Dear Editor and Reviewers,

We are grateful for your constructive review of our manuscript. We made our best to address all the suggestions and provide an improved and fully revised manuscript. A response to each of the reviewers' comments is given below but we would like to highlight the most important updates of manuscript:

- We now present a research article with improved visuals and more in-depth discussion.
- We compare our FAC dataset and maps to three regional climate models.
- The construction of empirical functions is slightly updated, simplified and presented in the main text.

We thank the reviewers for improving significantly the study.

Sincerely,

Baptiste Vandecrux on behalf of the co-authors

Review #1 by Sergey Marchenko

Reviewer's comment	Authors' response
General comments Physical geography. Authors use the mean annual air temperature and net surface accumulation as arguments in functions describing the spatial distribution of FAC10. The functions are fitted to minimize the misfit with empirical estimates of FAC10 from cores. One important thing that is missing in the text is a detailed description of the physical (or may be practical) motivation for the choice of the above mentioned arguments. Both characteristics (net annual surface accumulation and mean annual air temperature) integrate the effects of processes occurring during the cold and warm parts of a year.	
Net annual surface accumulation is the result of mass accumulation in winter and surface melt in summer. While the first one can be expected to be positively linked with FAC (more accumulation in winter -> more pores), the second one can be expected to be negatively linked with FAC (more melt -> thinner snow layer by the end of summer with less pores, more water available for refreezing).	**In our study $\dot{\bar{b}}$ is defined as "net snow accumulation" (snowfall + deposition – sublimation) and is not "Net annual surface accumulation". It therefor already corresponds to the "precipitation rate" that is recommended. We now give more explanation in the text.**
Mean annual air temperature can be also separated in two parts: temperature in winter and in summer. The principal difference between the two is the likely range of values: significantly negative in winter and close to melt point in summer. High winter temperatures can be expected to result in a lesser cold content of the subsurface profile, leading to a less active refreezing during	**We now state that our motivation for using long term mean annual temperature are 1) its control on firn temperature and dry firn compaction 2) its control on melt amount in the summer. Both temperature-dependent processes have a densifying effect on the**

consecutive summer and larger FAC values. Air temperature during the warm part of a year is commonly used as a proxy for melt rate (e. g. Ohmura, 2001). High air temperatures in summer lead to faster melt and larger potential for refreezing as there is more water available with the effect of smaller FAC values. As noted above the melt rate (as a contribution to the net annual accumulation) and air temperature in summer (as a contribution to the mean annual air temperature) are closely correlated and probably interchangeable for the purposes of FAC parameterization. There are, thus, 3 proxies left: precipitation rate, winter air temperature and summer air temperature (or melt rate). Along with gravitational settling liquid water refreezing is one of the two contributors to the density increase over time. It can be limited by one of the three parameters: availability of liquid water, pore space or cold content. Subsurface temperature and density, defining the FAC, are heavily dependent on the relation between the three parameters.	**firn and therefore act similarly on the FAC.** **We do not aim at quantifying the cold content and therefore do not need to include the winter temperature.** **Also we believe that our dataset does not offer the possibility to constrain empirical functions taking more than two input variables.** **Eventually the amount of meltwater effectively retained in the firn indeed depends on the "availability of liquid water, pore space or cold content". However, this is out of the scope of our study and we choose to focus on the retention capacity of the firn. Future work will need to address how this capacity is effectively being used under different conditions.**
In the course of a temporal or spatial transition towards a warmer climate, air temperature increases. The associated rise in melt rates will deliver more water. Depending on whether the potential of pore space or cold content will be exhausted first, two different scenarios can be applied to a subfreezing firn profile: transition towards superimposed ice nourishment or development of a warm firn pack, possibly, with perennial firn aquifers in case runoff is impeded. This is exactly what happens in Greenland and what the authors of the manuscript, probably,	**For a matter of conciseness and because we do not question or discuss facies definition, we choose to cite Shumskii and Benson's work rather than paraphrasing it. The reader is left free to investigate the original references for more information.** **We also added a reference to Braithwaite**

attempted to reproduce by introducing three different domains: DSA, LAWSA and HAWSA. The above presented logic goes back to the theory of glacier zones presented in (Shumskii 1955). English translation was published in 1964 (see ch. 18 and 20). Definitions of glacier zones are also given in Cogley et al. (2011). One can also address the project report Marchenko (2012) and the phd thesis (2018) for a detailed description of the logic and Braithwaite et al. (1994) of some aspect thereof. The approach was applied by Pfeffer et al. (1991, see appendix there) and Janssens and Huybrechts, (2000) for estimating refreezing rates in Greenland. The idea of geographical patterns in Greenland firn pack development was recently expressed by Michael MacFerrin the his PhD thesis (see ch. 5.2.3), perhaps, worth citing in ch. 2.4 along with the other above published sources.	**et al. 1994 for their observation of meltwater refreezing "within a wetted layer of thickness 2-4 m".**
One option is to use the three above mentioned parameters as arguments in functions for extrapolating and interpolating observed FAC values. That could be precipitation rate and mean temperatures during summer and winter months. The latter two can be replaced by either the annual sums of positive and negative degree-days or mean annual temperature and some continentality index. It is also possible that precipitation expresses continentality to some extent with higher values associated with more maritime climates. It is impossible to say without testing, but it may be possible to adequately describe the FAC10 values from cores around all of the Greenland ice sheet by a sum of three piecewise-linear functions of the earlier mentioned three parameters. These were just some suggestions and authors are, of course, free to choose the logic used for FAC10 estimates. In any case choice of arguments used for the spatial distribution of the empirical FAC10 values has to be motivated.	**As mentioned above, we already have one predictor (net snow accumulation) for all the processes that replenish the FAC and another predictor (mean air temperature) for all the processes depleting the FAC (firn compaction and melt). We do not believe that our dataset allow any higher degree of complexity.**

Comparing results with earlier published data I suggest a more extensive referencing of published FAC estimates for the Greenland Ice Sheet. There is, apparently, a considerable spread in values of both FAC10 and total FAC. This is noted in ch. 3.5 of the manuscript, but should, preferably, appear much earlier, already in the Introduction chapter. An overview of the published values would provide one important motivation point for undertaking this kind of studies. Furthermore, comparisons of results with published estimates could make an interesting discussion as the present study suggests an alternative approach to calculation of the firn air content. For example, Ligtenberg at al. (2018) make a reference to the dataset containing results of simulations on which the publication is build - https://doi.org/10.1594/PANGAEA.884617. A rough calculation of the total FAC in Greenland gives the value of 26300 Gt (please see the code used for the exercise in the appendix of the review), That is 20 times more than value from Harper et al. (2012) referenced in ch. 3.5, p. 8, ln. 8 of the manuscript. Full simulation results are available from Ligtenberg et al. and FAC10 value can be also calculated. The earlier study by van Angelen et al. (2013) is not referenced at all. It would also be interesting to compare the FAC10 values presented in the manuscript with corresponding output from the subsurface component CROCUS of the regional climate model MAR, surface data from which is used in the manuscript. Steger et al. (2017) also have figures showing FAC estimates for different areas in Greenland derived using the another layered model – SNOWPACK.	**We now compare our FAC10 dataset to existing RCM.** **van Angelen et al. (2013) is now cited in the introduction.**
Scale of the manuscript	**We now changed to a research article**

One of the shortcomings of the manuscript is that the reader is forced to refer to supplementary material while going through the methods chapter. At the same time the suggested approach to deriving distributed FAC values is elegant, novel and promising. In case authors decide to introduce a more extensive discussion based on comparison of the results with earlier published values and relocate the "methods" figure from the supplementary material (S3) to the main paper text, the paper can be reclassified to a "research article" instead of "brief communication", which it is now. In case authors will prefer to keep the manuscript as "brief communication", the number of references has to be greatly reduced. The list of references now contains 55 entries, while only 20 are allowed for this type of manuscripts according to the The Cryosphere protocol (https://www.the-cryosphere.net/about/manuscript_types.html). I would also suggest to: – transfer the table from the main manuscript to the supplement, – reduce the number of panels in fig 2 and 3 – merge panes from fig 3 in fig. 2, add the "methods" figure in the main text.	**format.** **Figures were updated.**

Specific comments

N	address	Comment	Authors' response
1	Abstract	Include the estimate of the total FAC in Greenland in Gigatonns. The reader see the firn area, the absolute and relative values of FAC10 decrease in LAWSA, but both values would be more informative if the	**We added the loss of retention capacity in the LAWSA (in Gt) to the abstract.**

		Gt estimate would be found somewhere not very far.	
2	Ch. 1, p. 2, ln. 5-6	The phrase “for that depth range” seems to be out of place.	**Changed to “It indicates, for a specified depth range, the maximum volume…”**
3	Ch. 1, p. 2, ln. 9-11	Add the quantitative estimates of FAC from Ligtenberg et al., 2018, van Angelen et al., 2013, Steger et al., 2017	**We now compare our dataset to the output from three RCMs**
4	Ch. 1, p. 2, ln. 12-21	Bring the sentence on deep water percolation evidences from Humphrey et al., 2012 earlier, so that it appears second in the paragraph. This will group together the evidences of shallow percolation from Machguth et al. (2016) and Heilig et al., (2018).	**Here our intention was to show that 1) Braithwaite et al. and Heilig et al. give evidence of shallow percolation 2) Humphrey et al. give evidence of deep percolation when sufficient melt is present 3) Machguth show that in some conditions, even when sufficient surface melt is available, deep percolation does not occur because of ice layers.** **We tried to make it clearer and rephrased the paragraph.**
5	Ch. 1, p. 2, ln. 13	Heilig et al., (2018) had their installation at 2120 m asl, not at 2300 m.	**Updated**
6	Ch. 1, p. 2, ln. 23	How does this collection of core data relate to the data from Fausto et al., 2018 in Frontiers? They at least partly overlap, as is seen on the maps of core locations.	**They use partly the same sources (e.g. PARCA, Sumup…) but Fausto et al. focuses on the average density of the top 10, 20 and 50cm of the snow. As a consequence they also use snow pits that we do not use.**
7	Ch. 2.2, p. 3, ln. 2	Same as above	
8	Ch. 2.2., p. 3, ln. 3	”...as part of the FirnCover campaigns...” It is not obvious what is “FirnCover campaigns”, are these field activities affiliated with a University or some other organization? Either a reference or a	**We removed the name of the fieldwork and refer to Machguth et al. (2016) for the field procedure.**

		description of the routines applied in the field has to be given.	
9	Ch. 2.2, p. 3	I encourage a more extensive use of density data. FAC values are secondary with respect to the density-depth profiles. • Instead of extrapolating FAC values from too shallow cores, one can extrapolate the density profiles. This will make it possible to include the description of the extrapolation technique (ch. 2.3, p. 3, ln. 15-19) in ch. 2,2, right after the first sentence, which seems more logical.	**We consider that extrapolating FAC profiles is more straightforward as it allows later to evaluate the uncertainty associated to our extrapolation method directly in terms of FAC10. Also, we do not believe that extrapolating density instead of FAC10 would lead to substantial improvement to the final extrapolated values.**
		• Describe the "upwards extrapolation" technique (the 315 kg m^-3 value) before describing how gap filling is done.	**Updated.**
		• I guess that the data from all cores was resampled to a common grid. If yes, then what is the spacing between neighboring nodes? Do not let readers guess!)	**Indeed when comparing two FAC10 profiles they need to be resampled on the same grid (in our case every cm). We believe it is the only method possible and therefore do not need to be specified.** **The scripts supporting the article are available on GitHub and advertised in our acknowledgement for the readers who are curious about our sampling strategies.**
10	Ch. 2.3, p. 3	I recommend more descriptive explanation of what FAC is. That also includes reformulation of equation [1]. A few tips: • Use references! FAC values were calculated earlier.	**We now define the FAC as:** **"The FAC is the integrated volume of air contained in the firn from the surface to a certain depth per unit area (van Angelen et al., 2012; Ligtenberg et al., 2018). It is a measure of the firn porosity and indicative, for a specified depth range, of the maximum volume available to store percolating meltwater either in liquid or refrozen form (Harper et al., 2012; van Angelen et al. 2012)."**

			As a comparison, the only description of FAC in Ligtenberg et al. (2018) is: "The firn air content (FAC) is used as an integrated measure for the amount of pore space present in a firn column and is defined as the vertically integrated difference of the firn density and the ice density (taken to be 917 kg/m3). "
		• Express FAC values through porosity, which is a widely applies and more basic concept – that will make it more understandable for an unprepared reader	**We believe there has been more work done on firn air content recently (van Angelen et al. 2013; Ligtenberg et al. 2018) than on porosity.** **We do not believe using porosity would lead to a significant improvement of the study.**
		• Use [m] for units! It is more straightforward than [m^2 m^-3] and more descriptive.	**Updated**
		• Using the threshold of 873 kg m^-3 for FAC calculation contradicts the very definition of FAC as firn AIR content and also the below stated scope of the manuscript (ch. 2.3., p. 3, ln. 13-14). I assume that authors prefer to avoid the discussion of permeability of firn to water, if this is the case, in has to be stated.	**Indeed it was an error on our side. We now use 917 kg/m3.** **Discussion of whether it is filled by infiltration ice or liquid water is brought up again in section 3.5.**
		The value from Machguth et al. (2016) is a result of study in western Greenland. In this manuscript geographical differences in the firn pack are one of the main points and using the value seems not logical.	**This point is now discussed in Section 3.5.**
		Ligtenberg et al. 2018 used the physically motivated value of pure ice density, 917 kg m^-3, in their FAC assessment for the entire Greenland. One can even argue that the value of 1000 kg m^-3 is	**We now differentiate the FAC (calculated 917 kg/m3) and the retention capacity (calculated by filling the FAC with ice until it reaches infiltration ice density, Harper et al. 2012).**

		valid: water fills all the pores and then expands, increasing the bulk volume. That is known as frost heave and is widely spread in permafrost areas. Pingos can be higher than 50 m suggesting that lifting 10 m of firn is well possible for frost heave action.	**Firn frost heaves are out of the scope of our study.**
11	Ch. 2.3, p. 3, ln. 23	What is “sites” here? Is that 1*1 km spatial domains, or “clusters” with core data? It also remains not clear why are cores grouped according to the original publication? Would you not unite in one group cores that are close by (less than 1 km) but come from different publications?	**This paragraph was rephrased.**
12	Ch. 2.4, p. 4, ln. 1	“all locations”: what is the grid spacing for FAC10 extra- and interpolation and, consequently, for bn and Ta?	**We now specify:** **“To put our FAC10 measurements in their climatic context, we extract the long-term (1979-2014) average net snow accumulation $\overline{\dot{b}}$ (snowfall – sublimation) and air temperature ($\overline{T_a}$) for each FAC10 measurement location from the nearest cell in the Modèle Atmosphérique Régional (MARv3.5.2; Fettweis et al., 2017) available at 5 × 5 km horizontal resolution.”**
13	Ch. 2.4, p. 4, ln. 10	The slope of FAC10 against Ta is not much different between HAWSA and DSA as it is evidenced by Fig. 1d.	**Indeed the slope was the same. We modified our method accordingly.**
14	Ch. 2.5.1., p. 4, ln. 28	What does the Arthern et al., 2010 model take as arguments?	**We now avoid using dry compaction laws and use a linear regression on Ta to describe FAC10 in the DSA.**
15	Ch.	Perhaps, a better place to describe the uncertainty quantification logic	**Updated**

	2.5.1., p. 5, ln. 2	(UQ) for the DSA is here, not in ch. 3.2. At least for other domains UQ is described in ch. 2.5.	
16	Ch. 2.5.2., p. 5, ln. 6	What is the spacing between Ta bins in the “decreasing piecewise-linear function”?	**We updated the construction of empirical functions and replaced this piecewise linear function by a more simple bilinear interpolation.**
16	Ch. 2.5.2., p. 5, ln. 7	“to resolve the FAC10 distribution each year”: is this expected at all? Reader likely does not expect that, since earlier in ch. 2.5.1. data from different years was lumped together.	**Removed.**
17	Ch. 2.5.3., p. 5, ln. 25-27	From Fig. 1b it is obvious that Ta and bn are strongly correlated. It is most probable that this fact above and not the amount of measurements explains the poor correlation between bn and residuals of the air temperature fit. In other words, adding more data will, likely, not help.	**In the revised version we revised our protocol and updated these parts.**
18	Ch. 2.5.3., p. 6, ln. 5	Are any routines applied to ensure a smooth transition of the FAC10 model between HAWSA and DSA? Earlier in ch. 2.5.2. such a routine is described for LAWSA-DSA transition.	
19	Ch. 3.1., p.6, ln. 13	“...average from 18 years of data” – comparing this with what is given in ch. 2.1. suggests that “average” is not a valid word here.	**Removed.**
20	Ch. 3.1., p.6, ln. 15-16	“...we do not believe that...” is not a valid expression. The low significance of the FAC in patchy firn just above the equilibrium line can be motivated by its likely small thickness.	**Changed to “Owing to the likely thinness of the accumulation area lower boundary, we expect the boundary does not play a negligible role in the overall retention capacity of the firn area.”**

21	Ch. 3.2., p.6, ln. 22	"...absence of temporal trend...": it would have been good to show that in a figure.	**Now showed in Figure 2b.**
22	Ch. 3.3., p.7, ln. 6	Where is 180 +-78 km^3 coming from? 690-520 =170...	**Updated**
		How is the uncertainty value of the difference (+-78) calculated?	**We now state how we calculate uncertainty:** **"The uncertainty applying on our estimated FAC_{10} and FAC_{tot} at a location cannot be considered independent because all estimates are made using the same functions of $\overline{T_a}$ and $\dot{\bar{b}}$. Consequently, we consider that the uncertainty of the mean of several FAC values is the mean of each value's uncertainty and that the uncertainty of a sum or difference of FAC values is the sum of the uncertainty applying on these FAC values."**
23	Ch. 3.3., p.7, ln. 7-8	I assume that 150 +-68 Gt comes from multiplying 180 km^3 by the assumed ice density (843 kg m^-3) and dividing by the density of water (1000 kg m^-3). If that is the case, it needs to be explicitly said. This logic is in direct contradiction with the phrase "...if we assume that all the air content can be used to store meltwater...". Also see the comment n. 9 above.	**We updated the way we calculate the firn retention capacity from infiltration ice (density 843kgm-3) filling the air content, to "the amount of water that needs to be added to the firn to bring its density to 843 kg m^{-3}" more in accordance with Harper et al. 2012.**
24	Ch. 3.3., p.7, ln.	Perhaps, residuals of fits, widely used in this manuscript, could be of help here as well...? Are the differences between the empirical fit and	**The inclusion of RCM now allows to discuss the temporal evolution of the FAC (Section 3.6).**

	17-19	FAC10 from cores drilled after high melt seasons in 2010 and 2012 show larger values than other cores?	
25	Ch. 3.4., p. 7, ln. 25	An observation: the stated mean FAC10 value in HAWSA of 2.4 m seems rather low, when visually comparing panels b and c in Fig. 2. It is considerably lower than in LAWSA for both periods. Check the value!	**We updated the number.**
26	Ch. 3.5, p. 8, ln. 5-11	As mentioned higher up a more extensive comparison of results of the manuscript with previously published FAC values is expected here. The fact that Harper et al., 2012 report Greenland-wide FAC10 value that is 17 times less than presented here deserves a wider discussion. It is claimed that their data had a lesser spatial coverage. But from that it does not follow that the FAC10 value should necessarily be less.	**We now extract the total firn air content from our estimate over Harper et al.'s considered area and compare the two.**
		Then again, results from van Angelen et al., 2013, Steger et al., 2017 and Ligtenberg et al., 2018 are of high relevance for the discussion. The authors are also using MAR data, which, most probably was run alongside with the subsurface model CROCUS. What FAC10 values does these simulation yield?	**We now compare our work to the output of HIRHAM, RACMO and MAR.**
27	Ch. 3.7., p. 8, ln. 26	Who measured the FAC10 in 2006-2007?	**This part was removed.**
28	Ch. 4, p.	"...21% decrease of FAC10...": in ch. 3.3, p. 7., ln. 2 an increase of 23%	**Updated**

	9, ln. 16	was reported	
29	Ch. 4, p. 9, ln. 21-25	"FAC10 observations also indicated that meltwater may percolate deeper than 10 m from the surface making FAC10 insufficient to describe the retention capacity of the firn there.": is this a result of the present manuscript?	**This discussion point was removed.**
		"*In a similar way*, Machguth et al. (2016) showed that *under conditions not completely understood*, ice formation may prevent meltwater from accessing the entire top 10 m of firn.": there is no similarity between this statement and the preceding one, rather opposition. What conditions are not completely understood here? It looks like authors intend to say here that depending on the subsurface conditions (temperature, density, stratigraphy, water permeability, slope of the impermeable layers with respect to horizontal) a different fraction of the FAC may be effectively used for storing the melt water. So, FAC10 is good, but, perhaps, not good enough and more research is needed to close the question here...	**We removed this point from the conclusion as it was more of a discussion point.**
	Fig. 1	Few suggestions: • Panel a: It is possible to show not only the spatial but also the temporal distribution of the core data by color-coding the year	**This was made impossible with the high clustering of the observation sites. We also consider that it does not bring any crucial information that is discussed in the text.**

		individual cores were drilled.	
30		• Panel b: may be do not use white-centered markers. Use color shading right from the center and add a white border around for higher contrast with the background. Try a different color bar, white-blue for example: more intuitive and in larger contrast with the background.	**Updated**
		In the caption add description so that it is more obvious that the black line is the domain of the Greenland Ice Sheet firn area in the Ta-bn domain.	
		• Panels c and d: combine the two panels and show LAWSA and HAWSA cores using different colors for the markers.	
31	Fig. 2	It is possible to combine some panels. Panel a and panel c can be combined. Panel b (when considered together with c) and panel d essentially overlap. When the temporal difference is shown (panel d) the significance of panel b drops and, perhaps, the panel can be left out.	**We applied your suggestions.**
32	Fig. 3	Combine panels a and c	
33	Fig. S3	3D graphs give a poor representation of the 3D reality. Try contour plots for the fitted surfaces with contour lines color-coded in the same fashion as empirical markers – FAC10 value. Or may be try 2D plots with one parameter on the horizontal and	**We now use 2d plots.**

		FAC10 on the vertical axis. Several sets of fit curves plus empirical FAC10 values for different ranges of bn will give an understanding of how the fit relates to empirical data.	

Technical corrections

N	address	Comment	Authors' response
1	Literature list	Distinguish between Fausto at al. 2018 in Frontiers (6) and in Geol. Surv. Denmark Greenland Bull. (41) by introducing "a" and "b" in the year of publication. Ambiguity in interpretation of short references along the text is now possible as it is (Fausto at al. 2018) in both cases.	**Updated**
2	p. 1, ln. 35	"...contribute to THE sea-level rise..."	**Not applied (see https://www.nature.com/articles/nature11566)**
3	p. 2, ln. 3	"...end-of-summer snowlineS but did..."	**Updated**
4	p. 2, ln. 4	"simple" is not a valid term here	**Removed**
5	p. 2, ln. 8	"...in spite of the diversity *of firn structures* across the ice sheet...": replace italic by "in characteristics/properties of the firn profile"	**We replaced "structures" by "characteristics"**
6	p. 2, ln. 23	We then calculate the FAC10 using a set of 344 firn cores collected between 1953 and 2017. We finally present the spatial distribution and where possible the temporal evolution of FAC10. Rephrased: Using a set of 344 firn cores collected between 1953 and 2017 we calculate the spatially distributed FAC10 and where possible present the its temporal evolution.	**Updated** **We replaced "spatially distributed FAC10" by " spatial distribution of FAC10"**
7	p. 2, ln.	Rephrase: "Using these data, we *determine* the firn area, *defined* as the region	**Removed**

	29	where only snow has been detected during the entire 2000-2017 period.”	
8	Ch. 2.2., p. 3, ln. 3	”...as part of the FirnCover campaigns...” It is not obvious what is “FirnCover campaigns”, are these field activities affiliated with a University or some other organization? Either a reference or a description of the routines applied in the field has to be given.	**We removed the name of the fieldwork and refer to Machguth et al. (2016) for the field procedure.**
9	p. 3, ln. 10	Replace ”section” by ”layer”	**We changed to “depth interval”.**
10	p. 3, ln. 16, 18	”10+ m core” is not a valid expression. Use ”deeper than”.	**Updated**
11	p. 3, ln. 16	”...with THE lowest Root...”	
12	p. 3, ln. 16	Rephrase: ”We therefore *attach* to any...”	**Changed to “associate”**
13	p. 3, ln. 17	Replace ”masurement” by ”estimate”. FAC10 is not measured directly.	**Since, just like firn density, FAC10 can be determined by simple calculations using observations of the mass of in a firn core, we would like as much as possible to preserve the appellation “observation”.** **It is also opposed to the FAC10 value predicted by our empirical functions (which are then estimations).**
14	p. 3, ln. 28	Shorten the sentence to have: “We extract each core site’s long-term (1970-2014) average net snow accumulation (bn) and air temperature (Ta)...”	**Updated**
15	p. 4, ln. 3-	Avoid double referencing to the color and figure number (“amber area in Figure	**We believe it is clearer if we can guide the reader**

	11	1a”). Is amber=yellow?	**to the appropriate coloured area in the relevant figure. Amber was changed to yellow.**
16	p. 6, ln. 6	What are the ”well-known dry-firn compaction equations”? References are needed here.	**We now avoid using dry firn compaction schemes and use a linear function of Ta.**
17	p. 6, ln. 7	TowardS	**Updated**
18	p. 4, ln. 20	Replace: ”from our” -> “using the”	
		“observations” -> “firn cores”	**This part was rephrased.**
19	p. 4, ln. 21	Replace: “to predict FAC10 anywhere in the firn area” -> “to interpolate and extrapolate FAC10 for the whole firn area”	**Updated**
20	p. 4, ln. 24	Form of the functions is not *arbitrary*. The authors make an attempt to bring in physics in the extrapolation of the empirical FAC10 estimates.	**This statement was removed.**
21	p. 4, ln. 28	Remove “we” before “tuned the surface snow density”	**Removed.**
22	p. 4, ln. 29	Add “a” after the reference to Figure S3.	
23	p. 5, ln. 4	Add “b” after the reference to Figure S3.	
24	p. 5, ln. 23	Replace ”...as additional measurements where FAC...” by ”...as an additional proxy of FAC...”	**This sentence was rephrased.**
25	p. 5, ln. 26	Replace: “meaning” -> “suggesting”	**Removed.**
26	p. 5, ln.	Replace: “We can make three estimates...” -> “Three principal assumptions are	

	28	possible ...”	
27	p. 6, ln. 12	Replace: “Spatial heterogeneity in melt and snowfall leave...” -> “Spatial heterogeneity in snowfall and melt leave...”	
28	p. 6, ln. 13	Replace: “missed by the method of Fausto et al. (2018).” -> “missed by the method applied by Fausto et al. (2018).”	
29	p. 6, ln. 19-20	Remove the unnecessary paragraph	
30	p. 6, ln. 21	Replace ”Assuming a normal distribution of errors, 95% of...” -> “Assuming a normal distribution of errors with zero mean, 95% of...”	**Removed**
31	p. 7, ln. 1	Subscript in FAC10 symbol	**Updated**
32	p. 7, ln. 5	“Summing the FAC10 and its uncertainty indicates that...” I assume that lateral integration across the domain covering the Greenland Ice Sheet is meant here. The phrase, as it is now, can be misinterpreted, one might think that you are summing actual values and their assumed uncertainties.	**Now rephrased in Section 2.6.**
33	p. 7, ln. 5-6	Replace: ”...of air is contained within...” -> ”...of air was contained within...”	**Updated**
34	p. 7, ln. 28	Add ”b” after ”Figure 1”	
35	p. 8, ln. 2	Rephrase: “...occur at deeper than 10 m” -> “...occur below the depth of 10 m”	**Remove.**
36	p. 8, ln. 13	Rephrase: “...impactS our FAC10 maps...” -> “...impact our FAC10 maps...”	**Updated**

37	p. 8, ln. 16	Rephrase: “...Since Box et al. (2013) giveS 2 m air temperature...” -> “...Since Box et al. (2013) give 2 m air temperature...”	**Removed**
38	p. 8 ln. 24	Rephrase: ”...provide insight on *how* the FAC10 *might have been* at a given place and time.”. For example “what were the properties of...”. Also add either “an” before or “s” after “insight” – “an insight” or “insights”, but not just “insight”.	**This paragraph was removed**
39	p. 9 ln. 2	“...systematically different *than* our calculated FAC10...” -> “...systematically different FROM our calculated FAC10...”.	
40	p. 9, ln. 3	“*A last* measurement raises questions...” -> “One more measurement raises questions...”	
41	p. 9, ln. 12-13	”...to 10 m depth (FAC10) *could be* calculated” -> “to 10 m depth (FAC10) WAS calculated”	**We rephrased the conclusion according to our new findings.**
42	p. 9, ln. 13	“...three regions *on* the firn area *in which FAC10* where we *could* fit empirical...” -> “...three regions WITHIN the firn area where we fit empirical...”	
43	p. 9, ln. 17	“This decreas*ing* FAC*10* translates into the loss of...” -> “This decreasED FAC$_{10}$ translates into the loss of...”	
44	p. 9, ln. 18	“...of meltwater retention capacity 1998-2008 and 2011-2017.” -> “...of meltwater retention capacity BETWEEN 1998-2008 and 2011-2017.”	

Reviewer #2

The manuscript describes the firn air content of the Greenland ice sheet. The amount of air in the firn layer is a good measure for the amount of meltwater that can be buffered in the ice sheet and that therefore cannot contribute directly to sea level change. A total firn area is presented based on earlier work and a compilation of 344 firn cores is used to derive a spatial map of firn air content in the upper 10m (FAC10). The firn area is divided into 3 regions: dry snow (DSA), low-accumulation wet snow (LAWSA), and high-accumulation wet snow (HAWSA). For the DSA, no change over time has been found from 1953 to 2017, while LAWSA show a substantial decrease over the last two decades with a FAC loss of ~25%.

For me, the manuscript needs substantial revisions before it is suitable for publication in The Cryosphere. The current manuscript is in a sloppy state and would have benefited greatly from another review round by its co-authors. With sloppy, I refer to the lack of flow in the text due to typo's and bad sentence structure in general, but also things that should have been spotted by the author or co-authors before submission. I illustrate this with 3 examples, while all comments are listed in the rather long list of 'minor comments' at the end of this review:

Reviewer's comments	Authors' response
1) Some numbers in the manuscript do not add up: the temporal decrease in LAWSA FAC10 is noted (P7, L5-7) to be 180 km3 (or 26%, or 150 Gt), while the absolute amounts presented are 690 km3 (1997-2008) and 520 km3 (2011-2017). This results in a difference of 170 km3, or 24.6%. In the conclusions section, even different numbers are presented (P9, L16-18): here, a 21% decrease from 1998-2008 (1997-2008 and 1998-2008 are used interchangeably, it seems) to 2011-2017 corresponds to 168 Gt of loss in meltwater retention capacity. Such juggling with numbers make the other results also less reliable.	**We apologize for these mistakes** **We now updated the numbers throughout the manuscript.** **Both our data and scripts will be made available to unsure reproducibility.**
2) There are two references to Fausto et al., 2018 used, but in the text they are not differentiated into Fausto et al., 2018a (snow density) and Fausto et al., 2018b (snow-line	**We now differentiate between the two sources.**

elevation). Fausto et al., 2018b is used as basis for one of the main conclusions of the manuscript (the firn area extent), but is not well-known -as it is an internal GEUS report- compared to the peer-reviewed Frontiers paper (Fausto et al., 2018a). It left me searching for a while in the Frontiers paper	
3) The figures need to be upgraded: Figure 1c and 1d are too small, while there is sufficient room for expansion; the colour scale used in Figure 2a and 2b does not show sufficient detail; Figure 3a is useless due to the colour scale used.	**We changed the color scale according to the suggestions of Reviewer #1.**
Next to the above points on the general state of the manuscript, I also have 3 major points that need to be addressed before the manuscript should be eligible for publica- tion. Afterwards, a list of minor points is given on a line-by-line basis (where P and L refer to page and line, respectively). Major Points: 1. I think the authors should rethink if this manuscript should be considered as a normal-size publication in TC or as brief communication (BC). To me, a normal-sized publication would fit better with the content of the manuscript. Currently, there are 7 supplementary figures in the Supplementary Material (SM), which to me is not fitting for a BC-style paper. This style has very strict limitations on pages and number of figures to keep the publication brief. If the authors feel the need to show more information with extra figures, it is better to switch to a normal style publication. This also gives the authors room to expand the methodology and include the accompanying figures in the text instead of the SM (where much less people will read them). Moreover, the text include three references to subjects that are “out of scope for this paper” (P3, L14; P7, L23; P8, L3), while I think it is very relevant to include them into the scope of this manuscript. If the publication is expanded to a	**We now present a full size research article, provide better discussion and reduce our use of the supplementary materials.**

normal-sized, these topics could be properly addressed. If the authors choose to keep the manuscript in the BC format, they should at least remove the SM figures.	
2. For the three firn regions of the GrIS, the average FAC10 is given in the manuscript: DSA at 4.9 m3 m-2 LAWSA at 4.3 m3 m-2; and HAWSA at 2.4 m3 m-2. This does not at all agree with what I would expect. As a consequence, I have strong doubts about the empirical relations and method used to calculate the spatial FAC10 maps that lead to these average numbers. Based on the published knowledge of the GrIS firn layer, one would expect the FAC10-ratio between DSA:LAWSA:HAWSA to be in the order of 5:2:4. In the LAWSA, there is low accumulation and substantial surface melt (enough to be considered "wet snow"). Most surface melt is refrozen in the cold firn leading to many ice lenses and high densities, as observed by for example Harper et al., 2012 and Machguth et al., 2016. If the LAWSA covers the entire firn area between the DSA (FAC10 5 m3 m-2) and bare ice (FAC10 = 0 m3 m-2), one would expect the average FAC10 to be 2-3 m3 m-2, and not 4.3 m3 m-2 as reported here. For the HAWSA on the other hand, the reported FAC10 of 2.4 m3 m-2 is much lower than one would expect. The HAWSA is mainly found in the south- and southeast of the GrIS and coincides quite well with locations where firn aquifers are found. At these locations, the high accumulation and relatively high firn temperatures cause less refreezing of meltwater near the surface resulting in deep percolation and recharge of the firn aquifer at depth. As a consequence, not many (thick) ice lenses are found in these regions. Due to the high accumulation, the firn in the upper 10m is relatively young (3-5 years old), resulting in less time to densify compared to low-accumulation regions. Considering this, it is to be expected that the average FAC10 of the HAWSA is higher than that of the LAWSA, while the opposite is	**We updated these numbers and now "calculate an average FAC_{10} of 5.1± 0.3 m in the DSA, an average FAC_{10} of 2.8 ± 0.3 m in the HAWSA during the 2010-2017 period and an average FAC_{10} of 3.9 ± 0.3 m in the LAWSA during the 1998-2008 period, which decreased to 2.6 ± 0.3 m in the 2010-2017 period."** **We would like to remind that the HAWSA does not characterize only the aquifer region but also stretches down glacier to the firn line where no air content is available. We therefore expect the FAC_{10} to be much lower than in the DSA for example.** **Nevertheless it is true that the average FAC_{10} calculated in the HAWSA remains rather low, potentially explaining also the overestimation of RCMs in the HAWSA compared to our estimation (Figure 8d). It is now discussed in Section 3.6.**

reported in this manuscript. In the current manuscript, the above average FAC10 numbers are presented without much discussion. Only on P9, L1-6, a couple of sentences are used to discuss the HAWSA FAC10. I think it is very important that this is more elaborately discussed! If the average FAC10 numbers turn out to be true, this is a very important result as it would change our view on how firn (and FAC) is spatially distributed around the GrIS. However, I think it is more likely that these numbers show that the method used is not sufficient to describe the variations in FAC10. My guess is that either the number of firn cores (or spatial diversity in them) is not sufficient to constrain the empirical solution, or the atmospheric input of only average accumulation and temperature is not sufficient.	
3. The results of Fausto et al., 2018 (snow-line extent) are heavily used to support one of the two main conclusions of the manuscript: the firn area extent of the GrIS. However, Fausto et al., 2018 is not a peer-reviewed publication, so their methodology is not tested nor reviewed. Here, the results of Fausto et al., 2018 are used without prudence, while some discussion on the methods used is needed. If the authors follow up on my suggestion to switch to a normal-sized publication, a short methodology can be included in this manuscript.	**The GEUS bulletin is a peer-reviewed journal (https://portal.issn.org/resource/issn/1904-4666). We also now refer to Fausto et al. 2007 which presented the method that Fausto et al. 2018 applied on the more recent MODIS data.**
Minor Points:	
P1, L25: “its characteristics are still little known” is better replaced by something along the lines of “still little is known about its characteristics”. P1, L25: Remove space between 2000-2017. P1, L26: Provide a percentage with the firn area extent P1, L26: “We also present” P1, L27-28: Presenting the results for the DSA (74%) and LAWSA (12%) leaves the casual abstract reader wondering what happened to the other 14%.	**We rewrote the abstract.**

P1, L27-28: "warmest and driest 12%" is not true. Correct would be that it is the driest part of the warmest part of the firn area. Please rephrase.	
P2, L5: "The FAC is the integrated volume"	**Updated**
P2, L12: firn temperature is also an important constrain the depth to which meltwater might percolate. P2, L12-16: No mention here of firn aquifers while they are known to have very deep percolation (up to 20-30 m). P2, L20: I find this a very crude and simple assumption. Both on the drier western side of GrIS (Humphrey et al., 2012) and the wetter eastern side (Forster et al., 2014) are indications of percolation deeper than 10 meters. By only looking at the upper 10m a substantial amount of the retention capacity of the GrIS is missed! P2, L21: The maximum volume that can be retained is much higher when the dry interior firn is included. An upper limit can be extracted from models (RCM or firn model) for example.	**We now use a simple method to estimate FAC_{tot} (the FAC of the whole firn layer) from FAC_{10} and do not rely on the assumption that meltwater retention only happens in the top 10 m.**
P2, L27: Fausto et al 2018a! P3, L1: "From literature, we gathered ..."	**Updated**
P3, L13: Strange way of notation. Why is there a plus/minus sign in front of the 1, while 1 to 10 already indicates a range and therefore a lack of precision? And, why is the FAC10 range not given as "1 to 5"? P3, L20: Similar to previous comment.	**We now give absolute uncertainty.**
P4, L1: Why not use the latest model estimates (HIRHAM, RACMO, MAR), or use all 4	**We now use MAR3.5.2 as the principal source for our Ta**

products to have some sort of best estimate.	**and ba. In the discussion, we show that we can fit equally well our FAC10 dataset with the older products from Box et al. (2013). We therefore believe that it is necessary to apply other sources which will probably fit equally well.**
P4, L4: "(3)" should be "(2)". P4, L8: it is stated that two patterns are evident in Figure 1, which is true. However, 1-2 sentences of explanation or analysis should be given after such a statement.	**Updated**
P4, L10: Figure 1c and 1d are so small that the variation in slopes is hard to see. Please increase these figures, or remove this statement.	**Sentence removed.**
P4, L14: Ta = -16C is taken as the boundary between DSA and WSA, however how true is this in a changing climate. It is well documented that GrIS is warming and the ELA increases. Currently, the 1970-2014 average temperature is used, but it is likely that the spatial pattern of the boundary changes (a lot?) over time.	**The boundary between DSA and WSA is only defined by the inflection of the FAC10 curve in Figure 1c. Our dataset does not allow us to describe the evolution of this inflection point, although it is expected in a changing climate. We therefore cannot address this discussion point with our dataset and need to work with static Snow Areas within which FAC may change through time.**
P4, L28: Interesting to see that the firn model equations of Arthern et al. 2010 are used, while 6 lines earlier (P4, L22) it is clearly stated that this manuscript attempts to construct a firn map without the use of RCM or firn models. . . P4, L29: Why not use the 315 kg m-3 as reported by Fausto et al., 2018(a)? P5, L1-2: Would be interesting to show or list how the various densification laws per- formed, and which ones were tested.	**Following your suggestion, we replaced the densification equation from Arthern et al. 2010 by a linear function of Ta, making our approach fully empirical and avoiding the use of firn models that anyway do not fit our dataset.**
P5, L4: Figure S3 is very complex as they are 3-dimensional. When using multiple 3D figures it would help if they are all oriented similarly to make the figure clearer and less dizzying.	**We now opted for 2D plots instead.**

P5, L5: In the WSA, the characteristics are very complex and different depending on slight changes in climate forcing, as you also discuss in the introduction. It seems too simplistic to constrain this behavior only by average accumulation and temperature. The complex behavior is mainly caused by melt intensity and duration, which is not captured by using the average temperature. If RCM results would be included, surface melt could also be included in the empirical functions.	**We now show that our empirical functions of average temperature and accumulation fit our FAC10 dataset better than current state of the art RCM.** **However, we do not believe that our dataset allows us to use more than two input variables.**
P5, L7: Here, the measurements from different years are grouped (likely to accommo- date for climate change), so why was this not done for the boundary between DSA and WSA (see comment on P4, L14).	**We now present the deviation between observed and estimated FAC10 for each decade in the DSA.**
P5, L23: Due to lack of measurements in the HAWSA, the firn line (where FAC10 = 0) is used as an extra observation to better constrain the empirical functions. Would this also be a good addition for the LAWSA? It would at least be more consistent.	**The use of remotely sensed firn line is judged less reliable than direct FAC10 measurements and is only used when insufficient in-situ measurements are available. It is made clear that in the LAWSA enough cores are available.**
P6, L8: Should refer to Figure 1a, I think. P6, L18: Should refer to Figure 2a. P6, L18: Add comma between region and representing.	**Updated**
P6, L23-24: Here, conclusions are drawn about the temporal evolution of the FAC10 in the DSA. However, the FAC10 is calculated using the steady-state model solutions of Arthern et al., 2010, which makes it difficult to use them for temporal analysis. Steady state density profiles have no memory of previous climate and change directly based on the average climate input. From the text I cannot sense how much this would influence the results, but please add a discussion about this to the manuscript.	**Even though we now use a linear function of Ta in the DSA, I believe your question still applies.** **If the FAC had been decreasing in the DSA, the fitted time-independent linear function would normally underestimate older FAC10 measurement and overestimate recent FAC10 measurement. In other words, the temporal evolution would appear within the residuals presented in Figure 2b.**

	Since it is not the case, we consider that time cannot explain any variance in our FAC10 dataset or in other words that there has not been detectable temporal changes of FAC10 in the DSA.
P7, L1: FAC10 should be FAC10. P7, L5: Should refer to Figure 2d.	**Updated**
P7, L5-7: As referred to in the start of this review, the stated difference in FAC10 and the difference between the absolute values does not match.	**Indeed there was a mistake from our side. We now updated the numbers.**
P7, L8-9: Please rephrase "that had become unavailable by 2011-2017". P7, L11: Multiple references should be in chronological order. P7, L12: I would remove "greatly". I agree that accumulation has a great and immediate effect on firn density, however, changes in accumulation over time are almost never substantial enough to give a significant effect in FAC. Especially not in places where surface melt is involved.	**Updated**
P7, L18: The influence of the extreme melt summer of 2010 and 2012 might be minimal at some locations with higher accumulation, as the 2010- and 2012-snow and refrozen meltwater might be buried below the 10m boundary used in this manuscript. Could you indicate for what locations this might be true?	**Given a density of 400kgm-3, the upper 10m of firn contains 4000kgm-2 of water and for the 2012 horizon being buried in 2017 would require 5 years of at least 800 mm weq yr-1. These areas of high accumulation are mainly located in the HAWSA. Since we describe changes in the LAWSA, we do not believe such discussion is needed.**
P7, L26: Refer to Figure 2c and Figure 3c.	**Figures were rearranged.**
P7, L30-31: This is not really a hypothesis. The firn aquifer is studied by multiple papers and it is clear that meltwater percolates deeper than 10m and that the high snow accumulation	**We removed this discussion point**

insulates it from the winter cold. Possible references: Kuipers Munneke et al., 2015, Miller et al., 2017, Miller et al., 2018.	
P8, L5: It is not the total FAC! The total FAC includes also all FAC below 10m, which is substantial in the DSA.	**We now use either spatially summed FAC10.**
P8, L17: Add comma after Nonetheless.	**Updated**
P8, L21: The way this sentence is written implies that all variations in FAC10 can be explained by average accumulation and temperature. This is not the case, so please rephrase.	**We do not mean "all variation" and specify the "spatial pattern" so we would like to pursue with the current phrasing.**
P8, L13-21: Here, model results are used to estimate the uncertainty in the generated firn maps. When comparing to model results, would it not be better to compare to firn model output directly. For example, Steger et al., 2016, Langen et al., 2017, and Ligtenberg et al., 2018 all present GrIS-wide firn model simulation from which FAC10 could be derived.	**We now compare the output of three RCMs.**
P8, L24: "to be used in mapping FAC10." P9, L5-6: These two options are listed as if they are equally likely. In my opinion, the hypothesized drastic decrease in FAC10 is much less likely.	**This paragraph was removed.**
P9, L9: Not true. Fausto et al., 2018 presents the first delineation of the firn area of GrIS. Please rephrase.	**Although we believe that the firn line is a product of our study and that Fausto et al. 2018 only provided yearly snow lines while never even mentioning the word "firn", we now do not stress this result anymore.**
P9, L13: "on" should be "of". P9, L16-18: As referred to in the start of this review, the numbers for LAWSA FAC do not match the numbers in the remainder of the text. P9, L17: "FAC10" should be "FAC10".	**Updated**

P9, L18: add “between” before “1998-2008”.	
P9, L21: FAC10 might not only be insufficient to describes the retention capacity in the HAWSA, according to Humphery et al., 2012 there is also deep percolation observed in the LAWSA.	**Removed**
Figure 1: - Figure c) and d) should be much larger, while the axis label can be a bit smaller. Just use the figure area better. - In b), an interesting peak is visible in the firn area extent around T=-11C and b=150 mm yr-1. You would expect that the firn area is a smooth curve across the temperature-accumulation space. What area causes this peak and might it not be worthwhile to discuss it in the text.	**We updated Figure 1 according to the suggestions from reviewer #1. The remotely-sensed firn line is not as smooth as one would think when plotted in the Ta-ba space. There are many non-climatic factors that can affect the position of the firn line: topography, wind-driven snow transport, surface roughness, shading from surrounding topography…**
Figure 2: - Due to the color scale, Figure 2a show little detail. - No need to show the core location again in Figure 2 as they are already shown in Figure 1. - The pattern of FAC10 in southwest Greenland on the boundaries from LAWSA to HAWSA looks very abnormal. Since you have a transfer-function to go from the DSA to LAWSA (P5, L12-13), why is there not transfer function between LAWSA-HAWSA?	**We modified the colour scale according to the suggestions of reviewer #1. We keep the location of FAC10 observations so that the reader is reminded that the FAC10 map is constrained by them and that areas with few observations are subject to greater uncertainty.** **With our new empirical approach there is a smooth transition between LAWSA and HAWSA.**
Figure 3: - Due to the color scale, Figure 3a is useless. - Figure 3b also show very little detail for the same reason. Perhaps use a exponential scale.	**We updated that figure, kept the same colours but adapted the scale.**

References: All other references are similar to the publications use in the manuscript.

Kuipers Munneke, P., S. R. M. Ligtenberg, E. A. Suder and M. R. van den Broeke. 2015. A model study of the response of dry and wet firn to climate change. Annals of Glaciology, 56, 70, 1-8. doi:10.3189/2015AoG70A994.

Miller, O. L., D. K. Solomon, C. Miège, L. Koenig, R.R. Forster, L. N. Montgomery, N. Schmerr, S. R. M. Ligtenberg, A. Legchenko and L. Brucker. 2017. Hydraulic conduc- tivity of a firn aquifer system in southeast Greenland. Frontiers in Earth Science, doi: 10.3389/feart.2017.00038.

Miller O. L., D. K. Solomon, C. Miege , L. Koenig , R. Forster, N. Schmerr, S. R. M. Ligtenberg and L. Montgomery. 2018. Direct evidence of meltwater flow within a firn aquifer in Southeast Greenland, Geophysical Research Letters, doi:10.1002/2017GL075707.

~~Brief communication:~~ Firn data compilation reveals the evolution of the firn air content on the Greenland ice sheet

Baptiste Vandecrux[1,2], Michael MacFerrin[3], Horst Machguth[4, 5], William T. Colgan[1], Dirk van As[1], Achim Heilig[6], C. Max Stevens[7], Charalampos Charalampidis[8], Robert S. Fausto[1], Elizabeth M. Morris[9], Ellen Mosley-Thompson[10], Lora Koenig[11], Lynn N. Montgomery[11], Clément Miège[12], Sebastian B. Simonsen[13], Thomas Ingeman-Nielsen[2], Jason E. Box[1]

[1] Department of Glaciology and Climate, ~~[1]~~ Geological Survey of Denmark and Greenland, Copenhagen, Denmark.
[2] Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark.
[3] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO USA
[4] Department of Geosciences, University of Fribourg, Fribourg, Switzerland
[5] Department of Geography, University of Zurich, Zurich, Switzerland
[6] Department of Earth and Environmental Sciences, LMU, Munich, Germany
[7] Department of Earth and Space Sciences, University of Washington, WA USA
[8] Bavarian Academy of Sciences and Humanities, Munich, Germany
[9] Scott Polar Research Institute, Cambridge University, United Kingdom
[10] Byrd Polar and Climate Research Center and Department of Geography, Ohio State University, Columbus, OH USA.
[11] National Snow and Ice Data Center, University of Colorado, Boulder, CO~~NV~~, United States
[12] Department of Geography, Rutgers University, Piscataway, NJ, United States
[13] DTU Space, National Space Institute, Department of Geodynamics, Technical University of Denmark, Kgs. Lyngby, Denmark

Correspondence to: B. Vandecrux (bava@byg.dtu .dk)

Abstract. The firn covering the Greenland ice sheet interior can retain part of the surface melt each summer, buffering the ice sheet~~sheet's~~ contribution to sea ~~-~~level rise. To quantify the ~~, but its characteristics are still little known. Using remote-sensing observations from 2000–2017, we estimate that~~ firn ~~covers 1,405,500 ±17,250 km^2 of the ice sheet. We present 344 firn-core-derived observations of the top 10 m firn air content (FAC$_{10}$), indicative of the firn's~~ meltwater retention capacity, we derive from 360 firn observations the Firn Air Content in the top 10 m (FAC$_{10}$) and in the entire firn column (FAC$_{tot}$). We then map ~~. FAC$_{10}$ remained stable in the coldest 74% of~~ the FAC over the entire firn area using empirical functions of long-term mean air temperature ($\overline{T_a}$) and net snow accumulation ($\bar{\dot{b}}$) fitted to observations. We find that the firn layer contains a total 26 800 ±1 850 km^3 of air, with 6 500 ± 450 km^3 in the top 10 m. The FAC was stable between 1953 and 2017 in the dry snow ~~during 1953-2017, while FAC$_{10}$ decreased in the warmest and driest 12% of the firn~~ area ($\overline{T_a}$ ≤-19°C), while it decreased by 24 ±16% in the low accumulation wet snow area ($\overline{T_a}$>-19°C, $\bar{\dot{b}}$ ≤ 600 mm w.eq. yr^{-1}) between 1997-2008 and 2011-2017 leading to~~, resulting in~~ a loss of ~~180 ±78 km^3 (-26 ±11%) of air from the near-surface~~ firn retention capacity between 150 ± 100 Gt (top 10 m) and 540 ± 450 Gt (whole firn column). The outputs of three regional climate models (HIRHAM5, RACMO2.3p2, MAR3.9) compare well with observed FAC$_{10}$. However model biases in FAC$_{tot}$ and other

mismatches with our dataset urge caution when using models to quantify the current and future evolution of the firn air content and retention capacity.

1. Introduction

As a consequence of anthropogenic carbon emissions and subsequent atmospheric and oceanic warming, ~~More than half of~~ the Greenland ice sheet is losing mass at an accelerating rate, and contributes~~sheet's current contribution~~ to about 20% of contemporary sea~~-~~level rise (Bindoff et al., 2013; Nerem et al. 2018). Over half of this mass loss stems from surface melt occurring every summer at the surface of the ice sheet and meltwater ~~and subsequent~~ runoff to the ocean (van den Broeke et al., 2016). While most runoff originates from the low-lying ablation area, surface melt has recently increased and expanded up-glacier into the firn-covered interior of the Greenland ~~During summer, surface melt occurs across a large area of the ice sheet, even reaching the highest~~ ice sheet (Mote et al. 2007, ~~elevations during extremely warm summers like 2012 (~~Nghiem et al., 2012). Yet, most~~Most~~ of the surface meltwater produced in ~~the~~ firn-covered regions percolates~~interior of the ice sheet is refrozen~~ into the snow and firn where it refreezes, and does not immediately contribute to sea-level rise (Harper et al., 2012). Hence the~~This~~ retention capacity of the firn area of the Greenland ice ~~is controlled by (i) the areal extent of the firn; (ii) the firn air content (FAC); iii) firn temperature; and iv) firn permeability. In this study, we use in-situ and remotely-sensed observations to estimate the firn's extent and its air content in the upper 10 m.~~

~~The first attempt to delineate the ice~~ sheet constitutes a key parameter in sea-level equation.

The firn ~~firn area into characteristic zones dates back to the 1950s (Benson, 1962). Later studies delineated the firn~~ area extent can be tracked using the firn line, which Benson (1962) described as "the highest elevation to which the annual snow cover recedes during the melt season".~~satellite remote sensing (e.g. Nolin and Payne, 2007) but had limited spatial and temporal coverage.~~ Recently Fausto et al. (2018a) updated the methods from ~~(2018) published~~Fausto et al. (2007) and presented maps of remotely-sensed end-of-summer ~~snowline but did not discuss the simple implication of these~~ snowlines over the 2000-2017 period that can be used to map the ~~for the~~ firn area~~ extent~~.

A second key characteristic for the retention of meltwater is the firn air content (FAC). The FAC is the integrated volume of air contained in the firn from the surface to a certain depth per unit area (van Angelen et al., 2012; ~~-~~Ligtenberg et al., 2018). It is a measure of the firn porosity and indicative,~~indicates~~ for a specified~~that~~ depth range, of the maximum volume available to store percolating meltwater either in liquid or refrozen form (Harper et al., 2012; van Angelen et al. 2012). While the role of FAC in meltwater retention has long been recognized, insufficient data from the firn area in Greenland made it necessary, until lately, to use simplifying assumptions (e.g. Pfeffer et al., 1991) or unvalidated outputs from regional climate model (RCM, van Angelen et al., 2013) to constrain the firn's meltwater retention capacity.~~2012).~~ Harper et al., (2012) gave a first observation-based estimate of this retention capacity of the ice sheet percolation area. Their approach was limited by the use of observations from ~~(2012) used~~ two years (2007 and 2008) and~~of observations from~~ 15 sites along the western slope of the ice sheet without regards to the ~~to estimate the spatially integrated FAC of the entire percolation area in spite of the~~ diversity of firn characteristics~~structures~~ across the ice sheet (e.g. Forster et al. 2014; Machguth et al., 2016). ~~Estimation of the FAC was also made using firn models forced by regional climate model (RCM) output (e.g. Ligtenberg et al.,~~ More recently, Ligtenberg et al. (2018) provided a RCM simulation of the FAC which compared well against 62 firn cores. Nevertheless, their FAC simulation still underestimated FAC~~2018) but model results differ significantly from each other~~ in the lower accumulation area. Focusing on meltwater percolation, Langen et al. (2017) also compared how the output of HIRHAM5 RCM compared against 75 ~~terms of~~ firn density profiles while its FAC has not been investigated. ~~and therefore of FAC (Steger et al., 2016).~~

The depth to which meltwater may percolate, and therefore the depth to which FAC must be calculated to constrain the firn's meltwater retention capacity, varies with melt intensity and firn permeability (e.g. Pfeffer et al., 1991). Braithwaite et al. (1994) reported meltwater refreezing within the top 4 m of the firn in western Greenland at ~1500 m a.s.l. while~~.~~ Heilig et al. (2018) did not observe meltwater percolation below~~deeper than~~ 2.3 m from~~below~~ the surface throughout 2016 melt season, at 2120~~2300~~ m a.s.l. also in west Greenland. Both studies indicate~~ indicating~~ that, at specific sites and years~~their study site~~, only the near-surface FAC was being used to store meltwater. However, in 2007-2009~~In a warmer region,~~ ~400 km to the north and at 1555 m a.s.l., Humphrey et al. (2012)~~(2012)~~ observed percolation below 10 m, meaning that, for certain firn temperature and stratigraphy and given sufficient surface meltwater, the FAC of the whole firn column, from the surface to pore-close-off depth, might be used for meltwater retention. Nevertheless, Machguth et al. (2016)~~(2016)~~ showed that percolation depth may not increase linearly with meltwater production and that low-permeability ice layers can limit meltwater, even if abundant, from accessing the full firn column. Given the complexity of meltwater percolation and the limited observations to map percolation depth on the Greenland ice sheet, reasonable upper and lower bounds of the firn's capacity can be estimated by determining both the FAC in the top 10 m of firn (FAC_{10}) and the total FAC (FAC_{tot}) (Harper et al. 2012). FAC_{tot} is also valuable information to convert remotely-sensed Greenland ice sheet surface height changes into mass changes (Simonsen et al. 2013; Sørensen et al., 2011, Kuipers Munneke et al. 2015a).~~melt intensity and that refrozen meltwater can reduce percolation, subsequently preventing meltwater from accessing part of the FAC. Due to the absence of an ice-sheet-wide estimation of percolation depth and to the scarcity of firn observations covering the whole firn column, we here focus on the top 10 m of firn, for which numerous observations cores are available, and assume that the firn air content in these top 10 m (FAC~~$_{10}$~~) represents the maximum volume of meltwater that can be stored in the firn.~~

In this study, we first estimate the firn area extent using remotely-sensed end-of-summer snow extent maps from Fausto et al. (2018a). ~~., (2018).~~ We then use~~calculate the FAC~~$_{10}$ ~~using~~ a set of 360~~344~~ firn observations~~cores~~ collected between 1953 and 2017 to calculate~~. We finally present~~ the spatial distribution of FAC_{10} and where possible present its~~the~~ temporal evolution. A simple extrapolation is introduced to estimate the FAC_{tot} from the FAC_{10}. By spatially integrating FAC_{10} and FAC_{tot} over the firn area, we calculate the lower and upper bounds of the firn retention capacity. Finally, we evaluate the performance of firn simulations in three regional climate models (RCMs), commonly used to evaluate firn retention capacity, but never validated with such extensive firn data collection ~~of FAC_{10}~~.

2. Data and methods

~~2.1. Firn area extent~~

~~Fausto et al.~~ (2018) used surface radiance remotely sensed by the MODIS Terra satellite between 2000 and 2017 along with in-situ measurements of albedo at PROMICE automatic weather stations (Ahlstrøm et al., 2008) to estimate the end-of-summer snow-covered and bare ice areas. Using these data, we determine the firn area, defined as the region where only snow has been detected during the entire 2000-2017 period.

~~2.2.~~2.1. Firn cores dataset

We gathered ~~from the literature~~ 324 published firn-density profiles from cores that were at least 5 m long (Table 1). To these, we add ~~and S1 of the Supplementary Material) supplemented by~~ 20 ~~firn~~ cores extracted in April-May 2016 and 2017 ~~as part of the FirnCover campaigns and~~ for which the density was measured at 10 cm resolution following the same procedure as Machguth et al. ~~. Potential~~(2016). Most of these density profiles are available in Montgomery et al. (2018). When near-surface snow densities were missing, we assigned a density of 315 kg m^{-3} (Fausto et al., 2018b) to the top cm and interpolate over the remaining gaps in ~~the~~ density profiles~~profile were filled~~ using a logarithmic function of depth fitted to the available densities.

Table 1. List of the publications presenting the firn cores used in this study.

Source	Number of cores	Source	Number of cores
Albert and Shultz (2002)	1	Langway (1967)	1
Alley (1987)	1	Lomonaco et al. (2011)	1
Bader (1954)	1	Machguth et al. (2016)	28
Baker (2012)	1	Mayewski and Whitlow (2016a)	1
Benson (1962)	55	Mayewski and Whitlow (2016b)	1
Bolzan and Strobel (1999)	9	Miège et al. (2013)	3

Buchardt et al. (2012)	8
Clausen et al. (1988)	8
Colgan et al. (2018)	1
Fischer et al. (1995)	14
Forster et al. (2014)	5
Hawley et al. (2014)	8
Harper et al. (2012)	32
Jezek (2012)	1
Kameda et al. (1995)	1
Koenig et al. (2014)	3
Kovacs et al. (1969)	1
Morris and Wingham (2014)	66
Mosley-Thompson et al. (2001)	47
Porter and Mosley-Thompson (2014)	1
Reed (1966)	1
Renaud (1959)	7
Spencer et al. (2001)	8
Steen-Larsen et al. (2011)	1
Vallelonga et al. (2014)	1
van der Veen et al. (2001)	10
Wilhelms (1996)	13
This study	20

~~When near-surface snow densities were missing, we assigned a density of 315 kg/m^3 (Fausto et al., 2018) to the top centimetre of snow before the gap-filling.~~In addition to our collection of firn density, we use the end-of-summer snowlines from Fausto et al. (2018a) to delineate the minimum firn area, which are the 1,405,500 km^2 where snow is always detected during the 2000-2017 period. Moving this firn line 1 km inward or outward (the resolution of the product from Fausto et al. (2018a)) suggest an uncertainty of ±17,250 km^2 (~1%). This uncertainty applies on the margin of the firn area where ephemeral or thinner firn patches may exist outside of our delineation. Owing to the likely thinness of the accumulation area lower boundary, we expect the boundary does not play a negligible role in the overall retention capacity of the firn area.

~~2.3.~~2.2. Calculation of ~~the~~ FAC_{10}

For a discrete density profile composed of N sections and reaching a depth z, the FAC~~FAC_{10}~~ in ~~m^3~~ m^{-2} is calculated ~~to depth z_N~~ as:

$$FAC_z = \cancel{FAC_{z_N}} = \sum_{k=1}^{N} m_k \left(\frac{1}{\rho_k} - \frac{1}{\rho_{ice}}\right) \cancel{\sum_{k=1}^{N} m_k (1/\rho_k - 1/\rho_{ice})} \qquad [1]$$

where, for each depth interval~~section~~ k, ρ_k is the firn density and m_k is the firn mass. ρ_{ice} is the~~The~~ density of the ice ~~formed after meltwater infiltration and refreezing, ρ_{ice}, is~~ set to 917 ~~873~~ kg ~~m^{-3} after Machguth et al. (2016).~~ /~~The value for ρ_{ice} was seen to vary within ±25 kg m^{-3} by Machguth et al., 2016 and Harper et al., 2012 used a value of 843 kg m^{-3}. Changing ρ_{ice} by ±25 kg m^{-3} leads to a variation of ±1 to 10% for FAC_{10} values ranging from 5 to 1~~ m^3 ~~m^{-2}. Addressing the variability of ρ_{ice} and its potential drivers is beyond the scope of this study~~.

With 121 cores shorter than 10 m in our dataset, we ~~need to~~ extrapolate shallow measurements to a depth of 10 m. We do this by finding~~For that we find~~ the 10~~+~~ m long core that best matches the FAC vs. depth profile of the shallow core, with the lowest Root Mean Squared Difference (RMSD) amongst all available cores, and append the bottom section of this 'twin' core to the FAC profile of the shallow core (see Figure S1 of the Supplementary Material). When testing this methodology on the available ~~10+ m long~~ cores deeper than 10 m, from which we remove the deepest 3 m of the FAC profile, we find a mean difference between extrapolated and real FAC_{10} inferior to 1% and a RMSD of 0.~~3~~15~~% for FAC$_{10}$ values ranging from 5 to 1 m^3~~ m~~$^{-2}$~~.

The accuracy of the firn density measurements~~and infiltration ice densities~~ as well as the effect of spatial heterogeneity can be assessed by comparing FAC_{10} measurements located within 1 km and collected in the same year (Figure S2 of the Supplementary Material). A~~The~~ standard deviation below 0.15 m is found in the majority of the ~~of~~ co-located and contemporaneous FAC_{10} observations ~~is below 0.15 m^3 m^{-2} for the majority of sites~~ (20 of 27 groups of comparable observations).~~).~~ We assign~~therefore attach~~ to ~~any~~ FAC_{10} measurements~~measurement~~ an uncertainty of ±0.3 ~~m^3~~ m, i.e.,~~$^{-2}$,~~ twice the standard deviation~~, ±6 to 30% for FAC$_{10}$ values ranging from 5 to 1 m^3 m^{-2}~~.

~~2.4.~~2.3. Zonation of ~~the~~ firn air content

The FAC_{10} is calculated from the firn density which depends, among other parameters, on the local near-surface air ~~site's~~ temperature and snowfall rate (Shumskii, 1964). The site's air temperature is a proxy for summer melt and refreezing within the firn, as well as firn temperature and compaction rates. Through these processes, air temperature has a lowering effect on FAC_{10}. On the other hand, snow accumulation introduces porous fresh snow ~~history and on meltwater refreezing~~ at the surface and has an increasing effect on FAC_{10}. To put our FAC_{10} measurements in their climatic context, we ~~depth (Reeh, 2008). We~~ extract the~~each core site's~~ long-term (1979~~1970~~-2014) average net snow accumulation $\bar{\dot{b}}$ (snowfall – sublimation) and ~~and long term (1970-2014) average~~ air temperature $\overline{T_a}$ for each FAC_{10} measurement location from the nearest cell in the Modèle Atmosphérique Régional (MARv3.5.2; Fettweis et al., 2017) available at 5 × 5 km horizontal resolution.~~respectively from Box (2013) and Box et al. (2013) (Figure 1a). We also find $\bar{\dot{b}}$ and $\overline{T_a}$ for all locations that occur within the firn area derived in this study (outlined area in Figure 1b).~~

In accordance with~~Borrowing~~ the terminology from Benson (1962), we define three regions where FAC_{10} shows distinct behaviour~~markedly different behaviours~~: (1) the dry snow area ~~Dry Snow Area~~ (DSA, yellow~~amber~~ area in Figure 1a); (2~~3~~) the low accumulation wet snow area~~Low Accumulation Wet Snow Area~~ (LAWSA, red area in Figure 1a); (3) the high accumulation wet snow area~~High Accumulation Wet Snow Area~~ (HAWSA, green area in Figure 1a). The DSA encompasses low temperature regions of high altitude and/or latitude where melt is uncommon~~rare~~ and where FAC_{10} can be related~~explained~~ by a linear function of $\overline{T_a}$ (yellow markers in Figure 1c). Towards higher ~~well-known dry-firn compaction~~

~~equations dependent on $\bar{\dot{b}}$ and~~ $\overline{T_a}$, i.e. at ~~(amber area in Figure 1a). Toward higher $\overline{T_a}$ (~~lower altitude and/or latitude~~,)~~ two patterns are visible in Figure 1c. Firstly, at~~evident. At~~ lower $\bar{\dot{b}}$ sites~~,~~ in the LAWSA, more scatter appears in FAC_{10}, and a slope change occurs in the FAC_{10}'s temperature dependency (Figure 1c). Secondly, at~~At~~ higher $\bar{\dot{b}}$ (in the HAWSA), the few available FAC_{10} observations describe a similar temperature dependency as in the DSA even though they are in relatively warm regions where melt occurs more frequently and cannot be referred to as “dry”. FAC_{10} observations in the HAWSA are up to five times~~FAC_{10} remains~~ higher than at locations with similar $\overline{T_a}$ in the LAWSA (Figure 1c~~and the slope of the temperature dependency is different from the one found in the DSA or LAWSA (green area in Figure 1d~~).

The boundary between the cold~~colder~~ (DSA) and warm~~warmer~~ regions (LAWSA and HAWSA) can be defined as the temperature where an inflection occurs in the linear dependency of FAC_{10} to $\overline{T_a}$ (Figure 1c). The transition between areas, just as between the facies described by Benson et al. (1962), is gradual, but for our analysis, we set this boundary to $\overline{T_a}$ = -19 °C. No~~where the dry firn densification cannot explain FAC_{10} variations and increasing scatter appears in the FAC_{10} values (Figure 1c). We set this threshold to $\overline{T_a}$ = -16°C as it is the temperature for which the standard deviation of FAC_{10} within 1°C-wide bins first exceeds 0.3 m^3 m^{-2} (Figure 1c). Few~~ firn observation is~~cores are~~ available in the transition~~ zone~~ from the LAWSA to the HAWSA. A~~ and a~~ boundary could be anywhere between 543 mm w.eq./yr (core with highest accumulation in the LAWSA, Figure 1b~~1a~~) and 650~~762~~ mm w.eq. yr^{-1} (core with lowest accumulation in HAWSA, Figure 1b~~1a~~). We chose the rounded value of $\bar{\dot{b}}$ = 600 mm w.eq. yr^{-1} to separate LAWSA from HAWSA. The spatial~~geographical~~ delineations of the DSA, LAWSA and HAWSA are illustrated~~presented~~ in Figure 1a.

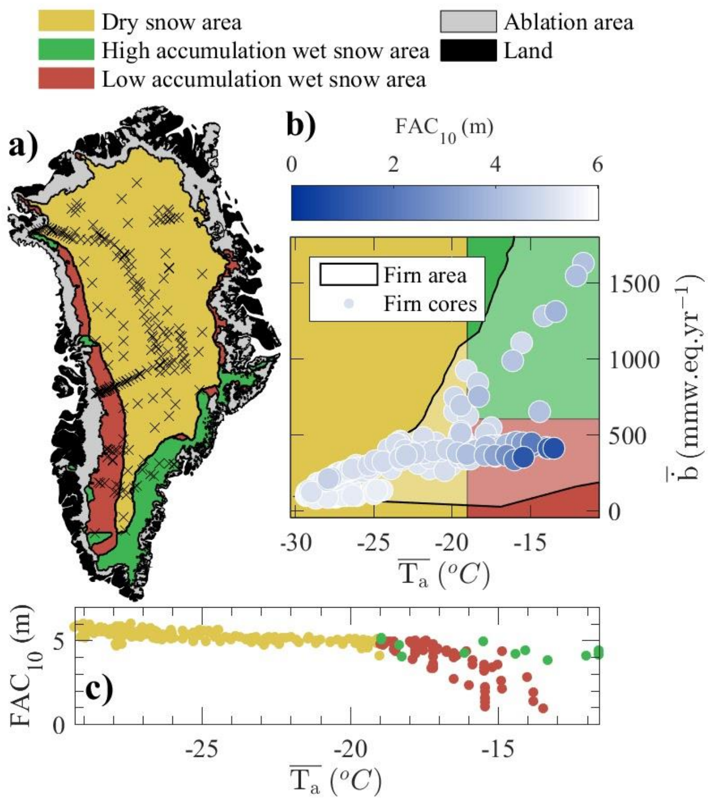


Figure 1. a) Spatial distribution of the FAC_{10} dataset. The DSA, LAWSA and HAWSA are indicated respectively using yellow, green and red areas. b) Distribution of the dataset in the accumulation-temperature space ($\bar{\dot{b}}$ and $\overline{T_a}$). FAC_{10} value is indicated by a coloured marker. Black lines and shaded areas indicate where the firn is detected in the accumulation-temperature space. c) Temperature dependency of FAC_{10} in the DSA (yellow markers), LAWSA (red markers) and HAWSA (green markers).

~~2.5.~~2.4. Firn air content mapping

To map FAC_{10} over the entire firn area~~ from our collection of observations~~, we fit empirical functions to the FAC_{10} observations~~of $\bar{\dot{b}}$~~ and ~~$\overline{T_a}$ to FAC_{10} measurements and~~ use these functions to spatially interpolate and extrapolate FAC_{10}. The construction of ~~predict FAC_{10} anywhere in the firn area. We prefer this empirical approach to purely statistical approaches (e.g. kriging) or to the use of RCM and firn models which still do not accurately reproduce observations of firn densities and thus FAC_{10} in the lower accumulation area (Steger et al., 2016; Langen et al., 2017). The form of~~ these empirical functions is described in the following sections and an overview of their form and their associated data~~arbitrary but~~ is presented in Table 2.

Table 2. Overview of the empirical functions fitted to FAC_{10} observations in each region of ~~tightly constrained by~~ the firn area.

Area	Period	Form	Observations used for fitting
DSA	1953 - 2017	Linear function of $\overline{T_a}$ (Eq. 2)	259 from the DSA 11 from the HAWSA
LAWSA & HAWSA	2010 - 2017	• Smoothed bilinear function of $\overline{T_a}$ and $\bar{\dot{b}}$. • Cannot exceed the FAC estimated with Eq. 2.	25 from the LAWSA 10 from the HAWSA 6 selected from firn line in the HAWSA
LAWSA	1998 - 2008		38 from the LAWSA 1 from the HAWSA 6 selected from the firn line in the HAWSA

2.4.1. Dry Snow Area

~~2.5.1. Dry Snow Area~~

~~In the DSA, we use the steady-state firn densification model by Arthern et al. (2010) and we tune the surface snow density to 302 kg m^{-3} through least squares method to match the 209 available FAC$_{10}$ observations (Figure S3 in the Supplementary Material). We also investigated other densification laws and the one from Arthern et al. (2010) gave the best match with FAC$_{10}$ observations.~~

~~2.5.2. Low Accumulation Wet Snow Area~~

~~FAC$_{10}$ observations in the LAWSA are correlated with $\bar{\dot{b}}$ and anti-correlated with $\overline{T_a}$ (Figure S3 in Supplementary Material). We therefore constrain the form of our empirical function $\widehat{FAC_{10}}(\bar{\dot{b}}, \overline{T_a})$ to the sum of an increasing linear function of $\bar{\dot{b}}$ and a decreasing piecewise-linear function of $\overline{T_a}$. There are an insufficient number of observations to resolve the FAC$_{10}$ distribution each year, so we group measurements from different years until there are enough points in each group to constrain our empirical function. We therefore group 10 observations from 1997-1998 (having good spatial coverage but limited number of cores) with 35 measurements from 2005-2008 (numerous but geographically concentrated) and fit a function $\widehat{FAC_{10}}_{1998-2008}(\bar{\dot{b}}, \overline{T_a})$ to them. We also group 35 FAC$_{10}$ observations from 2011-2017 to which we fit a function $\widehat{FAC_{10}}_{2011-2017}(\bar{\dot{b}}, \overline{T_a})$. To allow a smooth transition between these empirical functions used in the LAWSA and the one used in the DSA, we also include in the fitting process the FAC$_{10}$ observations available in the lower DSA where -17°C ≤ $\overline{T_a}$ < -16°C.~~

In the DSA, the 259~~numerous~~ FAC$_{10}$ observations obtained between 1953 and 2017 depend linearly on their local $\overline{T_a}$ (Figure 1c). This dependency is the same for the 11 FAC$_{10}$ observations from the HAWSA. We consequently use a linear function of

$\overline{T_a}$ fitted using least squares method to the FAC_{10} observed in both DSA and HAWSA (Figure 2a) binned into four equal $\overline{T_a}$ ranges (to avoid the overrepresentation of clustered data) to estimate the FAC_{10} in the DSA.

2.4.2. Wet Snow Areas

In the LAWSA and in the HAWSA, FAC_{10} observations exhibit a more complex dependency to $\bar{\dot{b}}$ and $\overline{T_a}$ (Figure 1b and 1c). Additionally, observations are unevenly distributed in space and time which forces us to group FAC_{10} measurements into time-slices that contain enough FAC_{10} observations to describe the spatial pattern of FAC_{10} and constrain our empirical functions.

Over the 2010-2017 period, 25 FAC_{10} observations were made in the LAWSA, from the transition with the DSA down to the vicinity of the firn line. During that same period, 10 firn cores were collected in the HAWSA. Unfortunately, in addition to their small number, the cores are located relatively far into the interior of the ice sheet and do not describe~~they should fit. In this section, we briefly explain~~ how the FAC_{10} decreases in parts of the HAWSA closer to the firn line. We consequently complement~~we build~~ these firn cores with 6 sites selected on the remotely-sensed firn line where FAC_{10} is assumed to be null (Figure S3).~~functions while further details and illustrations are available in Figure S3 of the Supplementary Material.~~

We define our empirical function, valid in the LAWSA and HAWSA for the 2010-2017 period, as a smoothed bilinear function of $\overline{T_a}$ and $\bar{\dot{b}}$ fitted through least squares method to the available observations (Figure 3a). We do not allow that function to exceed the linear function of $\overline{T_a}$ that describes FAC_{10} measurements in the DSA and in the interior of the HAWSA or to predict FAC_{10} below 0 m. The empirical function is then used to estimate the FAC_{10} in both the LAWSA and HAWSA during the 2010-2017 period.

In the years preceding 2010, insufficient data are available to document the FAC_{10} in the HAWSA. In the LAWSA, however, 34 observations were made between 2006 and 2008 and three cores were collected in 1998. We group these measurements to describe the spatial distribution of FAC_{10} in the LAWSA during the 1998-2008 period and to fit another function, this time only valid in the LAWSA during the 1998-2008 period, also smoothed bilinear function of $\overline{T_a}$ and $\bar{\dot{b}}$. To ensure that our empirical function has realistic values towards the transition with the HAWSA, we also include one core collected in the HAWSA in 1998 and the previously described six locations from the firn line in the fitting process (Figure 3a).

We investigate the robustness of our empirical functions in the HAWSA and LAWSA using,~~method using a sensitivity analysis~~ for each period separately, the following sensitivity analysis.~~.~~ For 1000 repetitions, we apply four types of perturbations to the FAC_{10} ~~randomly exclude four~~ observations ~~(respectively 9% and 11% of the observations in 1997-2008~~

~~and 2011-2017)~~ and fit our empirical function to this perturbed dataset. The effect of the availability of ~~$\widehat{FAC_{10}}(\bar{\dot{b}}, \overline{T_a})$ to the remaining~~ measurements in the LAWSA is tested by randomly excluding four observations in that region (respectively 16% and 11% of the observations in 1998-2008 and 2010-2017). The effect of uncertainty in the firn line location in the $\left(\overline{T_a}, \ \bar{\dot{b}}\right)$ space is tested by adding a normally distributed noise with mean zero and standard deviation 3 °C to the $\overline{T_a}$ of firn-line-derived FAC$_{10}$ (illustrated in Figure S3). The effect of the uncertain FAC$_{10}$ value at the firn line is assessed by assigning to the points selected from the firn line a random FAC$_{10}$ value between 0 and 1 m. Finally, the effect of the smoothing applied to the bilinear interpolation of FAC$_{10}$ measurements is assessed by modifying the amount of smoothing applied.~~.~~ We then calculate the standard deviation of all possible estimated FAC$_{10}$~~$\widehat{FAC_{10}}$~~ at each $\left(\overline{T_a}, \ \bar{\dot{b}}\right)$ ~~$(\bar{\dot{b}}, \overline{T_a})$~~ location and double it to quantify the 95% envelope of uncertainty that applies to any estimated~~predicted~~ FAC$_{10}$ in the LAWSA and HAWSA depending on $\left(\overline{T_a}, \ \bar{\dot{b}}\right)$. We~~$(\bar{\dot{b}}, \overline{T_a})$. Since we~~ do not consider that the uncertainty applying on an estimated FAC$_{10}$~~prediction~~ can be smaller~~more precise~~ than the one of FAC$_{10}$ observations. We consequently~~field measurements, we~~ set 0.3 ~~m^3~~ m^{-2} as the minimum possible uncertainty on any estimated FAC$_{10}$.~~High Accumulation Wet Snow Area~~

~~The HAWSA is described by only 15 firn cores drilled between 2010 and 2017 at 7 sites in the interior of the HAWSA, more than 20 km from the firn line. To overcome the scarcity of observations we use our remotely-sensed firn line as additional measurements where FAC$_{10}$ = 0 m^3 m^{-2}. We then fit our empirical function $\widehat{FAC_{10}}(\bar{\dot{b}}, \overline{T_a})$ as follows. In the surroundings of the core sites, we use a linear function of $\overline{T_a}$ fitted through least squares to the FAC$_{10}$ observations: $\widehat{FAC_{10}}(\overline{T_a}) = -0.07 * \overline{T_a} + 3.4$ (RMSD = 0.25 m^3 m^{-2}, Figure S3 in the Supplementary Material). The residuals of this fit did not show any correlation with $\bar{\dot{b}}$ meaning that not enough measurements are available to disentangle the control of $\bar{\dot{b}}$ and $\overline{T_a}$ on FAC$_{10}$ in the HAWSA. We then need to describe how the FAC$_{10}$ decreases from the core sites down to 0 m^3 m^{-2} at the remotely-sensed firn line. We can make three estimates: i) a mid-range estimate where FAC$_{10}$ is bilinearly interpolated between the available firn cores and the firn line; ii) an upper-range estimate where FAC$_{10}$ follows the temperature dependency presented above until the firn line where it drops abruptly to 0 m^3 m^{-2}; and iii) a lower-range estimate where the FAC$_{10}$ drops to 0 m^3 m^{-2} shortly after the observations. These three surfaces are presented in more detail in Figure S3 in the Supplementary Material. The mid-range estimate is considered as our most realistic estimation and is the empirical function $\widehat{FAC_{10}}(\bar{\dot{b}}, \overline{T_a})$ we use for the mapping of FAC$_{10}$ in the HAWSA while half the spread between the upper- and lower-range estimates quantifies the uncertainty applying to our FAC$_{10}$ map~~

2.5. Estimation of the FAC$_{tot}$

While FAC_{tot} may be calculated from the surface down to pore close off depth (Ligtenberg et al., 2018), to allow comparison with HIRHAM5 which sometimes do not reach pore close off, we calculate FAC_{tot} from the surface to 100 m depth. Only 29 of our 360 firn observations reach depths greater than 100 m so we complement them by 13 observations from Harper et al. (2012) that estimated FAC_{tot} at their core sites from ground penetrating radar. A linear function is fitted to these data and is used to estimate FAC_{tot} at the rest of our FAC_{10} observation sites.

2.6. Spatially integrated FAC, uncertainty and retention capacity

For each region, the spatially integrated FAC is the sum of the entire firn air volume either within the top 10 m or in the whole firn column. The uncertainty applying on our estimated FAC_{10} and FAC_{tot} at a location cannot be considered independent because all estimates are made using the same functions of $\overline{T_a}$ and $\bar{\dot{b}}$. Consequently, we consider that the uncertainty of the mean of several FAC values is the mean of each value's uncertainty and that the uncertainty of a sum or difference of FAC values is the sum of the uncertainty applying on these FAC values.

From the FAC, we calculate the firn's maximum retention capacity, which Harper et al. (2012) defined as the amount of water that needs to be added to the firn to bring its density to 843 kg m^{-3}, the density of infiltration ice.

2.7. Comparison with Regional Climate Models

We compare our FAC observations and maps to the available firn products from three RCMs: HIRHAM5, RACMO2.3p2 and MARv3.9. The two versions of HIRHAM5 presented in Langen et al. (2017) are used: with linear parametrization of surface albedo (thereafter referred as HH_LIN) and MODIS-derived albedo (thereafter referred as HH_MOD). Because of model output limitation, only FAC_{tot} could be extracted from the RACMO2.3p2 output presented by Ligtenberg et al. (2018) and the FAC_{10} was extracted from the more recent downscaled model output by Noël et al. (2019). MARv3.9 was presented in Fettweis et al. (2017) and simulates only FAC_{10} because of a shallower subsurface domain.

3. Results and discussion

~~3.1. Delineation of the firn area~~

~~The firn area, illustrated in Figure 1b, covers at least an area of 1,405,500 km~~$\cancel{^2}$ ~~or 78.5 % of the ice sheet (when compared to the contiguous ice extent from Citterio and Ahlstrøm (2013)). Moving the firn line 1 km in- or outwards (the resolution of the MODIS surface radiance product) suggest an uncertainty of ±17,250 km~~$\cancel{^2}$ ~~(~1%). However, one should keep in mind that~~

~~the firn line is an idealized view of a patchy and gradual transition from bare ice to snow and firn that survived the summer melt in previous years (Benson, 1962). Spatial heterogeneity in melt and snowfall leave isolated snow and firn patches at the end of the melt season which might be missed by the method of Fausto et al. (2018). Using the average from 18 years of data gives a robust firn line and reduces the noise from local heterogeneities but also provides the absolute minimum extent of the firn area during 2000-2017. Ephemeral or thinner firn patches may exist outside of our strict delineation but we do not believe they play an important role in the overall retention capacity of the firn.~~

3.1. FAC estimation

3.1.1. Dry snow area

In the DSA, the linear function of $\overline{T_a}$ used to estimate FAC_{10} reads as:

$$FAC_{10}(\overline{T_a}) = -0.08 * \overline{T_a} + 3.27 \quad [2]$$

We assign to any FAC_{10} estimated in the DSA an uncertainty equal to twice the regression's RMSD: 0.4 m. We consider the absence of a temporal trend in the deviation between measured FAC_{10} and FAC_{10} estimated using the linear function of $\overline{T_a}$ (Figure 2b) as evidence of the stability of the FAC_{10} in the DSA between 1953 and 2017. The stable FAC in the DSA is confirmed by firn cores in our dataset taken decades apart at the same sites and showing the same FAC (Summit, Camp Century, e.g.) and by recent firn modelling at weather stations located in the DSA (Vandecrux et al. 2018).

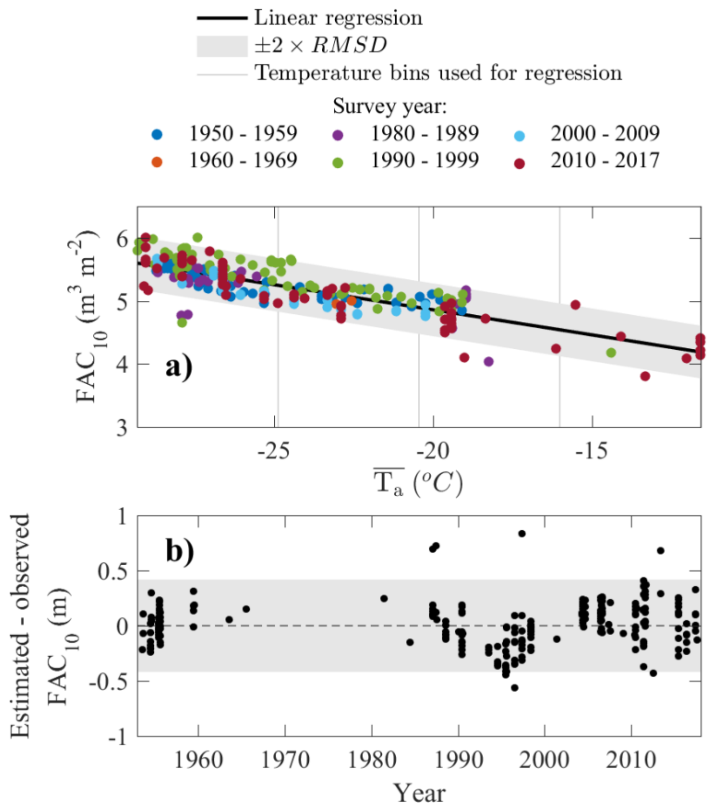


Figure 2. a) Linear function of $\overline{T_a}$ fitted to FAC$_{10}$ observations from the DSA and HAWSA. b) Residual between estimated (using linear regression) and observed FAC$_{10}$ as a function of survey year.

~~3.2. Stable FAC$_{10}$ in the Dry Snow Area~~

~~The spatial distribution of~~ FAC$_{10}$ estimated ~~in the DSA is shown in Figure 2. In that region representing 74% of the firn area, we find a spatiotemporally average FAC$_{10}$ value of 4.9 m^3 m^{-2}. We find a RMSD between predicted and observed FAC$_{10}$ of 0.2 m^3 m^{-2} (Figure S3 in the Supplementary Material). Assuming a normal distribution of errors, 95% of all FAC$_{10}$ observations~~ in the DSA ~~are within~~ an uncertainty equal to ~~range of ±0.4 m^3 m^{-2} (~~twice the regression's RMSD: 0.4 m~~) of the predicted one~~. We consider the absence of a temporal trend in the deviation between measured FAC$_{10}$ and FAC$_{10}$ estimated using the linear function of $\overline{T_a}$ (Figure 2b)~~and predicted FAC$_{10}$~~ as evidence of the stability of the FAC$_{10}$ in the DSA between 1953 and 2017. The stable FAC in ~~When integrating FAC$_{10}$ over the extent of~~ the DSA is confirmed by firn cores in our dataset taken decades apart at the same sites and showing the same FAC (Summit, Camp Century, e.g.) and by recent firn modelling at weather stations located in the DSA (Vandecrux et al. 2018). ~~and considering an uncertainty of ± 0.4 m^3 m^{-2}, we calculate that 5200 ±452 km^3 of air is contained within the top 10 m of firn.~~

3.1.2. Wet snow areas

~~3.3. Decreasing FAC$_{10}$ in the Low Accumulation Wet Snow Area~~

~~For~~In the LAWSA and HAWSA, we estimate the FAC$_{10}$ with the empirical functions presented in Figure 3. These empirical functions have a RMSD of 0.28 m in the LAWSA over the 1998~~, comprising 12 % of the firn area, we find an average FAC10 value of 4.3 m^3 m^{-2} for the 1997~~-2008 period, 0.27 m in the LAWSA over the 2010~~. The estimated average FAC$_{10}$ for the 2011~~-2017 period and 0.17 m in the HAWSA over the 2010-2017 period. The ability of our empirical functions to fit the FAC$_{10}$ observations~~is 3.3 m^3 m^{-2}, 23% lower than for 1997-2008. The result of the sensitivity analysis (Figures 3b and 3c),~~ confirms our choice of an empirical approach as opposed to relying on RCMs and firn models which still do not accurately reproduce observations of FAC in certain regions (see Section 3.6).

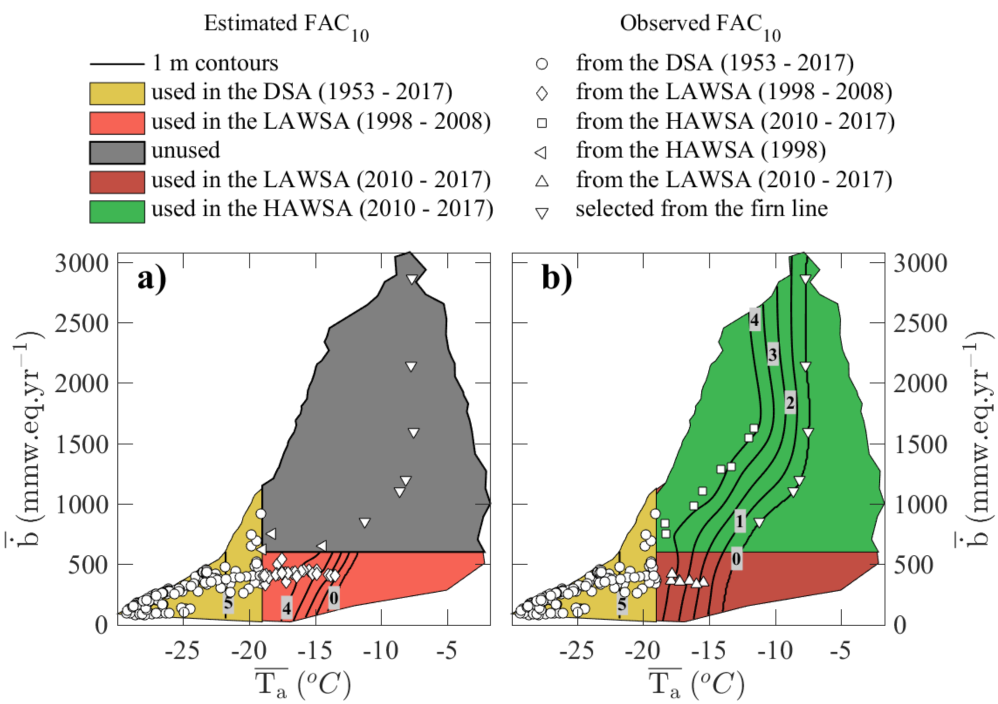


Figure 3. Contours (labelled black lines) of the empirical functions of $\overline{T_a}$ and $\overline{\dot{b}}$ used to estimate FAC$_{10}$ along with the FAC$_{10}$ observations used to constrain the functions. Two functions could be constructed: one describing ~~that the decrease in~~ FAC$_{10}$ in~~between~~ the LAWSA during 1998~~1997~~-2008 (a) and another describing FAC$_{10}$ in the LAWSA and HAWSA during 2010~~2011~~-2017 (b).

3.1.3. FAC$_{tot}$

We use the following linear regression between FAC_{10} and FAC_{tot} (Figure 4):

$$FAC_{tot} = 4.1 * FAC_{10} \quad [3]$$

We assign 3.6 m, twice the RMSD of the linear regression, as the typical uncertainty applying on an estimated FAC_{tot} value, representing less than 20% of estimated FAC_{tot} ~~is~~ greater than 20 m but up to 100% of the estimated FAC_{tot} at the firn line.

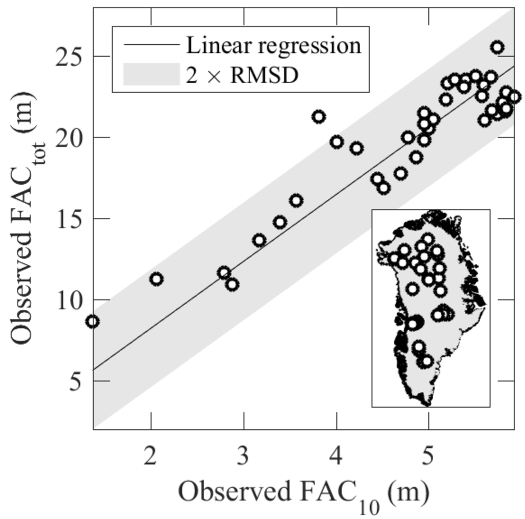


Figure 4. Linear regression used to estimate FAC_{tot} from FAC_{10}. Linear regression was fitted using the least squares method with a prescribed intercept of zero.

One of the consequences of Eq. 2 is that a change FAC_{10} between two dates implies a change in FAC_{tot} over the same time period. This co-variation neglects that near-surface changes in the firn slowly propagate to greater depth with thermal conduction and downward mass advection (Kuipers Munneke et al., 2015b). Therefore we note that for a decreasing FAC_{10} (see Section 3.2.1), our estimated change in FAC_{tot} will always be the maximum possible change, if the whole firn column was given the time to adapt to the new surface conditions.

3.2. Spatio-temporal distribution of firn air content

3.2.1. FAC_{10} mapping

Using the 5x5 km $\overline{T_a}$ and $\bar{\dot{b}}$ grids from Fettweis et al. (2017) and the empirical functions presented in Figure 3, we map the FAC_{10} and its uncertainty across the firn area of the ice sheet (Figure 5). From these~~associated to the two FAC_{10}~~ maps we calculate an average FAC_{10} of 5.1± 0.3 m in the DSA, an average FAC_{10} of 2.6 ± 0.5 m in the HAWSA during the 2010-2017 period and an average FAC_{10} of 4 ± 0.3 m in the LAWSA during the 1998-2008 period, which decreased by 35 % to

2.6 ± 0.3 m in the 2010-2017 period.~~-~~ The FAC$_{10}$ loss in the LAWSA is concentrated in a 60 km wide band above the firn line in western Greenland (Figure 6).

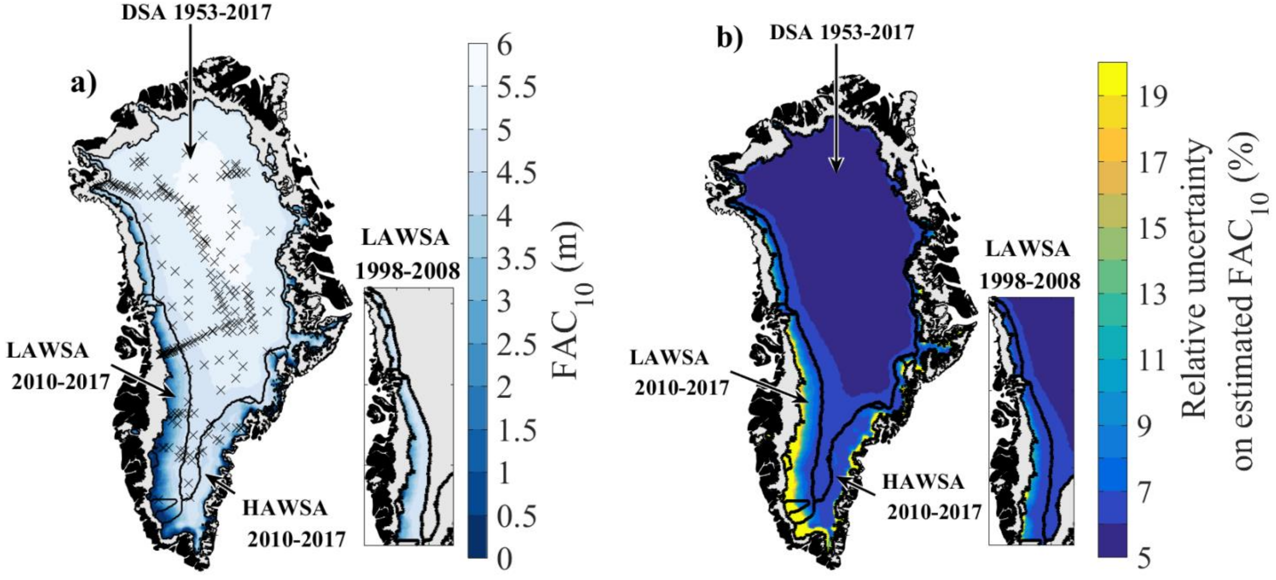


Figure 5. a) FAC$_{10}$ maps and location of ~~2). Summing~~ the FAC$_{10}$ measurements. b) Maps of the relative~~and its~~ uncertainty of the FAC$_{10}$ map.

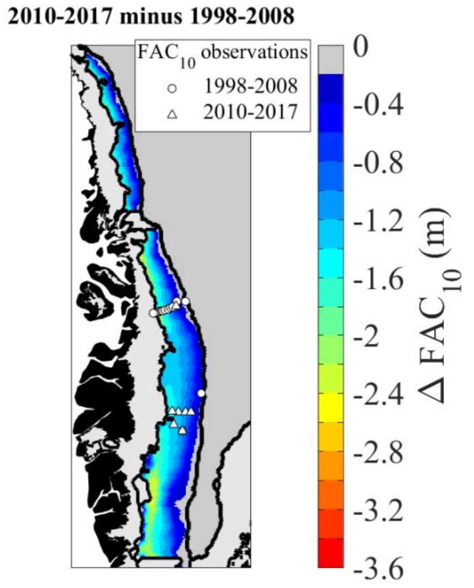


Figure 6. Change in FAC$_{10}$ between 1998-2008 and 2010-2017 in the LAWSA.

3.2.2. Spatially integrated FAC

We find~~indicates~~ that during the 2010-2017 period the entire firn area contains 6 500 ± 450 ~~690 ±50~~ km^3 in the top 10 m and up to~~of air is contained within the LAWSA in 1997-2008 and 520 ±60 km^3 in 2011-2017. This loss of 180 ±78 km^3 of air content,~~ 26 800 ± 1 850 km^3 if the whole firn column is accounted for (Table 3). About 83 ± 5% of this~~±11% of the 1997-2008~~ air content is contained in the DSA, which represents 74% of the firn area. The HAWSA, which covers 12% of the firn area, contains about 8 ± 1% of the firn's air independently of whether we consider the top 10m or at the entire firn layer.

Table 3. Spatially integrated FAC_{10} and FAC_{tot} over each ice sheet region

Area	Period	Spatially integrated FAC (km^3)	
		FAC_{10}	FAC_{tot}
DSA	1953 – 2017	5 400 ± 310	22 300 ± 1 280
LAWSA	1998 – 2008	750 ± 60	3 100 ± 250
LAWSA	2010 – 2017	570 ± 60	2 400 ± 250
HAWSA	2010 – 2017	530 ± 80	2 200 ± 330
All	2010 – 2017	6 500 ± 450	26 800 ± 1 850

In the LAWSA, that comprises 14 % of the firn area, decreasing FAC_{10} between 1998-2008 and 2010-2017 lead to a loss of 180 ± 120 km^3 of air from the top 10 m of firn,~~in the LAWSA represents, if we assume that all the air content can be used to store meltwater, 150 ± 68 Gt (0.4± 0.2 mm sea level~~ equivalent to 24 ± 16% of the 1998-2008 spatially integrated FAC_{10}. The subsequent decrease in FAC_{tot} indicate that the whole firn column lost up to 700 ± 500 km^3 of air~~) of storage capacity available in 1997-2008 that had become unavailable by 2011-2017~~.

Recent studies attributed the increasing near-surface firn densities and subsequent loss of FAC to increasing surface melt and meltwater refreezing (de la Peña et al., 2015; Charalampidis et al., 2015; Machguth et al., 2016; Graeter et al., 2018)~~;~~ ~~Charalampidis et al., 2015).~~ However, firn density and FAC are also ~~greatly~~ dependant on annual snowfall ~~(Herron and Langway, 1980)~~ and a decrease in snowfall can drive an increase in firn density and consequently~~could also trigger~~ a decrease in FAC_{10} (e.g. Vandecrux et al., 2018).~~.~~ Nevertheless, the lack of widely distributed observation of snow accumulation for the 1998~~1997~~-2017 period and the contradicting trends in precipitation output~~given~~ by the RCMs (Lucas-Picher et al., 2012; van den Broeke et al., 2016; Fettweis et al., 2017) make it impossible to precisely partition~~quantify~~ the melt and~~contribution of~~ snowfall contributions to changes~~into change~~ in FAC_{10} at ice sheet scale.

~~. In our regional approach, we grouped measurements from different years, which made it impossible to define the precise years that were responsible for this loss of FAC_{10}. However, repeated observations in western Greenland (Machguth et al.,~~

~~2016; Charalampidis et al., 2015) indicate that 2010 and 2012 extreme melt seasons are responsible for the greatest changes in near-surface firn density and FAC$_{10}$ during the 1997-2017 period.~~

~~Finally, the loss of FAC$_{10}$ near the firn line likely turned firn areas into bare ice and triggered the upward migration of the firn line. Unfortunately the relative uncertainty of our FAC$_{10}$ maps is greatest near the firn line (Figure 2 and 3) making it difficult to infer firn line migration from FAC$_{10}$ changes. Using our remotely-sensed firn line for all periods was a simplification but discussing its temporal evolution requires additional data and is beyond the scope of this study.~~

~~Potential deep meltwater percolation in the High Accumulation Wet Snow Area~~

~~In the HAWSA, comprising 14 % of the firn area, we calculate an average FAC$_{10}$ value of 2.4 m^3 m^{-2}. The spatial distribution of FAC$_{10}$ is shown in Figure 2 while our estimated uncertainty map is presented in Figure 3. Summing over the HAWSA, we calculate that 560 ±154 km^3 of air exists within the top 10 m of firn.~~

~~The markedly (up to 90%) higher FAC$_{10}$ in the HAWSA compared to the LAWSA for any given $\overline{T_a}$ (Figure 1) indicates that for similar surface melt (of which $\overline{T_a}$ is a proxy) the firn in the HAWSA was less dense and potentially less saturated by ice than in the LAWSA. In line with observations at aquifer sites located in the HAWSA (Forster et al., 2014), we hypothesize that in this region meltwater percolation may exceed 10 m, facilitated by high snow accumulation insulating the firn from the winter cold. This deep percolation also implies that FAC$_{10}$ may not be the most adequate indicator of the firn's retention capacity in the HAWSA as additional retention may occur at deeper than 10 m. The fate of this deep meltwater whether it refreezes below 10 m, flows to the nearest aquifer, or reaches the bed, remains unknown and requires further investigation.~~

~~Total firn meltwater storage capacity~~

~~The total air content in the DSA during 1953-2017, in the LAWSA during 2011-2017 and in the HAWSA during 2010-2017 can potentially accommodate 5,480 ± 420 Gt of meltwater (15 ± 1.2 mm sea level equivalent). Harper et al. (2012) estimated that the firn located in the long-term percolation area (as modelled by a RCM) could potentially store between 322 ±44 Gt (when considering the top 10 m of firn) and 1 289 $^{+388}_{-252}$ Gt (if considering the FAC to pore close-off depth). The smaller retention capacity found by Harper et al. (2012) mainly owes to the smaller area considered in their study. With our distributed approach, it is now possible to determine each year which areas of the firn are available to store meltwater and the available FAC$_{10}$ given the extent of surface melt.~~

~~Uncertainty of long-term average climatic conditions~~

3.2.3. Effect of the $\bar{\dot{b}}$ and $\overline{T_a}$ data source FAC$_{10}$ maps

To investigate how uncertainties in $\overline{T_a}$ and $\bar{\dot{b}}$ impact~~and $\overline{T_a}$ impacts~~ our FAC$_{10}$ maps, we repeat our procedure using the 1979-2014 $\overline{T_a}$ and $\bar{\dot{b}}$ estimated by Box (2013) and Box et al. (2013) (hereafter referred to as "Box"). The Box~~and $\overline{T_a}$ predicted by the Modèle Atmosphérique Régional (MAR; Fettweis et al., 2017), as illustrated in Figures S4 to S7 of the Supplementary Material. The MAR~~-derived FAC$_{10}$ fits equally well (within measurements uncertainty, RMSD < 0.3~~03 m^3~~

m) to ~~$^{-2}$)~~ the FAC_{10} observations and lead to spatially integrated FAC values within uncertainty from the MAR-derived values (Table 3).

However, due to differing model formulations and forcing, the spatial patterns of~~. Since Box et al. (2013) gives 2 m~~ air temperature and snowfall are different between Box and MARv3.9.2 (detailed in Fettweis et al. 2017),~~MAR gives surface temperature the value of $\overline{T_a}$ threshold between DSA and LAWSA/HAWSA is adjusted to -20 °C. Nonetheless differences between the two FAC_{10} predictions exist in areas where the spatial pattern of temperature and accumulation in Box (2013) and MAR differ,~~ especially in the southern and eastern firn area, which leads to different estimations of FAC_{10} in ~~. In~~ these regions (Figure S4). Additionally, in these regions no firn observations ~~fewer cores~~ are available to constrain our~~the~~ FAC_{10} estimates. More observations in the~~these~~ sparsely observed southern and eastern regions would therefore not only improve FAC_{10} estimates, but also elucidate which $\overline{T_a}$ and $\bar{\dot{b}}$ ~~and $\overline{T_a}$~~ source best describes the spatial pattern in FAC_{10}.

~~3.4. Isolated FAC_{10} measurements~~

~~In the LAWSA and HAWSA, our dataset also contains 40 firn cores that were too isolated in space and time to be used FAC_{10} in mapping. Isolated measurements nevertheless provide insight on how the FAC_{10} might have been at a given place and time. Renaud (1959) reported a measurement in the LAWSA with a FAC_{10} ~30% higher (+ 1 m^3 m^{-2}) than the one measured in 2006-2007. Conclusions from a single measurement are dubious, but it still indicates that the FAC_{10} may have been significantly higher in the 1950's. Ten observations in the LAWSA in the 1980's by van der Veen, et al. (2001), did not appear systematically different than our calculated FAC_{10} for the 1997-2008 period, suggesting that FAC_{10} was similar in the LAWSA during these two periods. A last measurement raises questions in the HAWSA: the core 6348 by Mosley-Thompson et al. (2001) drilled in 1998 indicates a FAC_{10} of 3.9 m^3 m^{-2}. It is a factor of 2.2 higher than our mid-range FAC_{10} estimate based on measurements from 2010-2017 and indicates either a drastic decrease in FAC_{10} between 1998 and 2010-2017 or inaccuracies of our methodology for that location. A re-survey of that location would be of great interest even though the 1998 core, being a single point in space, can always be suspected to be anomalous or not representative.~~

3.3. Firn retention capacity

Between 1998-2008 and 2010-2017, the decrease in FAC_{10} in the LAWSA indicates a 150 ± 100 Gt, or 0.4± 0.3 mm sea level equivalent (s.l.e.), loss of meltwater retention capacity from the top 10 m of the firn. For the entire firn column, we estimate a loss could be up to 540 ± 450 Gt (1.5 ± 1.2 mm s.l.e.). While these volumes are small as compared to the average mass loss of the ice sheet (~270 Gt/y), the impact of reduced retention capacity has an important time-integrated effect, in amplifying meltwater runoff each year, especially in a succession of anomalously high melt years as was the case 2007-2012, resulting in a sharp increase in western Greenland runoff (Machguth et al. 2016).

Table 4. Firn storage capacity for the top 10 m and for the entire firn column

Area	Period	Firn storage capacity (Gt)					
		Upper 10 m			Whole firn column		
DSA	1953 – 2017	4 200	±	370	12 800	±	1 170
LAWSA	1998 – 2008	550	±	50	1 490	±	220
LAWSA	2010 – 2017	400	±	50	950	±	230
HAWSA	2010 – 2017	370	±	70	960	±	300
All	2010 – 2017	5 000	±	410	14 700	±	1 600

Harper et al. (2012), using observations from 2007-2009, estimated that the firn located in a 150 000 km^2 percolation area (as delineated in an earlier version of MAR) could potentially store between 322 ±44 Gt in the top 10 m of firn and $1\ 289\ ^{+388}_{-252}$ Gt if considering the entire firn column. We find that the warmest 150 000 km^2 of our firn area in 2010-2017 can retain 150 ± 67 Gt of meltwater in the top 10 m of the firn. When considering the whole firn layer we find a storage capacity of 310 Gt associated with an uncertainty of 688 Gt. Our lower estimated retention capacity reflects the recent decrease of FAC in the LAWSA. Interestingly, we reach equivalent uncertainty intervals than Harper et al. (2012) in spite of using ~20 times more firn observations. We also note that the estimation from Harper et al. (2012) only used observations in the LAWSA, while most (69%) of the percolation area they use is located in the HAWSA. Finally, our distributed approach, as opposed to the lumped approach of Harper et al. (2012), now makes it possible to determine, given a certain melt extent, how much of the firn retention capacity is available to store meltwater.

Both our estimated retention capacity and the one of Harper et al. (2012) use the same infiltration ice density, 843 ± 36 kg m^{-3}, which was measured in portions of firn cores saturated by refrozen meltwater. In a later study also in western Greenland, Machguth et al. (2016) measured an infiltration ice density of 873 ±25 kg m^{-3}. Using the value from Machguth et al. (2016) increases our estimated firn storage capacity of the top 10 m of firn by 8 to 13% depending on the region but remained within the uncertainty intervals of our first estimations (Table 4). Additional field measurements will be needed to ascertain the infiltration ice density, its variability and its potential climatic drivers. Our definition of retention capacity assumes that retention occurs through the refreezing of meltwater and neglects potential liquid water retention seen in firn aquifer (Forster et al. 2014). Nevertheless, recent work in Southeast Greenland showed that meltwater resides less than 30 years in the aquifer before it flows into nearby crevasses and eventually leaves the ice sheet (Miller et al. 2018). On the contrary, the water refrozen within the firn is potentially retained for centuries until it is discharged through a marine terminating outlet glacier or reaches the surface in the ablation area, melts and finally runs off the ice sheet. By neglecting liquid water retention in firn, our study, in line with Harper et al. (2012), focuses on long-term meltwater retention.

3.4. Regional Climate Model performance

3.4.1. Comparison with the FAC dataset

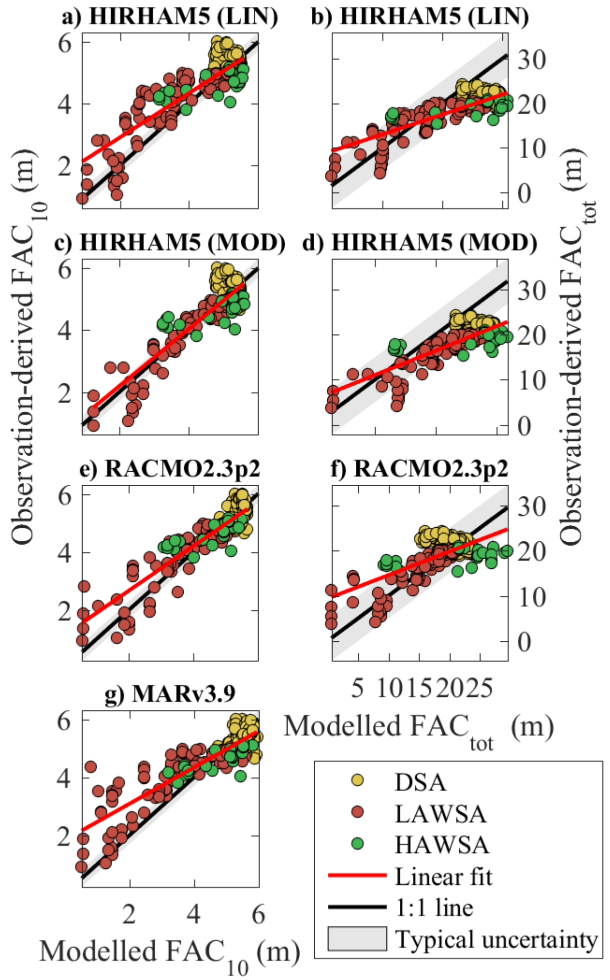


Figure 7. Comparison between the observation-derived FAC_{10} and FAC_{tot} and the simulated FAC in the corresponding cell of three RCMs.

All models reproduce the FAC_{10} observations in the DSA and HAWSA with bias ≤ 0.2 m, RMSD ≤ 0.6 m. Nevertheless, RACMO2.3p2, MARv3.9.2, and HH_LIN tend to underestimate the FAC_{10} in the LAWSA while HH_MOD did not show any bias in that area. The greater biases and RMSD regarding FAC_{tot} reflect both the performance of the RCM but also the greater uncertainty applying on our observation-derived FAC_{tot}. Overall we find that HH_MOD is the best candidate to simulate FAC_{10} and RACMO2.3p2 to simulate FAC_{tot}. Nonetheless, it appears that none of the RCMs can simultaneously simulate both FAC_{10} and FAC_{tot} accurately, which justifies our empirical approach to map FAC_{10} and FAC_{tot} across the whole firn area.

Table 5. Performance of the RCMs for FAC_{10} and FAC_{tot}. Bias is the average difference between model and observation. RMSD stands for Root Mean Squared Error. Intercept and slopes are calculated from the linear fit between simulated and observed FAC (red line in Figure 7)

		DSA		LAWSA		HAWSA		GrIS			
	RCM	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Intercept (m)	Slope (-)
FAC_{10}	HH_LIN	-0.1	0.4	-0.3	0.7	0.1	0.6	-0.2	0.6	1.5	0.7
	HH_MOD	-0.1	0.4	0.1	0.4	0.2	0.6	0.0	0.4	0.4	0.9
	RACMO2.3p2	0.1	0.3	-0.2	0.6	0.0	0.5	0.0	0.5	1.1	0.8
	MARv3.9.2	0.2	0.3	-0.3	0.9	0.2	0.5	0.0	0.6	1.8	0.6
FAC_{tot}	HH_LIN	6.4	7.1	2.7	5.3	5.6	8.3	4.9	6.6	8.6	0.4
	HH_MOD	6.5	7.2	5.3	6.2	7.0	8.9	6.1	7.0	5.6	0.5
	RACMO2.3p2	-0.4	3.3	-0.3	3.1	2.6	6.2	-0.1	3.6	9.4	0.5

3.4.2. Comparison with the spatially integrated FAC

The same pattern emerges with RCMs being able to simulate spatially integrated FAC within observational uncertainty in the DSA and underestimating it in the LAWSA. HH_MOD overestimates the spatially integrated FAC_{tot} in the DSA by 21%, leading to a 25% overestimation on the entire firn area. RACMO2.3p2 underestimates the spatially integrated FAC_{tot} by 10% in the DSA which, combined with the model's positive bias in the HAWSA, lead to a Greenland-wide estimation of spatially integrated FAC_{tot} within our observation-derived estimate's uncertainty interval.

HH_MOD uses a higher albedo than HH_LIN, and therefore calculates less surface melt and refreezing and, as a consequence, higher FAC_{10} in the LAWSA. The HH_MOD vs HH_LIN validation here confirms the sensitivity of simulated subsurface conditions, not only to the model's subsurface module but also to surface forcing (Langen et al., 2017). In a similar way, the slight negative bias in surface mass balance of RACMO2.3p2 (Noël et al. 2018), indicating excessive melt relative to snowfall, could also explain the model's underestimation of FAC_{10} in the LAWSA. Counterintuitively, HH_MOD, HH_LIN and MARv3.9.2 have in common a slight positive bias SMB (too much precipitation relative to melt) but also underestimate FAC_{10} in the LAWSA.

The way firn densification is treated in the snow models can also explain differences in simulated FAC_{10}: HIRHAM5 and MARv3.9.2 uses the same snow compaction scheme (Vionnet et al. 2012) while RACMO uses a dry compaction scheme after Kuipers Munneke et al. (2015a). HIRHAM overestimation of FAC_{tot} in the DSA arises from the relatively low firn densities modelled below ~40 m in HIRHAM, most likely because of the inadequacy of the compaction law from Vionnet et al. (2012) at depth. RACMO produces more realistic FAC_{tot} in the DSA, potentially because the densification law it uses has been tuned so that the modelled FAC matches 62 firn core observations (Kuipers Munneke et al., 2015a). Nevertheless the FAC_{tot} in the LAWSA is also underestimated by RACMO.

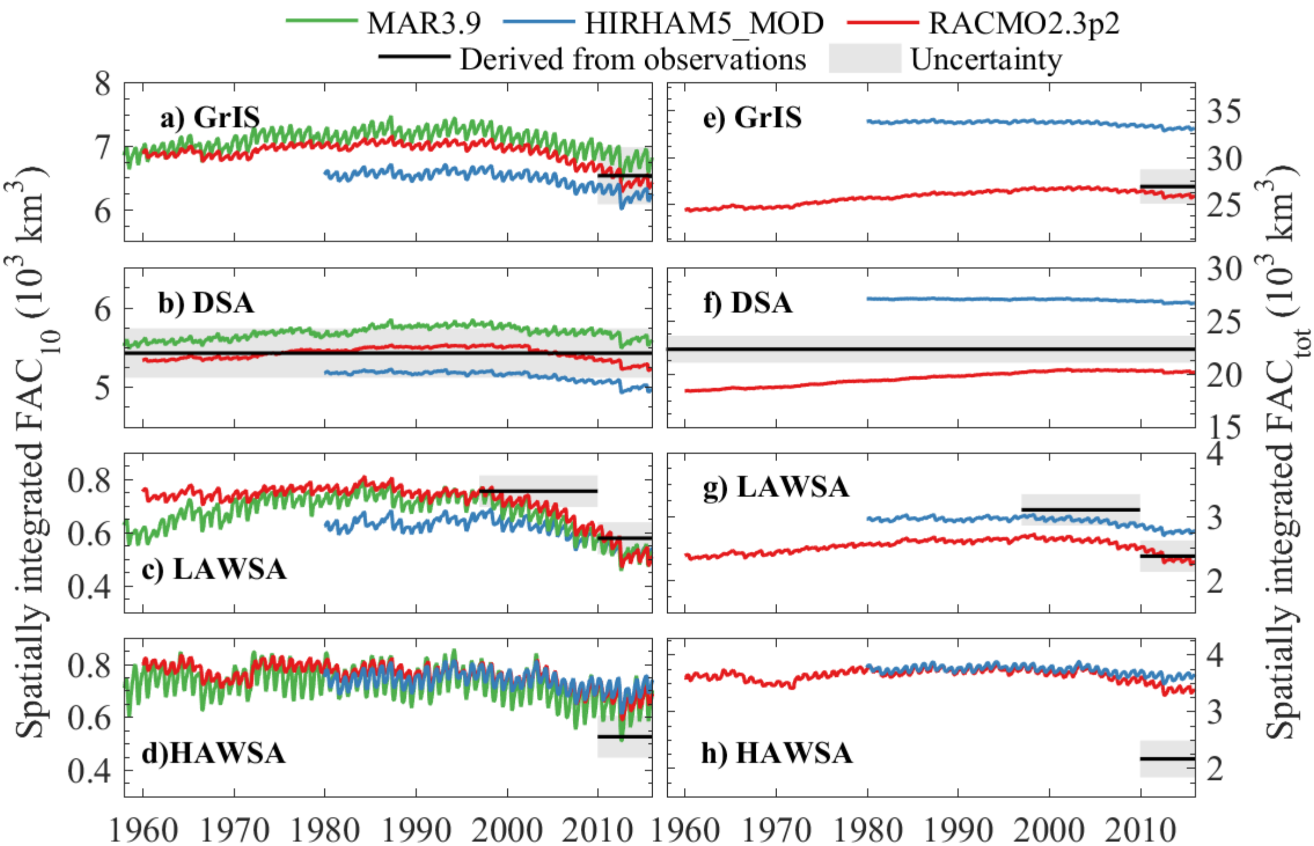


Figure 8. Temporal evolution of the FAC in the RCMs compared to the observation-derived FAC_{10} maps.

We also note that RCMs overestimate the spatially summed FAC_{10} in the HAWSA (Figure 8d) whereas they compare well with FAC_{10} observations of the HAWSA (bias ≤ 0.2 m in Table 5). It can be due to the fact that, while the RMCs reproduce the observed FAC_{10} in the interior of the HAWSA, their modelled FAC_{10} remains high in the lower HAWSA, when approaching the firn line. On the contrary, our observation-derived estimation of FAC_{10} decreases linearly with increasing with $\overline{T_a}$ and takes lower values than in the RCMs in the lower HAWSA. Nevertheless no firn observation is available in the lower HAWSA and future FAC_{10} measurements in the HAWSA should help to know which of the RCMs or our estimation of FAC_{10} describes best in FAC_{10} the HAWSA.

Last but not least, we see that in spite of their respective biases, RCMs reproduce the decreasing FAC_{10} in the LAWSA as observed (Figure 8b). The RCMs indicate that this loss of air content was initiated in the early 2000s and accelerated in 2010 and 2012. All RCMs show a decreasing FAC_{10} in the DSA over the last two decades which contradicts with our observations (Section 3.1.1, Figure 2). This decreasing FAC_{10} could be due to the RCM missing for example an increase snowfall in the DSA which would compensate the recent warming seen in the firn area (McGrath et al., 2014; Graeter et al., 2018). Another possibility would be that the models overestimate the sensitivity of firn compaction rate to increasing temperatures.

~~4. Conclusions~~

~~Our study provides, for the first time, a delineation of the firn area of the Greenland ice sheet over the 2000 – 2017 period. Using remote-sensing observations from 2000 to 2017, we estimate that firn covers 1,405,500 ± 17,250 km^2 or 78.5% of the ice sheet. This result allows further study of possible migration of this boundary in the past or in the future. Additionally, we present a collection of 344 firn cores spanning 65 years from which the firn air content from the surface to 10 m depth (FAC_{10}) could be calculated. We identify three regions on the firn area in which FAC_{10} where we could fit empirical functions of long-term accumulation and temperature averages ($\dot{\bar{b}}$ and $\overline{T_a}$) to FAC_{10} measurements and explain the spatio-temporal evolution of FAC_{10}. The stability of the FAC_{10} in the Dry Snow Area (where $\overline{T_a} \leq -16^{o}C$) over the 1953-2017 period contrasts with a 21% decrease of FAC_{10} in the Low Accumulation Wet Snow Area (where $\overline{T_a} > -16^{o}C$ and $\dot{\bar{b}} \leq 600$ mm w.eq. yr-1) between 1998-2008 and 2011-2017. This decreasing FAC10 translates into the loss of 168 ± 138 Gt (0.5± 0.4 mm sea level equivalent) of meltwater retention capacity 1998-2008 and 2011-2017. In the High Accumulation Wet Snow Area (where $\overline{T_a}$ >= -16oC and $\dot{\bar{b}}$ < 600 mm w.eq. yr-1) we find an average FAC10 of 2.9 m3 m-2 during the 2000-2017 period. FAC10 observations also indicated that meltwater may percolate deeper than 10 m from the surface making FAC10 insufficient to describe the retention capacity of the firn there. In a similar way, Machguth et al. (2016) showed that under conditions not completely understood, ice formation may prevent meltwater from accessing the entire top 10 m of firn. Therefore, further investigation of the firn permeability will help to understand how much of the FAC is used for meltwater retention. The firn area delineation and FAC10 dataset and maps can be used to constrain firn models and monitor the future evolution of the firn and are available for download at www.promice.dk.~~

4. Conclusions

A collection of 360 firn density profiles spanning 65 years allow us to quantify the firn air content (FAC) on the Greenland ice sheet as function of long-term air temperature and net snow accumulation averages ($\overline{T_a}$ and $\overline{\dot{b}}$). During the 2010-2017 period, we calculate that the firn layer contained 6 500 ± 450 km^3 of air in its top 10 m and 26 800 ± 1 850 km^3 within the whole firn column. We find that over the 1953-2017 period, the FAC remained constant (within measurement uncertainty) in the Dry Snow Area (DSA, where $\overline{T_a} \leq -19^{o}$C). In the Low Accumulation Wet Snow Area (LAWSA, where $\overline{T_a} > -19^{o}$C and $\overline{\dot{b}} \leq 600$ mm w.eq. yr^{-1}), we calculate that the FAC decreased by 24 ±16 % between 1998-2008 and 2010-2017. This decreased FAC_{10} translates into the loss of meltwater retention capacity of 150 ± 100 Gt (0.4 ± 0.3 mm sea level equivalent) in the top 10m of the firn and up to 540 ± 450 Gt (1.5 ± 1.2 mm sea level equivalent) in the entire firn layer. The output from three regional climate models (HIRHAM5, RACMO2.3p2 and MAR3.9.5) indicate that our calculated decrease in FAC may have initiated in the early 2000's and accelerated in 2010 and 2012. But the mismatch between RCMs and our dataset reminds that RCMs should be used with caution when used to calculate the firn retention capacity or when converting the ice sheet's volume changes into mass changes. Finally, our study highlights the importance of in situ firn density measurements to document the evolution of the Greenland ice sheet and to improve models and sea level projections. We also illustrate how new knowledge can be gained from the synthesis of multiple data sources and encourage the scientific community to make both recent and historical data available.

5. Acknowledgement ~~and data availability~~

This work is part of the Retain project funded by the Danish Council for Independent research (Grant no. 4002-00234) and the Programme for Monitoring of the Greenland Ice Sheet (www.PROMICE.dk).~~www.PROMICE.dk).~~ The FirnCover field campaigns were funded by the NASA grant NNX15AC62G. Achim Heilig was supported by DFG grant HE 7501/1-1. ~~The source code is available at github.com/BaptisteVandecrux/FAC10_study.~~ We thank Hubertus Fischer (Climate and Environmental Physics, University of Bern) for providing low resolution density data from firn cores collected during the EGIG expeditions 1990 and 1992. We are grateful to Peter Langen from the Danish Meteorological Institute, Stefan Ligtenberg from the Institute for Marine and Atmospheric Research at Utrecht University (IMAU) and Xavier Fettweis from the Laboratory of Climatology, Department of Geography, University of Liège (Belgium) for providing the regional climate model output~~drilled during the EGIG expeditions 1990 and 1992~~.

6. Data Availability

The FAC dataset, maps along with the firn area delineation are available at https://arcticdata.io/ and the majority of the original firn density measurements can be found in the SUMup dataset at https://doi.org/10.18739/A2JH3D23R. The source code is available at github.com/BaptisteVandecrux/FAC10_study.

~~6.~~7. References

Ahlstrøm, A., Gravesen, P., Andersen, S., Van As, D., Citterio, M., Fausto, R., Nielsen, S., Jepsen, H. F., Kristensen, S. S., Christensen, E. L., Stenseng, L., Forsberg, R., Hanson, S., and Petersen~~. . . Peters~~, D.:~~. &.:~~ A new programme for monitoring the mass loss of the Greenland ice sheet, Geol. Surv. Denmark Greenland Bull., 15, 61-64, pdf, 2008.~~2008.~~

Albert, M., and Shultz, E.: Snow and firn properties and air–snow transport processes at Summit, Greenland, Atmos. Environ., 36, 2789-2797, https://doi.org/10.1016/S1352-2310(02)00119-X, 2002.~~2002.~~

Alley, R.: Transformations in Polar Firn, Ph.D. Thesis, University of Wisconsin, Madison, WI, USA, 1987.

~~Arthern, R. J., Vaughan, D. G., Rankin, A., Mulvaney, R., and Thomas, E. R.: In situ measurements of Antarctic snow compaction compared with predictions of models, J. Geophys.l Res. Earth, 115, F3, doi:10.1029/2009JF001306, 2010.~~

Bader, H.: Sorge's law of densication of snow on high polar glaciers, J.~~Journal~~ of Glaciol.~~Glaciology~~ , 2, 15, 319-411, https://doi.org/10.3189/S0022143000025144, 1954.

Baker, I.: Density and permeability measurements with depth for the NEEM 2009S2 firn core, ACADIS Gateway, https://doi.org/10.18739/A2Q88G,~~doi:10.18739/A2Q88G,~~ 2012.

Benson, C. S.: Stratigraphic Studies in the Snow and Firn of the Greenland Ice Sheet, U.S. Army Snow, Ice and Permafrost Research Establishment, 1962.

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang: Detection and Attribution of Climate Change: from Global to Regional, in: Climate Change 2013: The Physical Science Basis.Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867–952, https://doi.org/10.1017/CBO9781107415324.022, 2013.

Bolzan, J. F., and Strobel, M.: Oxygen isotope data from snowpit at GISP2 Site 15., PANGAEA, https://doi.org/10.1594/PANGAEA.55511,~~doi:10.1594/PANGAEA.55511,~~ 1999.

Box, J.: Greenland ice sheet mass balance reconstruction. Part II: Surface mass balance (1840-2010), J. Climate, 26, 6974-6989, https://doi.org/10.1175/JCLI-D-12-00518.1,~~doi:10.1175/JCLI-D-12-00518.1,~~ 2013.

Box, J., Cressie, N., Bromwich, D. H., Jung, J.-H., van den Broeke, M. R., van~~v.,~~ Angelen, J.,Forster, R.R., Miège, C., Mosley-Thompson, E., Vinther, B.,~~, V., . . .~~ McConnell, J. R.: Greenland ice sheet mass balance reconstruction. Part I: Net snow accumulation (1600-2009), J. Climate, 26, 3919-3934, https://doi.org/10.1175/JCLI-D-12-00373.1,~~doi:10.1175/JCLI-D-12-00373.1,~~ 2013.

Braithwaite, R., Laternser, M., and Pfeffer, W. T.: Variation of near-surface firn density in the lower accumulation area of the Greenland ice sheet, Pâkitsoq, West Greenland, J. Glaciol., 40, 136, 477-485, https://doi.org/10.3189/S002214300001234X, 1994.

Buchardt, S. L., Clausen, H. B., Vinther, B. M., and Dahl-Jensen, D.: Investigating the past and recent delta 18O-accumulation relationship seen in Greenland ice cores, Clim. Past, 8, 6, 2053-2059, https://doi.org/10.5194/cp-8-2053-2012, 2012.~~2012.~~

Charalampidis, C., Van As, D., Box, J. E., van den~~Van Den~~ Broeke, M. R., Colgan, W~~L~~. T., Doyle, S. H., Hubbard, A. L., MacFerrin, M., Machguth, H. and~~. . .~~ Smeets, C. J.: Changing surface-atmosphere energy exchange and refreezing capacity of the lower accumulation area, West Greenland, Cryosphere, 9, 6, 2163-2181, https://doi.org/10.5194/tc-9-2163-2015,~~doi:10.5194/tc-9-2163-2015,~~ 2015.

~~Citterio, M., and Ahlstrøm, A. P.: The aerophotogrammetric map of Greenland ice masses, Cryosphere, Brief Communication, 7, 445-449, doi:10.5194/tc-7-445-2013, 2013.~~

Clausen, H., Gundestrup, N. S., Johnsen, S. J., Binchadler, R., and Zwally, J.: Glaciological investigations in the Crete area, Central Greenland: a search for a new deep-drilling Site, Ann. Glaciol., 10, 10-15, https://doi.org/10.3189/S0260305500004080, 1988.

Colgan, W., Pedersen, A., Binder, D., Machguth, H., Abermann, J., and Jayred, M.: Initial field activities of the Camp Century Climate Monitoring Programme in Greenland. ~~Geological Survey of Denmark and Greenland Bulletin,~~ Geol. Surv. Denmark Greenland Bull., 41, 75-78, pdf, 2018.

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., and~~. . .~~ Sole, A. J.:~~.:~~ Changes in the firn structure of the western Greenland Ice Sheet caused by recent warming, Cryosphere, 9, 1203-1211, https://doi.org/10.5194/tc-9-1203-2015,~~doi:10.5194/tc-9-1203-2015,~~ 2015.

Fausto, R., Mayer, C., Ahlstrøm, A.: Satellite-derived surface type and melt area of the Greenland ice sheet using MODIS data from 2000 to 2005, Ann. Glaciol., 46, 35-42. https://doi.org/10.3189/172756407782871422, 2007.

Fausto, R. S, Andersen, S. B., Ahlstrøm, A. P., van As, D., Box, J. E., Binder, D., Citterio, M., Colgan, W., Haubner, K., Hansen, K., Karlsson, N. B., Mankoff, K. D., Pedersen, A. Ø., Solgaard, A. and Vandecrux, B.:~~Fausto, R. S and the PROMICE team:~~ The Greenland ice sheet – snowline elevations at the end of the melt seasons from 2000 to 2017, Geol. Surv. Denmark Greenland Bull., 41, 71-74, pdf, 2018a~~2018~~.

Fausto, R. S., Box, J. E., Vandecrux, B., van As, D., Steffen, K., MacFerrin, M., Machguth H., Colgan W., Koenig L. S., McGrath D., Charalampidis C. and~~. . .~~ Braithwaite, R. J.: A Snow Density Dataset for Improving Surface Boundary

Conditions in Greenland Ice Sheet Firn Modeling, Front. Earth Sci., 6, 51, https://doi.org/10.3389/feart.2018.00051, 2018b~~doi:10.3389/feart.2018.00051, 2018~~.

Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., ~~K.,~~ Lang, C., van As, D., Machguth, H.,, and~~. . .~~ Gallée, H.: Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model, Cryosphere, 11, 2, 1015-1033, https://doi.org/10.5194/tc-11-1015-2017,~~doi:doi:10.5194/tc-11-1015-2017,~~ 2017.

Fischer, H., Wagenbach, D., Laternser, M., and Haeberli, W.: Glacio-meteorological and isotopic studies along the EGIG line, central Greenland., J. of Glaciol., 41, 139, 515-527, https://doi.org/10.3189/S0022143000034857, 1995.~~1995.~~

Forster, R. R., Box, J. E., van den Broeke, M. R., Miège, C., Burgess, E. W., Angelen, J. H.,, Lenaerts, J. T. M., Koenig, L. S., Paden, J., Lewis, C., Gogineni, S. P., Leuschen, C., and~~H., . . .~~ McConnell, J. R.: Extensive liquid meltwater storage in firn within the Greenland ice sheet., Nat. Geosci., 7, 95-19, https://doi.org/10.1038/NGEO2043,~~doi:10.1038/NGEO2043,~~ 2014.

Graeter, K. A., Osterberg, E., Ferris, D. G., Hawley, R. L., Marshall, H. P., Lewis, G., Meehan, T., McCarthy, F., Overly, T. and Birkel, S.D., and~~. . .~~ Birkel, S.: Ice Core Records of West Greenland Melt and Climate Forcing, Geophys. Res. Lett., 45, 7, https://doi.org/10.1002/2017GL076641,~~doi:10.1002/2017GL076641,~~ 2018.

Harper, J., Humphrey, N., Pfeffer, W. T., Brown, J., and Fettweis, X.: Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn, Nature, 491, 240-243, https://doi.org/10.1038/nature11566,~~doi:doi:10.1038/nature11566,~~ 2012.

Hawley, R. L., Courville, Z. R., Kehrl, L., Lutz, E., Osteberg, E., Overly, T. B., and Wong, G.: Recent accumulation variability in northwest Greenland from ground-penetrating radar and shallow cores along the Greenland Inland Traverse, J. Glaciol., 60, 220, 375-382, https://doi.org/10.3189/2014JoG13J141,~~doi:10.3189/2014JoG13J141,~~ 2014.

Heilig, A., Eisen, O., MacFerrin, M., Tedesco, M., and Fettweis, X.: Seasonal monitoring of melt and accumulation within the deep percolation zone of the Greenland Ice Sheet and comparison with simulations of regional climate modeling, Cryosphere, 12, 1851-1866, https://doi.org/10.5194/tc-12-1851-2018,~~doi:10.5194/tc-12-1851-2018,~~ 2018.

~~Herron, M., and Langway, C.: Firn Densification: an Empirical Model, J. Glaciol., 25, 93, 373-385, doi:10.3189/S0022143000015239, 1980.~~

Humphrey, N. F., Harper, J. T., and Pfeffer, W. T.: Thermal tracking of meltwater retention in Greenland's accumulation area, J. Geophys. Res., 117, F01010, https://doi.org/10.1029/2011JF002083,~~doi:10.1029/2011JF002083,~~ 2012.

Jezek, K. C.: Surface Elevation and Velocity Changes on the South Central Greenland Ice Sheet: 1980-2011 - Data Summary. BPRC Technical Report No. 2012-01, Byrd Polar Research Center, The Ohio State University, Columbus, Ohio, 2012.

Kameda, T., Narita, H., Shoji, H., Nishio, F., Fuji, Y., and Watanabe, O.: Melt features in ice cores from Site J, southern Greenland: some implication for summer climate since AD 1550, Ann. Glaciol., 21, 51-58, https://doi.org/10.3189/S0260305500015597, 1995.

Koenig, L. S., Miège, C., Forster, R. R., and Brucker, L.: Initial in situ measurements of perennial meltwater storage in the Greenland firn aquifer, Geophys. Res. Lett., 41, 81-85, https://doi.org/10.1002/2013GL058083,~~doi:10.1002/2013GL058083,~~ 2014.

Kovacs, A., Weeks, W. F., and Michitti, F.: Variation of Some Mechanical Properties of Polar Snow, Camp Century, Greenland, CRREL Res. Rpt. 276, 1969.

Kuipers Munneke, P., Ligtenberg, S. R. M., Noël, B. P. Y., Howat, I. M., Box, J. E., Mosley-Thompson, E., McConnell, J. R., Steffen, K., Harper, J. T., Das, S. B., and van den Broeke, M. R.: Elevation change of the Greenland Ice Sheet due to surface mass balance and firn processes, 1960–2014, Cryosphere, 9, 2009–2025, https://doi.org/10.5194/tc-9-2009-2015, 2015a.

Kuipers Munneke, P., Ligtenberg, S.R., Suder, E.A. and van den Broeke, M.R.: A model study of the response of dry and wet firn to climate change. Ann. Glaciol., 56(70), pp.1-8, https://doi.org/10.3189/2015AoG70A994, 2015b.

Langen, P., Fausto, R. S., Vandecrux, B., Mottram, R., and Box, J.: Liquid Water Flow and Retention on the Greenland Ice Sheet in the Regional Climate Model HIRHAM5: Local and Large-Scale Impacts., Front. Earth Sci., 4, 110, https://doi.org/10.3389/feart.2016.00110,~~doi:doi: 10.3389/feart.2016.00110,~~ 2017.

Langway, C. C.: Stratigraphic analysis of a deep ice core from Greenland, CRREL Res. Rpt. 77, 1967.

Ligtenberg, S. R., Kuipers Munneke, P., Noël, B. P., and . van den Broeke, M.: Improved simulation of the present-day Greenland firn layer (1960–2016), Cryosphere, https://doi.org/10.5194/tc-12-1643-2018,~~doi:10.5194/tc-12-1643-2018,~~ 2018.

Lomonaco, R., Albert, M., and Baker, I.: Microstructural evolution of fine-grained layers through the firn column at Summit, Greenland, J. Glaciol., 57, 204, https://doi.org/10.3189/002214311797409730, 2011.~~2011.~~

Lucas-Picher, P., Wulff-Nielsen, M., Christensen, J. H., Aðalgeirsdóttir, G., Mottram, R., and Simonsen, S.: Very high resolution in regional climate model simulations for Greenland: Identifying added value, J. Geophys. Res., 117, D02108, https://doi.org/10.1029/2011JD016267,~~doi:10.1029/2011JD016267,~~ 2012.

Machguth, H., MacFerrin, M., As, D. v., Box, J., Charalampidis, C., Colgan, W., Fausto, R.S., Meijer, H.A.,~~. . .~~ Mosley-Thompson, E., and van de Wal, R.S.: Greenland meltwater storage in firn limited by near-surface ice formation, Nature Clim. Change, 6, 390-395, https://doi.org/10.1038/NCLIMATE2899,~~doi:10.1038/NCLIMATE2899,~~ 2016.

Mayewski, P., and Whitlow, S.: 2016. Snow Pit and Ice Core Data from Southern Greenland, 1984, NSF Arctic Data Center. https://doi.org/10.5065/D6S180MH,~~doi:10.5065/D6S180MH,~~ 2016.

Mayewski, P., and Whitlow S.: Snow Pit Data from Greenland Summit, 1989 to 1993. NSF Arctic Data Center. https://doi.org/10.5065/D6NP22KX, 2016.~~doi:10.5065/D6NP22KX, 2016.~~

Miège, C., Forster R.C., B. J., Burgess, E., McConnell, J., Pasteris, D., and Spikes, V. B.: Southeast Greenland high accumulation rates derived from firn cores and ground-penetrating radar, Ann. Glaciol., 54, 63, 322-332, https://doi.org/10.3189/2013AoG63A358,~~doi:10.3189/2013AoG63A358,~~ 2013.

Montgomery, L., Koenig, L., and Alexander, P.: The SUMup dataset: compiled measurements of surface mass balance components over ice sheets and sea ice with analysis over Greenland, Earth Syst. Sci. Data, 10, 1959-1985, https://doi.org/10.5194/essd-10-1959-2018, 2018.

Morris, E. M., and Wingham, D. J.: Densification of polar snow: Measurements~~Meaurements~~, modeling and implication for altimetry, J. Geophys. Res.-Earth, https://doi.org/10.1002/2013JF002898,~~Res.-Earth, doi:10.1002/2013JF002898,~~ 2014.

Mosley-Thompson, E., McConnell, J., Bales, R., Li, Z., Lin, P.-N., and Steffen, K.: Local to regional-scale variability of annual net accumulation on the Greenlandice sheet from PARCA cores, J. Geophys.~~l~~ Res., 106, 33839–33851, https://doi.org/10.1029/2001JD900067,~~doi:10.1029/2001JD900067,~~ 2001.

Mote T. L.: Greenland surface melt trends 1973–2007: Evidence of a large increase in 2007, Geophys. Res. Lett., 34(22), https://doi.org/10.1029/2007GL031976, 2007.

Nerem R. S., Beckley B. D., Fasullo J. T., Hamlington B. D., Masters D, Mitchum G. T.: Climate-change–driven accelerated sea-level rise detected in the altimeter era. P. Natl. Acad. Sci. U.S.A., 7:201717312, https://doi.org/10.1073/pnas.1717312115, 2018.

Nghiem, S.-V., Hall, D.-K., Mote, T.-L., Tedesco, M., Albert, M.-R., Keegan, K., Shuman, C.A., DiGirolamo, N.E. and~~, . .~~ Neumann, G.: The extreme melt across the Greenland ice sheet in 2012, Geophys. Res. Lett., 39, L20502, https://doi.org/10.1029/2012GL053611,~~doi:10.1029/2012GL053611,~~ 2012.

Noël, B., van de Berg, W. J., van Wessem, J. M., van Meijgaard, E., van As, D., Lenaerts, J. T. M., Lhermitte, S., Kuipers Munneke, P., Smeets, C. J. P. P., van Ulft, L. H., van de Wal, R. S. W., and van den Broeke, M. R.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 1: Greenland (1958–2016), The Cryosphere, 12, 811-831, https://doi.org/10.5194/tc-12-811-2018, 2018.

~~Nolin, A., and Payne, M. C.: Classification of glacier zones in western Greenland using albedo and surface roughness from the Multi-angle Imaging SpectroRadiometer (MISR), Remote Sens. Environ., 107, 1-2, 264-275, doi:10.1016/j.rse.2006.11.004, 2007.~~

Porter, S., and Mosley-Thompson, E.: Exploring seasonal accumulation bias in a west central Greenland ice core with observed and reanalyzed data, J. Glaciol., 60, 224, 1065-1074, https://doi.org/10.3189/2014JoG13J233,~~doi:10.3189/2014JoG13J233,~~ 2014.

Reed, S.: Performance Study of the Dewline Ice Cap Stations, 1963, CRREL Special Report 72, 1966.

~~Reeh, N.: A nonsteady-state firn-densification model for the percolation zone of a glacier, J. Geophys. Res., 113, F03023, doi:10.1029/2007JF000746, 2008.~~

Renaud, A.: Etude physiques et chimiques sur la glace de l'inlandsis~~l'indlandsis~~ du Groenland , Medd. Groenland, 2, 177, 100-107, 1959.

Shumskii P.A.: Principles of structural glaciology: the petrography of fresh-water ice as a method of glaciological investigation. Dover Publications Inc..1964.

Simonsen, S.B., Stenseng, L., Ađalgeirsdóttir, G., Fausto, R.S., Hvidberg, C.S. and Lucas-Picher, P.: Assessing a multilayered dynamic firn-compaction model for Greenland with ASIRAS radar measurements. J. Glaciol., 59(215), pp.545-558, https://doi.org/10.3189/2013JoG12J158, 2013.

Spencer, M. K., Aller, R. B., and Creyts, T. T.: Preliminary firn-densification model with 38-site dataset, J. Glaciol., 47, 159, 671-676, https://doi.org/0.3189/172756501781831765, 2001.~~2001.~~

Steen-~~-~~Larsen, H.-C., Masson-~~-~~Delmotte, V., Sjolte, J., Johnsen, S.-J., Vinther, B.-M., Bréon, F.~~.-~~M., Clausen, H.B., Dahl-Jensen, D., Falourd, S., Fettweis, X. and Gallée, H.:~~. . . .:~~ Understanding the climatic signal in the water stable isotope records from the NEEM cores, J. Geophys. Res., 116, D06108, https://doi.org/10.1029/2010JD014311,~~doi:10.1029/2010JD014311,~~ 2011.

~~Steger, C., Reijmer, C., Broeke, M.~~ Sørensen, L. S., Simonsen, S.B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R. and Hvidberg, C.: Mass balance of the Greenland ice sheet (2003–2008) from ICESat data–the impact of interpolation, sampling and firn density. Cryosphere, 5, pp.173-186, https://doi.org/10.5194/tc-5-173-2011, 2011.

~~v., Wever, N., Forster, R., Koenig, L., . . . Noël, B.: Firn meltwater retention on the Greenland ice sheet: a model comparison, Front. Earth Sci., 5:3, doi:10.3389/feart.2017.00003, 2016.~~

Vallelonga, P., Christianson, K., Alley, R. B., Anandakrishnan, S., Christian, J. E. M., Dahl-Jensen, D., Gkinis, V., Holme, C., Jacobel, R. W., Karlsson, N. B., Keisling, B. A., Kipfstuhl, S., Kjær, H. A., Kristensen, M. E. L., Muto, A., Peters, L. E.,~~. . .~~ Popp, T., Riverman, K. L., Svensson, A. M., Tibuleac, C., Vinther, B. M., Weng, Y., and Winstrup, M.: Initial results from geophysical surveys and shallow coring of the Northeast Greenland Ice Stream (NEGIS), Cryosphere, 8, 1275-1287, https://doi.org/10.5194/tc-8-1275-2014,~~doi:10.5194/tc-8-1275-2014,~~ 2014.

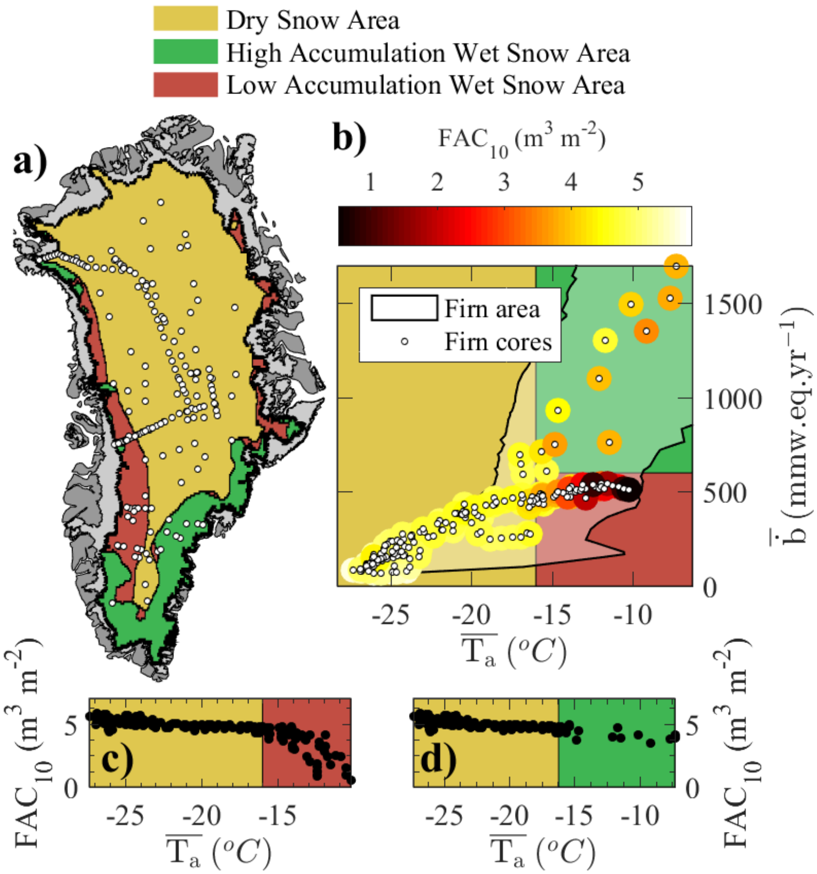
van Angelen, J., Lenaerts, J. T., van den Broeke, M. R., Fettweis, X., and van Meijgaard, E.: Rapid loss of firn pore space accelerates 21st century Greenland mass loss, Geophys. Res. Lett., 40, 2109-2113, https://doi.org/10.1002/grl.50490, 2013.

Vandecrux, B., Fausto, R.S., Langen, P.L., Van As, D., MacFerrin, M., Colgan, W.T., Ingeman-Nielsen, T., Steffen, K., Jensen, N.S., Møller, M.T. and Box, J.E.. Drivers of Firn Density on the Greenland Ice Sheet Revealed by Weather Station Observations and Modeling, J. Geophys.l Res.-Earth, https://doi.org/10.1029/2017JF004597, 2018.

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., and~~. . .~~ Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change, Cryosphere, 10, 1933-1046, https://doi.org/10.5194/tc-10-1933-2016,~~doi:doi:10.5194/tc-10-1933-2016,~~ 2016.

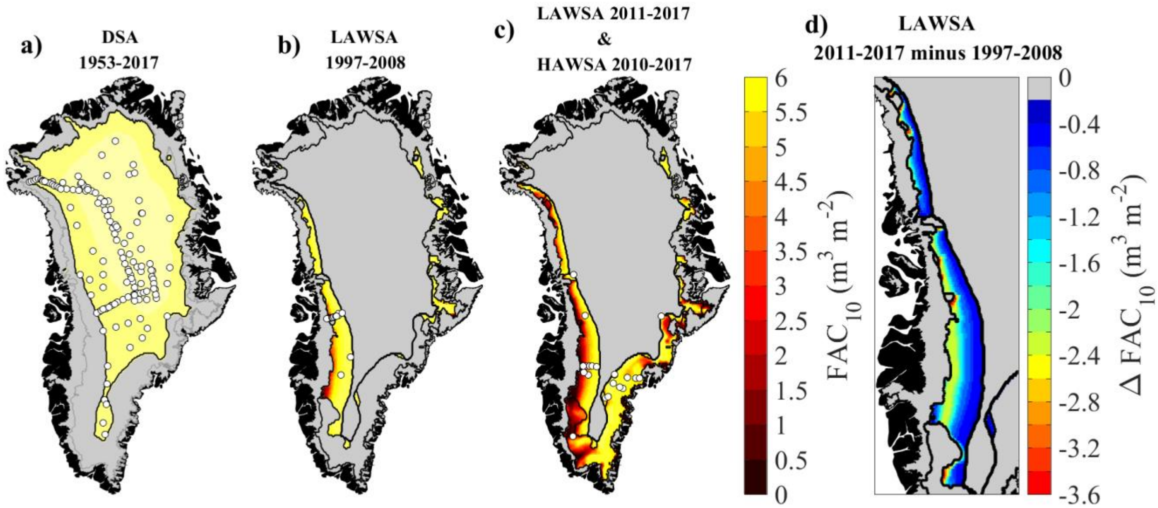
van der Veen, C. J., Mosley-Thompson, E., Jezek, K. C., Whillans, I. M., and Bolzan, J. F.: Accumulation rates in South and Central Greenland, Polar Geography, 25, 2, 79-162, https://doi.org/10.1080/10889370109377709,~~doi:10.1080/10889370109377709,~~ 2001.

Wilhelms, F.: Measuring the Conductivity and Density of Ice Cores, Ber. Polarforsch., 191, 1996.

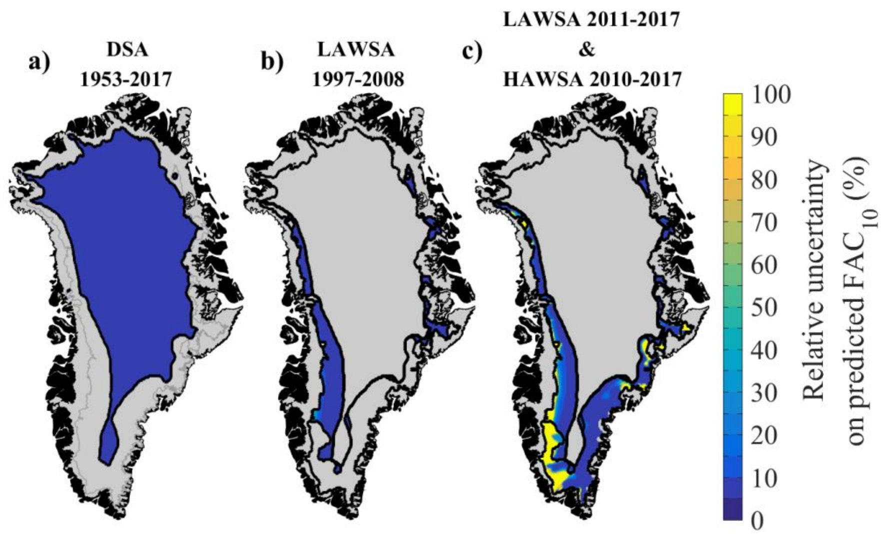


~~Figure 1. a) Geographical distribution of the FAC$_{10}$ dataset. b) Distribution of the dataset in the accumulation-temperature space ($\bar{\dot{b}}$~~

~~and $\overline{T_a}$). FAC$_{10}$ value is indicated by a coloured disk around each point. c) Temperature dependency of FAC$_{10}$ in the DSA and LAWSA d) Temperature dependency of FAC$_{10}$ in the DSA and HAWSA.~~



~~**Figure 2. FAC_{10} maps and location of the FAC_{10} measurements (a, b, c). Map of the change in FAC_{10} between the 1997-2008 and 2011-2017 periods in the LAWSA (c).**~~



~~**Figure 3. Maps of the relative uncertainty of the FAC_{10} maps in the DSA (a), LAWSA for the 1997-2008 period (b) and in the LAWSA for 2011-2017 and in the HAWSA for 2010-2017 period (c).**~~

~~**Table 1. List of the publications presenting the firn cores used in this study.**~~

~~Source~~	~~Number of cores~~	~~Source~~	~~Number of cores~~
~~Albert and Shultz (2002)~~	~~1~~	~~Langway (1967)~~	~~1~~
~~Alley (1987)~~	~~1~~	~~Lomonaco et al. (2011)~~	~~1~~
~~Bader (1954)~~	~~1~~	~~Machguth et al. (2016)~~	~~28~~
~~Baker (2012)~~	~~1~~	~~Mayewski and Whitlow (2016a)~~	~~1~~
~~Benson (1962)~~	~~55~~	~~Mayewski and Whitlow (2016b)~~	~~1~~
~~Bolzan and Strobel (1999)~~	~~9~~	~~Miège et al. (2013)~~	~~3~~
~~Buchardt et al. (2012)~~	~~8~~	~~Morris and Wingham (2014)~~	~~66~~
~~Clausen et al. (1988)~~	~~8~~	~~Mosley-Thompson et al. (2001)~~	~~31~~
~~Colgan et al. (2018)~~	~~1~~	~~Porter and Mosley-Thompson (2014)~~	~~1~~
~~Fischer et al., (1995)~~	~~14~~	~~Reed (1966)~~	~~1~~
~~Forster et al. (2014)~~	~~5~~	~~Renaud (1959)~~	~~7~~
~~Hawley et al . (2014)~~	~~8~~	~~Spencer, et al. (2001)~~	~~8~~
~~Harper et al. (2012)~~	~~32~~	~~Steen-Larsen et al. (2011)~~	~~1~~
~~Jezek (2012)~~	~~1~~	~~Vallelonga et al. (2014)~~	~~1~~
~~Kameda et al. (1995)~~	~~1~~	~~van der Veen et al. (2001)~~	~~10~~
~~Koenig et al. (2014)~~	~~3~~	~~Wilhelms (1996)~~	~~13~~
~~Kovacs et al. (1969)~~	~~1~~	~~This study~~	~~20~~