquartile
 174 range denoted by shading.

175 Previously discontinuous ice slabs merged laterally over time (Fig. 3b-d,f). On transect C, a 5 to
 176 10 m-thick ice slab developed above the 2010 upper limit (at 41 km) by 2013-14, fusing several
 177 previously thinner and isolated areas of ice slab. Consequently, the upper limit of ice slabs
 178 expanded inland by 26 km from 2010 to 2017. On transect D (Fig. 3d), the ice-free section in
 179 between 23-24.5 km (grey shading) saw initial ice slab generation during summer 2010. This
 180 area developed to 16 m by 2018, filling the gap between two previously unconnected slabs and
 181 expanding the continuous ice slab by 17.4 km. Similar behaviour is apparent in transect F (Fig.
 182 3f grey shading).

183 To examine ice slab initiation and thickening in more detail, we examined radargrams along a
 184 transect with good repeat radar coverage near to the KAN_U weather station at which
 185 meteorological measurements have been made continuously since 2009 (Fig. 4). No radar data
 186 were acquired in this area during 2002-03, but radargrams acquired in the nearby area during

2010 and 2011 show sub-surface decimeters to meters-thick ice content (Fig. S9a-b). 2014 and 2017 radargrams are offset by several hundreds of meters from 2012, 2013 and 2018 radargrams (900 m at 13.8 km, 1700 m at 40 km, Fig. 4a). The ice content can vary significantly between non-perfectly overlapping transects. For example, the ice content between 13.8 and 15.6 km is ~59% less in the 2014 retrieval compared to 2013 (Fig. 4b-c). Nonetheless, we still detected overall thickening through time (Figs. 4d, S9h). Between 2012 and 2018, the ice thickened between 0 and 13.8 km (+9%), increased substantially between 13.8 and 17.7 km (+43%), and a new ice slab developed from 18.5 km.

To relate the changes in ice thickness to the potential for meltwater percolation and refreezing, we used total annual Positive Degree Hours (PDH) as a first-order estimate of summer melting (Fig. S6). Following the extreme melt-year of 2012 with 1273 °C PDH, ice content between 13.8 and 17.7 km increased by 4,576 m² (19 %) from spring 2012 to spring 2013. From summer 2013 to 2017 there were 2233 °C PDH – 175% of 2012 – yet ice content increased by only 5,738 m² between spring 2013 and spring 2018, equivalent to 25 % more ice content formation than 2012 alone.

We observed that ice slabs can thicken by ice accretion (i) on top of existing ice content versus (ii) beneath. Considering top-down accretion, between 16.5 to 17.7 km there was 2.9 m thickening from above between 2012 and 2018 (Fig. 4d); the bottom of the slab deepened by 3 m with respect to the surface due to gradual burial (Text S4). Directly beneath KAN_U, 0.8 m ice was added to the top of the ice slab due to high PDH in summer 2012 (Fig. 4b), and 0.6 m during summer 2013 (Figs. 4b-c, S9h), even though the 2013 PDH was only 30% of the 2012 PDH (Fig. S6). The subsequent 2.5 m of top-down thickening between 2014 and 2018 occurred during only moderate melting in 2014 and 2016 and limited melting in 2015 and 2017 (Figs. 4c-d, S6, S9e-h). There is further evidence of accretion on top of existing ice slabs in transects C-F (Fig. S10).

Between 13.8 and 15.6 km there was ~4 m of thickening predominantly below the slab between 2012 and 2018 (Fig. 4b,d). This was generated by ~1.5 m of accretion predominantly below the existing ice slab due to summer 2012 (Fig. 4b), and a further ~2.5 m of accretion during 2014-2017 split between thickening from above and below (Figs. 4b,d, S9d,g). We also observed localized accretion below existing ice slabs in transects A, B and E (Fig. S10).

Ice slab expansion to higher elevations predominantly occurred through accretion on top of existing near-surface ice layers. At 2012's upper ice slab boundary (18.5 km), a ~ 1 m layer grew by spring 2013, subsequently thickening to 6 m by 2018 and yielding 5.7 km of inland slab expansion (Fig. 4d). Conversely, from ~ 25 km onwards the near-surface ice layer identified in spring 2013 (Fig. 4b) was buried by subsequent accumulation (Fig. 4d).

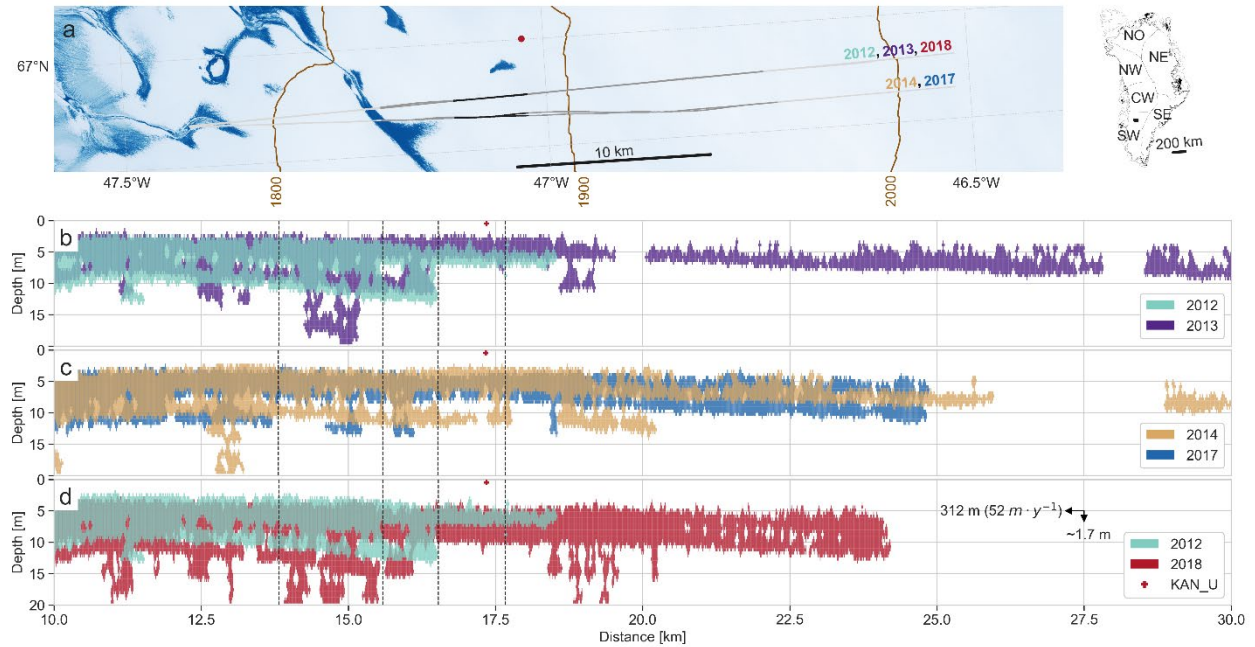


Figure 4. Ice thickness change through time along a transect close to KAN_U. (a) Near-infrared (band 8) Sentinel-2 image acquired on August 23rd, 2021, complete radargram extent (light grey), radargram extent (dark grey) shown in panels b-d, ~ 4 km transect of interest (black), location of KAN_U (red dot). (b-d) Maximum likely ice content between different repeat radargrams. The dashed vertical lines delineate specific areas discussed in the text. In panel d, the vertical arrow illustrates burial from 2013 to 2017 due to firn replenishment; the horizontal arrow illustrates the lateral movement of the ice from 2012 to 2018 (Text S4).

4 Discussion

4.1 Mechanisms of ice slab formation and thickening

We identify three principal mechanisms of ice slab formation and thickening. (i) Meltwater percolation and refreezing generates initial ice layers in porous firn. Then, accretion of ice by meltwater refreezing proceeds (ii) on top of, and/or (iii) beneath pre-existing ice layers.

In the data presented in Fig. 4, mechanism (i) was responsible for the initial generation of a 3 m-thick near-surface contiguous ice slab by the fusing of pre-existing discontinuous ice layers in porous firn from 18.5 km onwards during summer 2012. Culberg et al. (2021) and de la Peña et al. (2015) similarly showed that the initiation of near-surface ice layers can occur within a single extremely warm summer.

Radar observations can differentiate between subsequent thickening by accretion (ii) on top of, and (iii) below existing ice content. We interpret that unexceptional but sustained melting conditions such as in 2014 or 2016 predominantly cause thickening by accretion on top of pre-existing ice slabs (Figs. 4c, S6, S9c-g). Machguth et al., (2016) also evidenced top-down ice accretion due to the 2013 and 2014 moderate melt summers by comparing 2015 and 2013 cores. Hence, once ice slabs form, they thicken even in moderate melt years.

Accretion below existing ice slabs (Fig. 4b,d) was primarily associated with the large PDH sum during summer 2012 (Fig. S6). We propose that abundant meltwater - which may have originated from higher elevations (Clerx et al., 2022) - was able to exploit local areas of higher permeability. Previous observations show that deep percolation (> 10 m) can occur in firn without homogeneous wetting front advance (Humphrey et al., 2012; Machguth et al., 2016; Samimi et al., 2020). However, these processes are less likely to occur through several meters thick ice slabs. In northwest Greenland, Culberg et al., (2022) found that meltwater associated with visible runoff features probably exploits fractures to penetrate through the ice slab and refreeze underneath. We find multiple lines of evidence which support this process further south. First, crevasses have been observed at high elevations in the percolation zone of central-west Greenland (Colgan et al., 2016), providing paths for meltwater to flow vertically. Second, the accretion of ice beneath ice slabs observed downstream of KAN_U (Fig. 4) is associated with meltwater ponding in a slush field (Fig. S11). Third, sudden firn warming at 5 m depth at

KAN_U in September 2012 strongly supports abrupt meltwater penetration through a 3 m thick ice slab, followed by gradual cooling through winter indicative of refreezing (Machguth et al., (2016) Figs. S4 and S5a). Finally, firn cores acquired in 2012 and 2013 show ice accretion at a depth of 5 m in-between existing ice slabs (Machguth et al., (2016) Fig. S4c).

4.2 Changes in sub-surface firn and implications

Immediately above the current ice slab extent in SW Greenland, the firn is primed for further ice slab development. Indeed, cores from Site J (2040 m asl) acquired in 1989 and 2017 clearly show the merging of ice lenses into several ~1 m thick layers in the uppermost 12 m (Rennermalm et al., 2021), and cores acquired at Dye-2 (2,120 m asl) in 1998 and 2013 tell a similar story (Machguth et al., 2016). The increase in firn density and ice content is consistent with recent warmer surface conditions (de la Peña et al., 2015).

Surface melting is projected to increase in the percolation zone (Fettweis et al., 2013; Franco et al., 2013), and extreme summer melting events such as 2010 and 2012 are expected to become more frequent (Bevis et al., 2019). Yet, radargrams indicate that the fate of the near-surface ice layer generated in summer 2012 varied by elevation.

Towards the lower elevations of the ice layer that was mostly generated due to summer 2012 (from 18.5 km onwards), additional ice accreted, forming ice slabs by 2017-18 (Fig. 4). Conversely, at higher elevations where melt was infrequent between 2013 and 2017 (Fig. S6), the near-surface layer generated in 2012 was progressively buried to moderate depths, reducing the likelihood that it will support ice slab growth in the future. The upper limit of the summer 2012 ice layer (Fig. S9d) is located 260 m away from the location of Core 3 (Rennermalm et al., 2021). The later layer probably corresponds to the numerous ice layers found in the uppermost 9 m of Core 3 in 2013. By 2018, these ice layers had been buried and could no longer be identified by radar (Fig. S9e-g), in agreement with ~3.5 m of firn replenishment identified by the redrilling of Core 3 in 2019. This is consistent with Culberg et al. (2021), who showed that the 2012 near-surface melt layer above 2600 m asl in central Greenland was initially located at 1 m deep, and was still present in 2017 but had been buried to a depth of 5 m. Thus, the ability of near-surface ice layers to support subsequent ice slab development is likely to depend on whether strong melting occurs during several successive summers.

Considering recent sub-surface changes between 2013 and 2017, cores at KAN_U (Fig. 6a in Rennermalm et al. (2021)) show that the top of the ice slab was at roughly the same depth in 2017 as 2013. However, the 2015 and 2016 cores showed some evidence of firn replenishment. We suggest that this replenishment subsequently melted during summer 2016 (Fig. S6) and refroze on top of the slab. Thus, the effect of isolated years of firn replenishment, which temporarily bury an ice slab, can be easily erased by relatively moderate melting.

5 Conclusions

We interpreted accumulation radar data to show that ice slabs already existed in 2002-03 in SW, CW and NO Greenland, which are most likely a result of increasing surface melting from the mid-1990s onwards (van As et al., 2016). On an ice-sheet-wide basis we showed that ice slabs expanded inland from 2012 to 2018 by 13,400-17,600 km², or 37-44%.

We identified two mechanisms by which ice slabs thicken: wide-spread ice accretion on top of pre-existing ice slabs, and more localised ice accretion beneath pre-existing ice slabs. We suggest that deep percolation through ice slabs takes place beneath ponded surface meltwater features and exploits local fractures in otherwise near-impermeable ice slabs. Accretion below pre-existing ice slabs is therefore more likely during extreme melt seasons, while more moderate melt seasons predominantly result in top-down thickening.

Extremely warm summers such as 2012 can produce enough meltwater at higher elevations to generate a near-surface ice layer on the order of at least a meter thick, forming the basis for subsequent ice slab expansion via top-down ice accretion. Once formed, ice slabs continue to thicken, even under moderate melting conditions.

We suggest that future increases in melting at higher elevations will trigger further ice slab development, increasing the ice slab area non-linearly with elevation because of the non-linearity of the hypsometry of the ice sheet (Bauer, 1955). The recent expansion of the visible runoff area of the Greenland Ice Sheet (Tedstone & Machguth, 2022) is strongly linked with the expansion of ice slabs (Fig. S12), so future increases in ice slab area are likely to further increase the area which contributes runoff to the oceans.

Acknowledgments

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Open Research

2002-2003 and 2010-2018 accumulation radar data (CReSIS, 2021) are available on the CReSIS data repository (<https://data.cresis.ku.edu/data/accum/>). We used the ArcticDEM digital elevation model at 100m resolution, which provides elevation above the WGS84 ellipsoid (<https://www.pgc.umn.edu/data/arcticdem/>). The regional divisions of the GrIS are based on the Greenland Ice Sheet drainage basins from Rignot & Mouginot (2012). Air temperatures at the automatic weather station KAN_U station can be downloaded from <https://doi.org/10.22008/promice/data/aws>. Sentinel 2 satellite images can be downloaded at <https://scihub.copernicus.eu/dhus/#/home>. The scripts used to perform the analysis for this study can be found at https://github.com/jullienn/changing_Greenland_iceslabs. Our ice slab dataset is available at <https://doi.org/10.5281/zenodo.7505426>.

Author contributions

NJ, AT and HM designed the study. NK contributed to interpretation of the 2002-03 radargrams. NJ developed the methodology for ice identification in 2010-18 data, with contributions from VH, HM and AT. NJ carried out data processing, data analysis and interpretation. NJ and AT wrote the manuscript based on comments from all co-authors.

References

- Bauer, A. (1955). The Balance of the Greenland Ice Sheet. *Journal of Glaciology*, 2(17), 456–462. Cambridge Core. <https://doi.org/10.3189/002214355793702271>
- Bevis, M., Harig, C., Khan, S. A., Brown, A., Simons, F. J., Willis, M., Fettweis, X., van den Broeke, M. R., Madsen, F. B., Kendrick, E., Caccamise, D. J., van Dam, T., Knudsen, P., & Nylén, T. (2019). Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing. *Proceedings of the National Academy of Sciences*, 116(6), 1934–1939. <https://doi.org/10.1073/pnas.1806562116>

- Braithwaite, R. J., Laternser, M., & Pfeffer, W. T. (1994). Variations of near-surface firn density in the lower accumulation area of the Greenland ice sheet, Pâkitsoq, West Greenland. *Journal of Glaciology*, 40(136), 477–485. Cambridge Core. <https://doi.org/10.3189/S002214300001234X>
- Brown, J., Harper, J., Pfeffer, W. T., Humphrey, N., & Bradford, J. (2011). High-resolution study of layering within the percolation and soaked facies of the Greenland ice sheet. *Annals of Glaciology*, 52(59), 35–42. <https://doi.org/10.3189/172756411799096286>
- Carl, L., Lewis, C., Gogineni, P., Rodriguez, F., Paden, J., & Li, J. (2011). *IceBridge Accumulation Radar L1B Geolocated Radar Echo Strength Profiles, 2010, 2011, 2012, 2013, 2014, 2017, 2018 [Dataset]*. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media. <https://data.cresis.ku.edu/data/accum/>.
- Clerx, N., Machguth, H., Tedstone, A., Jullien, N., Wever, N., Weingartner, R., & Roessler, O. (2022). *In situ measurements of meltwater flow through snow and firn in the accumulation zone of the SW Greenland Ice Sheet* [Preprint]. Ice sheets/Glacier Hydrology. <https://doi.org/10.5194/egusphere-2022-71>
- Colgan, W., Rajaram, H., Abdalati, W., McCutchan, C., Mottram, R., Moussavi, M. S., & Grigsby, S. (2016). Glacier crevasses: Observations, models, and mass balance implications: Glacier Crevasses. *Reviews of Geophysics*, 54(1), 119–161. <https://doi.org/10.1002/2015RG000504>
- CRISIS. (2021). *Accumulation radar Data, 2002, 2003, 2010, 2011, 2012, 2013, 2014, 2017, 2018 [Dataset]* Lawrence, Kansas, USA. Digital Media. <http://data.cresis.ku.edu/>
- Culberg, R., Chu, W., & Schroeder, D. M. (2022). Shallow Fracture Buffers High Elevation Runoff in Northwest Greenland. *Geophysical Research Letters*, 49(23). <https://doi.org/10.1029/2022GL101151>
- Culberg, R., Schroeder, D. M., & Chu, W. (2021). Extreme melt season ice layers reduce firn permeability across Greenland. *Nature Communications*, 12(1), 2336. <https://doi.org/10.1038/s41467-021-22656-5>
- de la Peña, S., Howat, I. M., Nienow, P. W., van den Broeke, M. R., Mosley-Thompson, E., Price, S. F., Mair, D., Noël, B., & Sole, A. J. (2015). Changes in the firn structure of the western Greenland Ice Sheet caused by recent warming. *The Cryosphere*, 9(3), 1203–1211. <https://doi.org/10.5194/tc-9-1203-2015>
- Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M.-J., van Angelen, J. H., & van den Broeke, M. R. (2014). An improved mass budget for the Greenland ice sheet. *Geophysical Research Letters*, 41(3), 866–872. <https://doi.org/10.1002/2013GL059010>
- Fausto, R. S., van As, D., Mankoff, K. D., Vandecrux, B., Citterio, M., Ahlstrøm, A. P., Andersen, S. B., Colgan, W., Karlsson, N. B., Kjeldsen, K. K., Korsgaard, N. J., Larsen, S. H., Nielsen, S., Pedersen, A. Ø., Shields, C. L., Solgaard, A. M., & Box, J. E. (2021). *Programme for Monitoring of the Greenland Ice Sheet (PROMICE) automatic weather station data*. 27.
- Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., Lang, C., van As, D., Machguth, H., & Gallée, H. (2017). Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *The Cryosphere*, 19.
- Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., & Lenaerts, J. T. M. (2013). Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere*, 21.
- Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., Born, A., Box, J. E., Delhasse, A., Fujita, K., Gierz, P., Goelzer, H., Hanna, E., Hashimoto, A., Huybrechts, P., Kapsch, M.-L., King, M. D., Kittel, C., Lang, C., ... Tedesco, M. (2020). GrSMBMIP: intercomparison of the modelled 1980–2012 surface mass balance over the Greenland Ice Sheet. *The Cryosphere*, 24.
- Forster, R. R., Box, J. E., van den Broeke, M. R., Miège, C., Burgess, E. W., van Angelen, J. H., Lenaerts, J. T. M., Koenig, L. S., Paden, J., Lewis, C., Gogineni, S. P., Leuschen, C., & McConnell, J. R. (2014). Extensive liquid meltwater storage in firn within the Greenland ice sheet. *Nature Geoscience*, 7(2), 95–98. <https://doi.org/10.1038/ngeo2043>
- Franco, B., Fettweis, X., & Erpicum, M. (2013). Future projections of the Greenland ice sheet energy balance driving the surface melt. *The Cryosphere*, 7(1), 1–18. <https://doi.org/10.5194/tc-7-1-2013>
- Hall, D. K., Comiso, J. C., DiGirolamo, N. E., Shuman, C. A., Box, J. E., & Koenig, L. S. (2013). Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS: TEMPERATURE AND MELT OF GREENLAND ICE. *Geophysical Research Letters*, 40(10), 2114–2120. <https://doi.org/10.1002/grl.50240>
- Harper, J., Humphrey, N., Pfeffer, W. T., Brown, J., & Fettweis, X. (2012). Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn. *Nature*, 491(7423), 240–243. <https://doi.org/10.1038/nature11566>
- Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of Hydrology*, 282(1–4), 104–115. [https://doi.org/10.1016/S0022-1694\(03\)00257-9](https://doi.org/10.1016/S0022-1694(03)00257-9)

- Humphrey, N. F., Harper, J. T., & Pfeffer, W. T. (2012). Thermal tracking of meltwater retention in Greenland's accumulation area: THERMAL TRACKING OF MELTWATER RETENTION. *Journal of Geophysical Research: Earth Surface*, 117(F1), n/a-n/a. <https://doi.org/10.1029/2011JF002083>
- Kanagaratnam, P., Gogineni, S. P., Ramasami, V., & Braaten, D. (2004). A Wideband Radar for High-Resolution Mapping of Near-Surface Internal Layers in Glacial Ice. *IEEE Transactions on Geoscience and Remote Sensing*, 42(3), 483–490. <https://doi.org/10.1109/TGRS.2004.823451>
- Karlsson, N. B., Colgan, W. T., Binder, D., Machguth, H., Abermann, J., Hansen, K., & Pedersen, A. Ø. (2019). Ice-penetrating radar survey of the subsurface debris field at Camp Century, Greenland. *Cold Regions Science and Technology*, 165, 102788. <https://doi.org/10.1016/j.coldregions.2019.102788>
- King, M. D., Howat, I. M., Candela, S. G., Noh, M. J., Jeong, S., Noël, B. P. Y., van den Broeke, M. R., Wouters, B., & Negrete, A. (2020). Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat. *Communications Earth & Environment*, 1(1), 1. <https://doi.org/10.1038/s43247-020-0001-2>
- Lewis, C. (2010). *Airborne UHF Radar for Fine Resolution Mapping of Near-Surface Accumulation Layers in Greenland and West Antarctica*, (Master's thesis) [University of Kansas]. Retrieved from KU Scholar Works data repository (<http://hdl.handle.net/1808/7008>)
- MacFerrin, M., Machguth, H., As, D. van, Charalampidis, C., Stevens, C. M., Heilig, A., Vandecrux, B., Langen, P. L., Mottram, R., Fettweis, X., Broeke, M. R. van den, Pfeffer, W. T., Moussavi, M. S., & Abdalati, W. (2019). Rapid expansion of Greenland's low-permeability ice slabs. *Nature*, 573(7774), 403–407. <https://doi.org/10.1038/s41586-019-1550-3>
- Machguth, H., MacFerrin, M., van As, D., Box, J. E., Charalampidis, C., Colgan, W., Fausto, R. S., Meijer, H. A. J., Mosley-Thompson, E., & van de Wal, R. S. W. (2016). Greenland meltwater storage in firn limited by near-surface ice formation. *Nature Climate Change*, 6(4), 390–393. <https://doi.org/10.1038/nclimate2899>
- Miège, C., Forster, R. R., Brucker, L., Koenig, L. S., Solomon, D. K., Paden, J. D., Box, J. E., Burgess, E. W., Miller, J. Z., McNerney, L., Brautigam, N., Fausto, R. S., & Gogineni, S. (2016). Spatial extent and temporal variability of Greenland firn aquifers detected by ground and airborne radars. *Journal of Geophysical Research: Earth Surface*, 121(12), 2381–2398. <https://doi.org/10.1002/2016JF003869>
- Mikkelsen, A. B., Hubbard, A., MacFerrin, M., Box, J. E., Doyle, S. H., Fitzpatrick, A., Hasholt, B., Bailey, H. L., Lindbäck, K., & Pettersson, R. (2016). Extraordinary runoff from the Greenland ice sheet in 2012 amplified by hypsometry and depleted firn retention. *The Cryosphere*, 10(3), 1147–1159. <https://doi.org/10.5194/tc-10-1147-2016>
- Miller, J. Z., Culberg, R., Long, D. G., Shuman, C. A., Schroeder, D. M., & Brodzik, M. J. (2022). An empirical algorithm to map perennial firn aquifers and ice slabs within the Greenland Ice Sheet using satellite L-band microwave radiometry. *The Cryosphere*, 16(1), 103–125. <https://doi.org/10.5194/tc-16-103-2022>
- Nghiem, S. V., Hall, D. K., Mote, T. L., Tedesco, M., Albert, M. R., Keegan, K., Shuman, C. A., DiGirolamo, N. E., & Neumann, G. (2012). The extreme melt across the Greenland ice sheet in 2012. *Geophysical Research Letters*, 39(20), 2012GL053611. <https://doi.org/10.1029/2012GL053611>
- Pfeffer, W. T., & Humphrey, N. F. (1998). Formation of ice layers by infiltration and refreezing of meltwater. *Annals of Glaciology*, 26, 83–91. <https://doi.org/10.3189/1998AoG26-1-83-91>
- Pfeffer, W. T., Meier, M. F., & Illangasekare, T. H. (1991). Retention of Greenland runoff by refreezing: Implications for projected future sea level change. *Journal of Geophysical Research*, 96(C12), 22117. <https://doi.org/10.1029/91JC02502>
- Rennermalm, Å. K., Hock, R., Covi, F., Xiao, J., Corti, G., Kingslake, J., Leidman, S. Z., Miège, C., MacFerrin, M., Machguth, H., Osterberg, E., Kameda, T., & McConnell, J. R. (2021). Shallow firn cores 1989–2019 in southwest Greenland's percolation zone reveal decreasing density and ice layer thickness after 2012. *Journal of Glaciology*, 68(269), 431–442. <https://doi.org/10.1017/jog.2021.102>
- Rignot, E., Box, J. E., Burgess, E., & Hanna, E. (2008). Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophysical Research Letters*, 35(20), L20502. <https://doi.org/10.1029/2008GL035417>
- Rignot, E., & Mouginot, J. (2012). Ice flow in Greenland for the International Polar Year 2008-2009: ICE FLOW GREENLAND 2009. *Geophysical Research Letters*, 39(11), n/a-n/a. <https://doi.org/10.1029/2012GL051634>
- Rodriguez-Morales, F., Byers, K., Crowe, R., Player, K., Hale, R. D., Arnold, E. J., Smith, L., Gifford, C. M., Braaten, D., Panton, C., Gogineni, S., Leuschen, C. J., Paden, J. D., Li, J., Lewis, C. C., Panzer, B., Gomez-Garcia Alvestegui, D., & Patel, A. (2014). Advanced Multifrequency Radar Instrumentation for Polar Research. *IEEE Transactions on Geoscience and Remote Sensing*, 52(5), 2824–2842. <https://doi.org/10.1109/TGRS.2013.2266415>
- Rodriguez-Morales, F., Gogineni, P., Leuschen, C., Allen, C., Lewis, C., Patel, A., Byers, K., Smith, L., Shi, L., Panzer, B., Blake, W., Crowe, R., & Gifford, C. (2010). Development of a multi-frequency airborne radar instrumentation package for ice sheet mapping and imaging. *2010 IEEE MTT-S International Microwave Symposium*, 157–160. <https://doi.org/10.1109/MWSYM.2010.5518197>

- Samimi, S., Marshall, S. J., & MacFerrin, M. (2020). Meltwater Penetration Through Temperate Ice Layers in the Percolation Zone at DYE-2, Greenland Ice Sheet. *Geophysical Research Letters*, 47(15). <https://doi.org/10.1029/2020GL089211>
- Tedesco, M., & Fettweis, X. (2020). Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. *The Cryosphere*, 14(4), 1209–1223. <https://doi.org/10.5194/tc-14-1209-2020>
- Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E., & Wouters, B. (2013). Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. *The Cryosphere*, 7(2), 615–630. <https://doi.org/10.5194/tc-7-615-2013>
- Tedesco, M., Fettweis, X., van den Broeke, M. R., van de Wal, R. S. W., Smeets, C. J. P. P., van de Berg, W. J., Serreze, M. C., & Box, J. E. (2011). The role of albedo and accumulation in the 2010 melting record in Greenland. *Environmental Research Letters*, 6(1), 014005. <https://doi.org/10.1088/1748-9326/6/1/014005>
- Tedstone, A. J., & Machguth, H. (2022). Increasing surface runoff from Greenland's firn areas. *Nature Climate Change*. <https://doi.org/10.1038/s41558-022-01371-z>
- The IMBIE Team. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*, 579(7798), 233–239. <https://doi.org/10.1038/s41586-019-1855-2>
- van Angelen, J. H., van den Broeke, M. R., Wouters, B., & Lenaerts, J. T. M. (2014). Contemporary (1960–2012) Evolution of the Climate and Surface Mass Balance of the Greenland Ice Sheet. *Surveys in Geophysics*, 35(5), 1155–1174. <https://doi.org/10.1007/s10712-013-9261-z>
- van As, D., Fausto, R. S., Cappelen, J., van de Wa, R. S. W. I., Braithwaite, R. J., Machguth, H., & PROMICE project team, *. (2016). Placing Greenland ice sheet ablation measurements in a multi-decadal context. *GEUS Bulletin*, 35, 71–74. <https://doi.org/10.34194/geusb.v35.4942>
- van den Broeke, M. R., Enderlin, E. M., Howat, I. M., Kuipers Munneke, P., Noël, B. P. Y., van de Berg, W. J., van Meijgaard, E., & Wouters, B. (2016). On the recent contribution of the Greenland ice sheet to sea level change. *The Cryosphere*, 10(5), 1933–1946. <https://doi.org/10.5194/tc-10-1933-2016>
- Vandecrux, B., MacFerrin, M., Machguth, H., Colgan, W. T., van As, D., Heilig, A., Stevens, C. M., Charalampidis, C., Fausto, R. S., Morris, E. M., Mosley-Thompson, E., Koenig, L., Montgomery, L. N., Miège, C., Simonsen, S. B., Ingeman-Nielsen, T., & Box, J. E. (2019). Firn data compilation reveals widespread decrease of firn air content in western Greenland. *The Cryosphere*, 13(3), 845–859. <https://doi.org/10.5194/tc-13-845-2019>