Response to the editor

Dear Editor,

With this new version of the manuscript, we made our best efforts to respond the reviewers' comments. We applied the majority of the suggestions and discuss below the few points that remained unchanged. Most importantly we:

- Relocated few paragraphs from the results to the methods.
- We changed the symbol $\bar{b}$ to $\bar{c}$.
- Renamed the "wet snow areas" into "percolation areas".
- We re-framed the RCM evaluation to focus on our FAC observations and to be fairer with the models.
- We carefully checked the writing.

We are grateful to the reviewers, whose comments greatly improved the manuscript.

Sincerely,

Baptiste Vandecrux on behalf on the co-authors

Reviewer #1 (S. Marchenko)

General comments

Reviewer's comments	Authors response
Structure of the manuscript: * unite some small subchapters * change order of some chapters - verify presentation of methods - clean the language by removing grammar mistakes, shortening sentenses, tailoring phrasing to the context. "… The updated manuscript has numerous changes with respect to the initial submission. Of my two major comments to the initial submission one is satisfied - now the manuscript	 Structure was updated as suggested and some sub-sections merged. Proof-reading was conducted by native speaker. Regarding the choice of arguments for

contains extensive comparison of the results with the earlier published FAC estimates. My other comment was on more detailed motivation of the choice of arguments in the functions used to map FAC. This one is met only partly. I still think that it will make more sense to distinguish between air temperature in winter and in summer months. Their action on refreezing is different: summer temperature is a proxy for melt rate and limits refreezing in colder areas (LAWSA, western part of the GrIS), winter temperature is a proxy for the firn cold content and limits refreezing in warmer area (PFA domains in eastern part of the GrIS). Authors may, of course, choose whatever arguments they think are relevant, but motivation has to be backed by logic, clear presentation and be at least internally consistent. This is, however, not always the case."	the empirical functions fitted to FAC observations, we wish to keep our approach. We do not believe that we have enough data to add another argument. We acknowledge the importance of cold content and its relation to winter temperature. However, we consider that cold content is equally affected by the insulating effect of snow and by the refreezing of deep meltwater. Winter temperature will not describe these processes and we expect that including that argument will not substantially improve our results.

In-line comments:

Nr.	Reviewer's comments	Authors response
1	use	Rephrased
2	cores to derive	
3	See Cogey at al., 2011, table 1, c.	Changed for $\bar{c}$ as suggested
4	Gt to make comparable with the rates of change given later.	Here we find important to show that we are able to calculate the spatially-integrated FAC on one hand and then the evolution of the retention capacity on the other hand.
5	defined as the area with	We keep the parenthesis because more word-efficient.
6 7 8	Of for the for the upper 100 m of the firn column	Rephrased
9	The other way around. You rather compare the empirical FAC estimates with models. I see two possible logical approaches here. The one applied here is that empirical data is primary with respect to simulations. The other one is that results published earlier are primary and later research is compared to it. It is obvious that authors stick to the first one. Provided that the mothod used here is original and was not applied earlier, relies on a number of assumptions and external data sources (mainly Ta and b forcing) i would rather favor the second logic.	We now only mention the comparison of RCMs to the FAC point observations which can be considered as a standard model validation. The comparison of spatially integrated values, for which our estimate is subject to important uncertainties, is not mentioned in the abstract anymore.

10	this chapter also contains information on the firn line position, which calls for a change of the chapter title	Changed to “Firn core dataset and firn area delineation”
11	suggests	Updated
12	rephrase	
13	meters	
14	I would still suggest to use porosity when defining FAC. Porosity is a general physical property of a material. It is a very intuitive term and is widely applied in soil science One can, of course, define FAC without porosity, but the current formulation of FAC in eq. [1] is confusing because m_k essentially sits in rho_k as rho_k = m_k/V = m_k/h_k/A = m_k/ h_k, since unit area (A) is assumed. For layer k: FAC_k = h_k*p_k = h_k*(1-rho_k/rho_ref) h_k - thickness p_k - porosity rho_k - firn density rho_ref - reference density of ice	We would like to maintain the equation in its current form and avoid the introduction of a new firn characteristic (porosity) which would not be discussed in the rest of the text.
15	This list does not look logical, and refreezing is standing out as a more inclusive, integral parameter, that is heavily dependent both on melt and firn temperature.	There are certainly many parameters having an effect on refreezing and air temperature is one of them. The sentence does not claim that the relationship should be linear or straightforward.
16	It is not clear what has to happen with the air temperature for the FAC10 to become lower. Does it have to increase or decrease? Having this sort of statement right after the list of parameters and processes for which air temperature can be used as a proxy lifts the question: do all of these act similarly? Mind again that increase in temperature adds more water and reduces the cold content. It can work both ways and the effect will depend on what is lacking: liquid water or cold content. There will be vertical and lateral differences.	Rephrased. Indeed we believe they do to a certain extent. We now state “Through these processes, increasing air temperature acts to decrease FAC (Kuipers Munneke et al., 2015b).” Indeed air temperature is only an imperfect proxy for FAC. We here wish to make a first rough description of the relationship between air temperature and FAC and justify that we use it as indicator. Later on, we observe that FAC does not relate to Ta in the same manner in different regions (LAWSA vs. HAWSA) and discuss the interaction between FAC, cold content, meltwater supply and

		percolation depth.
17	this applies to FACtot sa well, not only to FAC10	Updated
18	... which increases the FAC	Rephrased
19	this applies to FACtot sa well, not only to FAC10	Updated
20	May be use symbol "C" for accumulation. That will comply with the Glossary on gl. mb and rel. terms (Cogley et al., 2011), see Table 1 on page 7. Using b is confusing as it calls for associations with the surface mass balance.	Updated
21	do the "DSA", "HAWSA" and "LAWSA" correspond to the original terminology by Benson? Here is a link to the reprint of the original publication (1962) published in 1996: http://hdl.handle.net/11681/2730	Benson defines dry snow, percolation and wet snow facies. For increased clarity, we update our "wet snow area" into "percolation area", more representative of the firn hydrology in that area.
22	there is already a ref to the fig 1C earlier on.	Removed
23	Which facies are meant here? Bensons classification has 4 and transition between all of them is gradual. Most probably is it the "dry snow" and "percolation" facies (page F3 here: http://hdl.handle.net/11681/2730)	Updated. We now use "percolation area" and mention that it encompasses the wet snow facies and percolation facies of Benson.
24	may be divergence?	We wish to maintain "inflection"
25	May be replace "no" by "few"? It is hard to expect a cores to densy cover the part of the Ta-b space corresponding to the transition. Moreover, even if there would be such a dataset, a different RCM will result in a slightly different border...	Rephrased
26	plural?	Updated
29	empirical data used for calibration (/constraining the functions).	Updated
30	that's a rather strict formulation. I'd suggest a softer, less demanding phrasing, smth. like: "can be approximated by a linear dependency/function"	Updated
31	1) Why is accumulation rate not included as argument in the function mapping FAC in DSA? What is different here with respect to the WSAs? In the beginning of the chapter 2.3 it is claimed that both air temperature and accumulation affect the subsurface density and through that also FAC. Several models describing the dry snow densification due to gravitational settling and strain of the snow grains (Herron and Langway, 1980; Helsen et al., 2008; Arthern et al., 2010;	We added: "Although FAC_{10} is also dependant on $\bar{c}$, the residuals from Eq. 2 do not present any correlation with their respective $\bar{c}$ values. It indicates that because of the intrinsic co-variability of $\bar{c}$ and $\overline{T_a}$, most of the variations in observed FAC_{10} can be explained using either $\bar{c}$ or $\overline{T_a}$. Insufficient data are available to disambiguate the role of $\bar{c}$ and $\overline{T_a}$ in FAC_{10} variations. We therefore choose to use only $\overline{T_a}$ in Eq. 2."

	Ligtenberg et al., 2011) use both the surface accumulation rate and air temperature. I admit that air temperature and accumulation rate are closely correlated. This may greatly reduce the importance of the second argument and justify usage of the single argument. In any case the choise has to be motivated, at least for the sake of consistency with description of routines applied in the other two domains and the motivation at the start of the chapter 2.3.	
	2) why not to include the equation [2] from ch. 3.1.1. in this chapter?	Equation was moved
	3) is it right that Ta here is the mean value for the 1953-2017 period?	In section 2.3 we state that the long term average temperature and accumulation are all calculated from MAR over the 1979-2014 period.
32	what does this mean? Are there 4 different linear functions for different ranges of Ta? If yes, then why is there only one equation given for DSA (eq. [2] in ch. 3.1.1.) Or may be the data is binned in 4 groups depending on Ta and eq. [2] links the averages of FAC10 values in different groups and the Ta values corresponding to the middles of the Ta ranges?	We rephrased to: These 278 FAC_{10} observations are then binned into four equal $\overline{T_a}$ ranges to avoid the overrepresentation of clustered data (Figure 2a). Eventually, a linear function of $\overline{T_a}$ is fitted to the bins' average FAC_{10} using least squares method to estimate the FAC_{10} in the DSA And moved Figure 2 next to this paragraph so that it serves as illustration.
33	Does inclusion of the 11 cores from HAWSA significantly change the coefficient? If not (which follows from the previous sentence and figure 1c), i would suggest to remove the cores from the optimization. Otherwise the same data (11 cores) is used to calibrate models with different arguments. That is as an internal inconsistency of the manuscript.	The inclusion of the HAWSA cores do not change the linear regression's coefficient. They are needed in Eq. 2 because Eq.2 is also used in the upper HAWSA. It is now mentioned in the text. We do not see any problem using the same cores to calibrate a temperature-dependant function in the DSA (when this data is combined with DSA cores) and a temperature and accumulation dependant function in the HAWSA (when this data is combined with remotely sensed firn line location).
34	Again as in the earlier version of the manuscript... I think the piece of information saying that the data for LAWSA and HAWSA is divided timewise in two parts is given in an unexpected way. A reader probably does not even expect this to be done, since in the DSA data from all years is lumped together... Moreover, it looks a bit like an excuse that it was not possible to have more groups in time...	Updated to: Additionally, observations are unevenly distributed in space and time. Thus to reveal the temporal trends in FAC_{10}, the observation dataset is divided into two time slices that each contain enough FAC_{10} observations to describe the spatial pattern of FAC_{10} and constrain our

	I suggest : "... to reveal the temporal trends in FAC the available empirical dataset is divided in..." instead of "... to group FAC measurements into ... "	empirical functions.
35	are there mean Ta and b values calculated for the period 2010-2017 or for the long period 1953-2017.	Section 2.3 states that 1979-2014 is taken as reference period for the long term average temperature.
36	Unnecessary repetition of the word "function". Rephrase: "For the period .. FAC in LAWSA and HAWSA is described by a smoothed..."	Updated
37	repetition: compare with the first sentense in the same paragraph	The sentence was removed.
38	see the comment above. The sentense can be rephrased and shortened: "These measurements are used to describe the FAC10 in LAWSA during 1998-2008 by a smoothed bilinear function of Ta and b."	Updated.
39	Is it right that Ta and b here are the mean values for 1998-2008?	In section 2.3 we state that long term Ta and b are only calculated on the 1979-2014 period.
40	not consistent with the title of ch. 2.2. Either remove "the" here or add it there.	Removed
41	why not to call it FAC100 then?	We prefer to highlight that FACtot represent the total FAC of the firn column. FAC100 would leave the reader wonder whether 100 m is sufficient to describe the firn down to pore close off. Observations showed that pore close off is less than 100m deep.
42	what is this function, what does it take as arguments and what does it return as output? How is it used? My first guess would be that it links FAC with depth from the surface down to 100 m and represents all the 29+13 = 42 empirical datasets. Then in each of the remaining 360-29 = 331 cases when the core record does not reach 100 m the "tail" of this function is appended to the FAC = f(z) function from the core in question to describe the FAC increase from the bottom of the core down to 100 m. The routine needs to be described in greater details. Locations of the deep cores used to constrain the FAC = f(z) function will play a great role: it is not the same story if all of them sit deep in the DSA and just above the ELA. Thus a reference to Fig. 4 should be given here. It will, perhaps, make sense to combine the map incise in Fig. 4 and fig 1a. ok, now having reached ch. 3.1.3. and seen the	Section 2.4 and 3.1.3 were merged and clarified.

	equation [3], i see what is meant here. This chapter (2.5) is a much more relevant place for the equation. I still leave the words above to illustarte the kind of thinking that a potential reader may have. It is not ok to let readers guess things.	
43	The information given in the present chapter can be more or less dissloved in other chapters. With not much harm for the flow of the text. The words about uncertainty can be incorporated in ch 2.4.2, at its very end. Perhaps it will even make sense to have a separate chapter about uncertainty quantification. If i understand right, max. retention capacity is calculated by using the media density of 843 kg/m^3, this information can be given in ch. 2.2.	We wish to keep that section separate as it applies to both FAC10 and FACtot in all regions. Section 2.4.2 is only for FAC10 in the WSAs and section 2.2 is about FAC10 calculation from a density profile. They are therefore not suitable locations for this paragraph.
44	=upper 100 m? is that the case?	Updated
45	perhaps 2018	Updated
46	Chapters 3.1.1. and 3.1.2. have only one paragraph. Ch. 3.1.3. has 2 paragraphs. They can be combined in one subchapter 3.1. Furthermore, while none of the chapters gives abolute values of the FAC10 estimates, both chapters (3.1.1 and 3.1.2) contain information on temporal and spatial dynamics of FAC10 values within the different snow areas. This information is secondary with respect to the actual values. It is impossible to understand what 0.27 m of rmsd in FAC10 in LAWSA mean without knowing the actual range of values: 0.27 is "a lot" for 0-1 m range in FAC and "not a lot" if the range is 0-5 m. I would expect references to Fig. 5a and some kind of verbal description of what happens there to appear earlier in the text. Suggestion is to change ther order of ch. 3.2 and 3.1.	3.1.1 ad 3.1.2 have been moved to the method as suggested. We now moved the equation and uncertainty calculation to the method section. We nevertheless kept the discussion of temporal evolution and spatial pattern in the results and discussion. We wish to keep the current structure where, in Figure 1, the readers can see that FAC10 observations take values between 0 and 6, later in the method absolute uncertainties are defined and finally in result the relative uncertainty is presented (Figure 5). It prevents us from referring , in the method, to a Figure presented in the result.
47	perhaps a better place for this equation would be in ch. 2.4.1.	Agreed
48	This info comes as a surprise is a chapter called "results and discussion". Why not to group info on uncertianty quantification for dry and wet snow areas is a separate chapter?	Moved to method.
49	an	Updated
50	rms differences between what and what? The first guess is that it is between the function	We added : “The empirical functions used to estimate the FAC_{10} in the LAPA

	and empirical FAC10 estimates. Alternatively it can be the rms differences between the mean FAC10 estimate within a specific snow area and individual points in there. In the first case the value is a measure of "goodness of fit" and heavily depends on the amount of "smoothing" applied for the surface fitted to the empirical FAC10 estimates. If one uses the "scatteredinterpolant" function in matlab the rmsd will be 0... This essentially ruins the derivations contained in the following sentense. In the second case the rmsd is a measure of spread in simulated FAC10 values within one snow area...	and HAPA (Figure 3), when compared to FAC_{10} observations, have a RMSD of 0.28 m in the LAPA over the 1998-2008 period, 0.27 m in the LAPA over the 2010-2017 period and 0.17 m in the HAPA over the 2010-2017 period." Indeed these RMSD depend on the smoothing on the fitted surface. That is why we also vary the smoothing in the uncertainty analysis. Complete scripts will be made available on GitHub for the readers that are curious to hear about the interpolation function.
51	ok, so that is probably the function used to	Section moved to method to avoid confusion.
52	As earlier, UQ routines should be described in the "methods", perhaps in a separate subchapter, but not in "Results and discussion"	Moved to methods.
53	These derivations are not very informative without the information of the range of values given in verbal form, as a histogram or on a map.	Changed to: We assign 3.6 m, twice the RMSD of the linear regression, as the typical uncertainty applying on an estimated FACtot value that can in theory vary between 0 and ~25 m.
54	Here i find it hard to follow the suggested logic. The statement in the sentense refers to the relation between temporal changes in FAC10 and FACtot. This has more to do with how FACtot is calculated from FAC10... The statement does not follow from equation [2]. Eq [2] links Ta and FAC10 in the DSA. There (in DSA) there's is no distinction in FAC for different time periods.	Here Eq. 3 was meant.
55	in	Updated
56	why not to use the FAC acronym here as well	Acronym used
57	Chapters and paragraphs are ways to divide text according to the content, to the topic covered in each bit of text. Chapters are higher order divisions and paragraphs are lower order divisions. from my experience is it uncommon to have chapters with single paragraphs in scientific texts. Chapters 3.2.1 and 3.2.2 can be united.	Sections were merged.
58	rephrase to have "an average FAC10" only once and shorten this and following sentences. average FAC10 values of 5.1 m for DSA in 1953-	One repetition was removed but we wish to keep the structure of these sentences.

	2017 and 2.6 and X m for HAWSA and LAWSA in 2010-2017 respectivey. The latter value is exceeded by the FAC10 estimate for LAWSA in 1998-2008 by 35%....	
59	this sentence can be rephrased to have "1998-2008" only once and also indicate the value of FAC10 750+-60 km^3. The latter will ensure consistency with respect to previous sentences giving similar information about DSA and HAWSA.	Rephrased.
60	s	Updated
61	the word "subsequent" (= "consecutivesee ", = "following") is, perhaps, not a valid word here. may be "respective"?	Replaced by "corresponding"
62	s	Updated
63	... on ...	Section heading removed.
64	is that right? The uncertainty appears to be larger than the value itself	The wrong number had been used there.
65	flip the subplots! A4 paper is high and narrow, it is, therefore, more compact to have 2 lines of subplots and 4 columns. Add panel labels after "FAC10" and "FACtot": a, c, e, g in the first case and b, d, f in the second.	Figure updated.
66	s	Updated
67	Allows	
68	Space	
69	S	
70	Been	
71	Unnecessary repetition	
	Supplementary material: more ticks both in x and y axis May be also grid lines in X direction to facilitate reading of the FAC values	Done for the ticks.

Reviewer #2

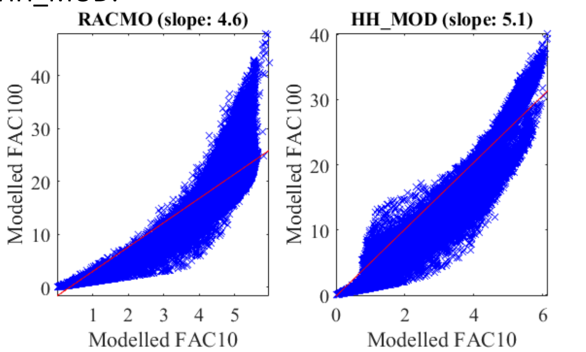
Reviewer's comments	Authors response
Review of "Firn data compilation reveals the evolution of the firn air content on the Greenland ice sheet" by Vandecrux et al. This manuscript is the second version of this	

paper and the previous revision round definitely benefitted the quality of the text. However, there are still too many points that need attention before the manuscript is publish-ready. Given the severity of the comments posted in the first round of reviews by both reviewers, I was surprised by the relatively short response time (<1 month) of the authors. As in the previous version of manuscript, I have again a long list of minor comments.	
In my view, these typo's, bad phrasings, and oversights should be spotted during a full correction round of the co-authors, rather than in a review round. Besides these irritating minor comments, I have one general comment that needs to be addressed before the manuscript can be published.	Thorough proof-reading was conducted by a native speaker among the co-authors.
This manuscript describes the spatial pattern of firn air content (FAC) across the Greenland ice sheet based on observed firn cores and is the first manuscript to do so. Previously, only modelled estimates using regional climate models or firn models have been made. In my opinion, the current manuscript tries too much to suggest that the observation-based method used here are superior to previously presented data, for example the following phrases are used: "urge caution when using models to quantify […] evolution of the FAC" (P1, L34), "confirms our choice of an empirical approach as opposed to relying on RCMs and firn models" (P10, L8), "none of the RCMs can simultaneously […] FAC accurately, which justifies our empirical approach" (P18, L1), "the mismatch between RCMs and our dataset reminds that RCMs should be used with caution" (P20, L20). I completely disagree with this type of reporting. First of all, I think science is not a competition of who has the best methods or results, but should be more about increasing understanding of processes involved. For me, the balance in the current manuscript is completely wrong. Second, the method used here uses (relatively simple) empirical relations to calculate a spatial pattern in FAC and subsequent area-integrated numbers. So although the method is based on observations, the eventual resulting numbers cannot be treated as such. A comparison with other data can therefore never "justify" that one method is better than the other.	If we wish to "urge caution" regarding RCM, it is not for promoting our product (which has a very coarse temporal resolution and is practically unusable by the altimetry community). It is to warn the users of RCM firn products that significant regional biases appear from our comparison between RCM and FAC measurements. We try to re-balance the manuscript by removing extrapolated FACtot values from the point-scale comparison (which then becomes a robust evaluation of the RCMs against observations only). We still compare spatially integrated FAC, but removed all judgmental statement as our observation-derived estimates is less reliable.
My suggestion would be to treat the observation-based method used here and the	I totally agree with this statement. We now differentiate the in situ observations (the FAC10

modelling method as complementary rather than as competing. Both schools have their definite pro's and con's and only by combining them the best result possible can be realized. Neither this manuscript nor any other currently available has the evident proof that for Greenland FAC one method is better than the other.	dataset and some FACtot values), used for validating the RCMs, and our spatially interpolated product, which is put on the same level as RCMs.
In my view, large parts of the results interpretation and discussion sections needs to be rewritten to do more justice to the results of both methods. To do so, it is also needed that the authors look critical at their own results. They should definitely highlight the regions or regimes were the observation-based method appears to perform better, but also be fair to report that in some regions/regimes it does not. For example, the lack of observations in the HAWSA is a serious problem or that models appear more capable of simulating temporal trends then sparse (in time) observations.	We mention the scarcity of data and the drawbacks of our methods. We have conducted a thorough uncertainty analysis and provide confidence interval with all values in the manuscript. The reader is left with all the information to assess the utility of our product.
Minor comments: P1, L26: Please be consistent with the hyphens throughout the manuscript. Technically, sea-level rise should be hyphenated (so that is correct), however, the phrase without hyphen (sea level rise) is used much more often. In the same line, however, ice-sheet contribution should be hyphenated! Any time there is a compound adjective (two words (ice & sheet) that act together to describe a noun (contribution)), you should hyphenate: ice-sheet contribution. Only when there is an adverb ending in –ly you should not hyphenate: remotely sensed data and not remotely-sensed data.	Updated.
P1, L29: The 6500 ± 450 km3 is very different from the 5200 ± 452 km3 reported in the previous version. The numbers are not even close to being "within the error margins", which makes you wonder how certain the used method, numbers and/or uncertainties are. Reported uncertainty estimates should theoretically indicate the possible range of outcomes based on uncertainties in the input. Such large difference between the two versions indicates that the reported uncertainty number is far too small.	6500 ± 450 km3 is the spatially integrated FAC10 for the entire firn area. In the first version of the manuscript, 5200 ± 452 km3 was the spatially integrated FAC10 for the DSA (section 3.2). It is therefore normal that the numbers diverge.
P2, L9: should be "in the sea level change equation".	Sentence was rephrased.
P2, L14: This paragraph needs 1-2 sentences more.	Paragraph was updated and merged with the next one.
P2, L18-19: Due to the density difference between water in liquid and refrozen form this	We state that FAC is indicative of a volume available for retention. The volume available is the

statement is not completely true.	same independently of the state of retained water. We agree that the mass that can be retained is dependent on the phase and density, but it is not what this sentence is about.
P2, L19-22: Sentence is too long.	We rephrased that sentence.
P2, L28: By comparing RCM output with density profiles, the model is indirectly compared to FAC. FAC is nothing more than an integrated density profile.	This sentence was removed to only mentioned studies which have provided estimation of either FAC or firn meltwater retention capacity.
P3, L1-5: Why is the firn aquifer not mentioned here? A firn aquifer region is the prime example of deep percolation (> 15 m).	Reference to firn aquifers was added.
P3, L22: Here, it is reported that 324+20 cores are used, while the abstract states 360 cores are used	The numbers were updated.
P3, L6-7: "does not play a negligible role" is somewhat double. Change into "does not play a role" or "has a negligible role".	We rephrased that sentence.
P4, L15: Why not use accumulation (b) and surface melt? There is clear relation between air temperature (Ta) and surface melt, but it is not linear due to feedback mechanisms such as albedo. Meltwater refreezing is a much more effective densification process than firn compaction, so to me it makes more sense to use surface melt instead of Ta. In the previous manuscript version, the atmospheric data from Box et al., 2013 was used, making the choice for b and Ta more logic (as surface melt is unavailable, I think). However, in the revised version MAR is used, making surface melt also easily available.	Melt would not be of any help in the dry snow area where it would have a small value everywhere. We do not want to add melt as a third argument to our empirical functions because we do not believe that our data allows to constrain more complex empirical functions. Additionally, there is no direct validation of RCM-derived melt amounts in the firn area. The non-linearity of the relationship between temperature, melt and FAC is reflected by the shape of our empirical functions in the LAWSA.
P4, L30: Here, -19C is used, while the previous version reports -16C. Is this difference only due to the difference in climatic forcing between Box et al., 2013 and MAR?	Indeed Box13's product gives warmer temperatures than MAR, especially in the percolation area. Box13 tunes the 2m temperature from RACMO2 to fit coastal and ice sheet station. MAR is forced by ERA interim, gives air temperature at 3 m and has a correction for model biases in topography. It is difficult to know where the difference come from (forcing, model formulation, topography…). But all the necessary information are given in the dataset's respective references. Nonetheless, we define our temperature threshold as the inflection point in the FAC vs. temperature curve. As a consequence, the -16°C isotherm in Box13 dataset is almost identical to the -19°C isotherm in MAR. This shows again how our

	empirical approach compensates for model biases.
P5, L5: Again, I think it would be good to introduce surface melt as a proxy. Did the authors make a FAC vs. melt-accumulation ratio figure? Or investigate if there are clear patterns found in the accumulation-surface melt space? Table 2: Why are 11 HAWSA cores also used for the DSA fitting?	For the reasons mentioned above, we wish not to include melt as an argument for our empirical functions. Since the linear relationship between Ta and FAC10 seems the same in the DSA and upper HAWSA, we use one equation to estimate FAC in those two regions. We now mention it in the text.
P8, L4-10: This method feels a lot like cherry picking… There are not enough cores, so one from the HAWSA 6 from the firn line are added. How does this influence the results and why are only these 1+6 added and not more or less?	Indeed scarce data force us to be inventive. We believe that the use of the firn-line locations increases the robustness of our approach compared to relying only on the cores. Selecting 6 firn-line sites to complement 10 cores in the HAWSA will give more importance to the cores in the fitting of empirical functions while still taking into account the firn-line sites. Other selection processes could be deemed as justified as ours but we wish not to investigate all of them as we state clearly that in the HAWSA we present an rough estimate based on scarce data (now stressed in the conclusion). Through Figure S3 we are completely transparent on how scattered the firn line appear in the (Ta, b) space and on which sites were selected. Eventually, we assess our empirical functions' sensitivity to the location and FAC of these firn-line sites and include that sensitivity in our uncertainty estimate.
P8, L26: I think Ligtenberg et al., 2018 calculates FAC to the density of ice and not pore-close off depth.	True, updated.
P8, L29: Refer to Figure 4. P9, P14: Referring to a 2019-paper is somewhat preliminairy.	We now moved Figure 4 to the method section. Updated.
P9, L23: In Figure 2b, I see a remarkable underestimation in 1995-2000 and a remarkable overestimation in 2000-2005. What explains this?	These variations fall within measurement uncertainty. These variations could be explained by the different teams and measuring technics involved in the data from these two periods or by the limitation of our predictor (here Ta) during these two periods. Therefore we do not think that the signal is clear enough to be interpreted.
P9, L24: add e.g. P9, L25: In light of the major remark (see above), I find it surprising that firn modelling is here	Done. We hope our new phrasing will reflect the value that we give to firn modelling as long as it is used in

used to confirm the found results.	combination with in situ measurements. In that sense, the firn modelling of Vandecrux et al. (2018) is fed by weather station data and tightly constrained by firn cores.
P11, L7: Was it checked how this relationship looks in modeled data: HH, RACMO, MAR? I would suspect it also varies spatially, was this checked?	Here is the FAC10 vs FAC100 plot for RACMO and HH_MOD:  The overall slope is of the same magnitude as the one we use (4.1). The slope is different in the two models and varies spatially and temporally. We wish to pursue with our empirically-derived relationship. And added mentions of the uncertainty applying on our estimation of FACtot throughout the text.
Also, for FAC10 < 3m the relationship in Figure 4 is lacking confidence. Why is it still fair to be used for lower FAC10 regions? Figure 6: Can be added to Figure 5 as Figure 5b. Figure 6: For the cores locations, it is visible that all 98-08 cores, expect one, were situated on the northern transect, while all 10-17 cores, expect one, were located on the southern transect. How robust does that make the reported temporal change (35%) in LAWSA between these periods? Are we not just looking at spatial differences in FAC rather than temporal differences?	I guess FACtot was meant here. In spite of its high uncertainty, we can still use our values of FACtot as the best observation-derived estimate. For the validation of RCM however, we agree that it should be done only with robust data. We now only use the 29 observed FACtot. We now also stress the uncertainty of our FACtot estimate when comparing with the RCM-derived spatially integrated FACtot. Updated. We added in the methods: "Although observation locations in 1998-2008 and 2010-2017 can be different, few samples available at the same sites (e.g. Crawford Point, Dye-2) in both time slices ensure that FAC_{10} changes are more likely due to a temporal evolution rather than from the different spatial coverage of each period's constraining dataset."
P14, L2: That is a very open door, as FAC10 and FACtot are linearly related in the used method…	Although trivial, we thought that not mentioning it would leave the reader wonder which depth interval this statement applies to.
P14, L7: Here it is stated that the LAWSA FAC10 loss from 98-08 to 10-17 is 24%, while on P12, L14 it is 35%. Please check your numbers carefully!	The numbers were updated.

P14, L8: Please remark that is likely unrealistic (as was also mentioned in P12, L4-9).	We added: "The corresponding decrease in FAC_{tot} indicates that potentially up to 700 ± 490 km^3 of air may have been lost from the total firn column. In this we assume that the FAC_{10} decrease propagated to the entire firn column (see Section 2.5), which might not be accurate. Insufficient data are available to determine precisely how much FAC was lost below 10 m and we can only give a hypothetical upper bound to the FAC_{tot} decrease."
P14, L10-16: I do not agree. It is (very) likely that melt is the main contributor, as in %-change in melt has a nth time higher effect on FAC than the same %-change in precipitation. Also, large changes in melt are well documented and observed, while precipitation changes are small or insignificant. P14, L19: I would replace "Box" by "Box13"	That is what we say: Numerous studies show that most of the densification is melt-related. However we remind the reader that changes in precipitation can also have an impact on density, that precipitation is currently not being monitored in the firn area and that RCMs give contradicting trends. Updated
P14, L24: By saying, "Additionally, in these regions no firn observations are available to constrain our FAC10 estimates", you basically say that this procedure should not be used in these regions. This is something I agree with. When there are sufficient FAC observations, the used method is valuable and definitely adds insight to what we know. However, when at most a handful of observations is available (as in the S and SE, or in the HAWSA as a whole), these regions should be masked from the results.	For comparison, Harper et al.'s Nature article used 15 firn cores and localized radar transects to define the retention capacity of the entire percolation area. We believe that the 10 cores available in the HAWSA are sufficient to make a rough estimate of the FAC in that sub-region. Yet we are transparent and mention several times that our estimate in the HAWSA could be improved by additional measurements.
L15, P5-6: Would help to re-iterate that the infiltration ice density is used to convert km3 in Gt. P15, L7-10: Sentence is too long. Table 4: Can be merged into Table 3 as the two are directly linked through the infiltration ice density.	The infiltration ice density is reintroduced and discussed two paragraphs later. The sentence was split. Tables were merged.
P15, L15-17. The difference between the here reported storage capacity (310 Gt) and the one by Harper et al., 2012 (1289 Gt) is a factor 4. Even with increasing knowledge, more observations, etc. this is a difference that very difficult to fully explain. Could the modeled FAC (HH, RACMO, MAR) indicate which of two might be more likely?	We give the recent FAC decrease as well as our assumptions may explain our lower estimates. Other biases apply to the RCMs: they generally predict bare ice in the western lower percolation zone and thick firn at the firn line in eastern Greenland. We already dedicate a full section to the comparison with RCMs. We wish, in this section, to to compare our product with another observation-derived estimate.

	Of course we believe that our approach is better than the one from Harper et al.. But we are little interested in these uncertain integrated values which are in fact not very useful in practice and rather highlight the real novelty of our approach: "Yet, beyond these integrated values, our approach allows to quantify the firn retention capacity and the corresponding uncertainty at any location of the firn area. Our product can therefore be used in combination with, for instance, remotely sensed melt extent to derive which areas of the firn actively retain meltwater and evaluate the retention capacity there."
P16, L7: "firn aquifers" or "the firn aquifer". P16, L8-10: I do not agree. Firn aquifers contain liquid water that can resides there for ~30 years, which to me is too long to simply neglect it. On the other hand, all refrozen meltwater is included here as it is "retained for centuries" (P16, L10). The latter is definitely not true in the current (fast-)changing climate. This manuscript reports that over the last decade alone the FAC in LAWSA has decreased with 24%. If that rate continues, some of the refrozen meltwater will re-melt and runoff in a summer within the next 30 years. To me, it is therefore not correct to include this refrozen retention while excluding the firn aquifer liquid water.	Updated Miller et al. 2018 themselves define aquifers as "short term" storage as opposed to refreezing: "Firn can serve as a substantial storage reservoir for meltwater (Harper et al., 2012; Humphrey et al., 2012). However, flow within the firn aquifer suggests that in areas where firn aquifers occur, storage is short term (residence time <30 years). " It is hard to know exactly the pace at which the firn will adapt to a warming climate. Yet, following the approach suggested by the reviewer we can make a simple extrapolation. Let us consider a firn location that lost 24% of its storage capacity over 20 years (1998-2017). Keeping the filling or warming rate constant, it will take potentially another 60 years to completely saturate and turn into ablation area. Then only the surface will start to ablate and it will take again many years until the water that was refrozen reaches the surface again and is finally melted.
P18, L5: RMSE. Table 5: Would be interesting to include the bias and RMSE for the empirical method as well, for comparison. P18, L15: Would be valuable to indicate the uncertainty interval.	Changed for RMSD. We already give our empirical function's RMSD in section 2.4.1 and 2.4.2. Here adding a number to that complex sentence may confuse the reader. We now point at the Figure 7e where the comparison and uncertainty are illustrated.
P18, L20-23: You refer to biases in the modeled SMB of RACMO and MAR, but biases compared to what? This paragraph is unclear.	The paragraph was rephrased: "Noël et al. (2018) found that the surface mass balance of RACMO2.3p2 in the accumulation area was on average slightly lower than observations, indicating excessive sublimation or runoff relative to snowfall in the model. This surface bias could explain the model's underestimation of FAC_{10} in the

	LAPA at point scale (Figure 6, Table 5) and on spatially integrated values (Figure 7). On the other hand, MARv3.9 has slight positive biases in surface mass balance compared to observations (Fettweis et al. 2017). And although the RCM simulates too much precipitation relative to melt, it also underestimates FAC_{10} in the LAPA. Surface forcing is therefore not the only factor influencing the FAC estimates by the RCMs.”
P19, L3: By saying “HIRHAM overestimation of FACtot in DSA…”, it is implied as if FACtot is an objective observation that can be used to test other estimates. FACtot is however far from a direct observation.	Mentions like “overestimate” were removed unless applying on the validation of RCMs against the dataset of observed FAC10 and observed FACtot.
P19, L12: I would be very hesitant to draw strong conclusions about the performance of RCMs in the HAWSA. The HAWSA FAC numbers reported here are based on only a few observations.	This paragraph does not present any strong conclusion. We intend to say that the RCM-derived FAC is further away from our estimate when comparing spatially integrated values than point observations. We relate this difference to our assumption that FAC goes to 0 at the remotely sensed firn line when the RCM calculate higher FAC around the south-eastern portion of the firn line. We conclude that no firn observation is available to ascertain what is the FAC gradient at the firn line in the HAWSA.
P20, L5: add “by the extreme summers of 2010 and 2012”. P20, L6: Is this decreasing FAC10 trend in the RCM significant? In Figure 2, it is visible that in the 1990s the highest FAC were reported, so does that not also generate a small decreasing trend in the observational record?	Added Statistical analysis on monthly values shows a significant trend. Yet it is difficult to discuss trends in RCM-derived FAC when these values do not come with confidence interval. Nevertheless we rephrased to: “In the DSA, RCMs show a FAC_{10} decrease ranging from -120 km^3 in MARv3.9 to -282 km^3 in RACMO2.3p2 between 1998 and 2017. These decreases contradict with our conclusion that FAC has not changed significantly in the DSA over that period (Section 3.1).”
P20, L7-9: Why should it be a flaw in the models? Would be fair to list all possibilities.	We added: “… iii) the spatial heterogeneity and uncertainty of FAC observations leading to spurious conclusions from our dataset. Yet, finding identical firn density profiles decades apart at several sites (e.g. Summit, Camp Century) adds confidence to our findings.”
P20, L18: This is a very shaky conclusion.	We give the upper bound of the decrease. We

Since FACtot and FAC10 are linearly related in this manuscript, these numbers follow logically from one another. However, it is very unlikely that the total FAC has decreased by this much.	add “potentially” to mark the hypothetical value.
P20, L21: As mentioned in my major remark (see above), I do not fully agree with this. Both methods have their pro’s and con’s. The results presented here also show that there are some regions where insufficient FAC observations are available to map all spatial variations in FAC. For these locations, RCMs estimates are very useful.	We believe that this statement is fair. We do not claim that our product is better. We add: “The RCMs also allow an estimation of FAC in regions where no measurements are available.” Yet warning RCM users about the biases of RCM firn product does not seem too controversial to us.

Firn data compilation reveals widespread decrease~~the evolution~~ of ~~the~~ firn air content in West~~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, 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, 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. A thick and porous layer of snow known as firn covers~~The firn covering~~ the Greenland ice~~-~~sheet interior. The firn layer buffers~~ can retain part of the surface melt each summer, buffering~~ the ice~~-~~sheet contribution to sea-level rise by retaining a fraction of summer melt as refrozen ice. In this study we ~~. To~~ quantify the firn air content (FAC), an indicator of meltwater retention capacity, associated with ~~we derive from~~ 360 point~~firn~~ observations. We quantify FAC in both the uppermost 10 m and the ~~Firn Air Content in the top 10 m (FAC_{10}) and in the~~ entire firn column before interpolating ~~(FAC_{tot}). We then map the~~ FAC over the entire ice-sheet firn area as an~~using~~ empirical function~~functions~~ of long-term mean air temperature ($\overline{T_a}$) and net snow accumulation ($\bar{\dot{c}}$).~~$\bar{\dot{b}}$) fitted to observations.~~ We assess~~find that the firn layer contains~~ a total ice-sheet wide FAC of 26 800 ± 1 840~~850~~ km^3, of which~~air, with~~ 6 500 ± 450 km^3 resides within~~in~~ the uppermost~~top~~ 10 m of firn, during the 2010-~~. The FAC was stable between 1953 and~~ 2017 period. In~~in~~ the dry snow area ($\overline{T_a}$ ≤ -19°C), FAC has not changed significantly since 1953. In~~≤ -19°C), while it decreased by 24 ±16% in~~ the low accumulation percolation~~wet snow~~ area ($\overline{T_a}$ > -19°C and $\bar{\dot{c}}$~~> -19°C $\bar{\dot{b}}$~~ ≤ 600 mm w.eq. yr^{-1}), FAC has decreased by 23 ± 16%~~)~~ between 1998~~1997~~-2008 and 2010~~2011~~-2017. This reflects~~ leading to~~ a loss of firn retention capacity of between 150 ± 100 Gt ~~(top 10 m)~~ and 540 ± 440~~450~~ Gt respectively from the top 10 m and entire~~(whole~~ firn column.~~).~~ The top 10 m FACs simulated by~~outputs of~~ three

Formatted: Normal

Style Definition: Heading 1: Font: No bullets or numbering

Style Definition: Heading 2: Font color: Auto, Space Before: 12 pt, No bullets or numbering

Style Definition: Heading 3: Font color: Auto, Space Before: 12 pt, No bullets or numbering

Style Definition: Heading 4: Font:

Style Definition: Heading 5: Font: (Default) Cambria

Style Definition: Heading 6: Font: 10 pt, Not Bold, Font color: Accent 1, Space Before: 10 pt, After: 0 pt, Keep with next, Keep lines together

Style Definition: Caption

Style Definition: Title: Font: (Default) Cambria, Not Expanded by / Condensed by

Style Definition: Subtitle: Font: (Default) Cambria, None, Indent: Left: 0 cm, Hanging: 0,63 cm

Formatted: From text: 0 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

regional climate models (HIRHAM5, RACMO2.3p2, and MARv3~~MAR3~~.9) agree within 12%~~compare well~~ with observations~~observed FAC$_{10}$~~. However, model biases in the total FAC and marked regional differences highlight the need for~~FAC$_{tot}$ and other mismatches with our dataset urge~~ caution when using models to quantify the current and future FAC~~evolution of the firn air content~~ and firn retention capacity.

1. Introduction

As a consequence of the ~~anthropogenic carbon emissions and subsequent~~ atmospheric and oceanic warming associated with anthropogenic climate change, the Greenland ice sheet is losing mass at an accelerating rate. The ice sheet is now responsible for approximately~~, and contributes to about~~ 20% of contemporary sea-level rise (Bindoff et al., 2013; Nerem et al. 2018). Over half ~~of~~ this ice-sheet mass loss stems from summer surface melt and subsequent ~~occurring every summer at the surface of the ice sheet and~~ meltwater runoff into~~to~~ the ocean (van den Broeke et al., 2016). While most meltwater runoff originates from the low-elevation~~lying~~ ablation area, the surface melt area is now expanding~~has recently increased and expanded up-glacier~~ into the high-elevation firn-covered interior of the Greenland ice sheet (Mote et al. 2007;~~,~~ Nghiem et al., 2012). Rather than flowing horizontally~~Yet~~, most of the ~~surface~~ meltwater produced at the surface of the~~in~~ firn area~~-covered regions~~ percolates vertically into the underlying~~snow and~~ firn where it refreezes, and thereby does not ~~immediately~~ contribute to sea-level rise (Harper et al., 2012). Hence, the meltwater retention capacity of Greenland's firn is a non-trivial parameter in the sea-level budget.

Assessing meltwater retention ~~the retention~~ capacity of the firn in Greenland requires knowledge of both the extent of the firn area, as well as the spatial distribution of depth-integrated firn porosity or firn air content (FAC). The extent of the firn area~~area of the Greenland ice sheet constitutes a key parameter in sea-level equation.~~

~~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". Recently, Fausto et al. (2018a) updated the methods from Fausto et al. (2007) and presented maps of remotely ~~-~~sensed end-of-summer snowlines over the 2000-2017 period. These maps effectively provide an annual delineation of Greenland's firn area. ~~that can be used to map the firn area.~~

~~A second key characteristic for the retention of meltwater is the firn air content (FAC). The~~ FAC is the integrated volume of air contained within~~in~~ the firn from the surface to a certain depth per unit area (van Angelen et al., 2013~~2012~~; Ligtenberg et al., 2018). FAC quantifies ~~It is a measure of the firn porosity and indicative, for a specified depth range, of~~ the maximum pore volume available per unit area to retain~~store~~ percolating meltwater, either in liquid or refrozen form (Harper et al., 2012; van Angelen et al. 2013). Previously, ice-sheet wide firn ~~2012). While the role of FAC in meltwater~~ retention capacity

Formatted: Normal

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

has long been estimated usingrecognized, insufficient data from the firn area in Greenland made it necessary, until lately, to use simplifying assumptions (e.g. Pfeffer et al., 1991) or unconstrained unvalidated outputs from regional climate model (RCM) simulations (, van Angelen et al., 2013).) to constrain the firn's meltwater retention capacity. Harper et al.., (2012) providedgave a first empiricalobservation based estimate of the firn's meltwaterthis retention capacity inof the ice- -sheet percolation area using two years . Their approach was limited by the use of observations from two years (2007 and 2008) atand 15 sites inalong the western Greenland. While pioneering, their approach did not acknowledge the slope of the ice sheet without regards to the diversity of firn characteristics across the ice sheet's diverse firn regimes (sheet (e.g. Forster et al. 2014; Machguth et al., 2016). More recently, Ligtenberg et al. (2018) provided ana RCM simulation of the FAC that generally compares which compared well against observations in 62 firn cores, but substantially. Nevertheless, their FAC simulation still underestimated FAC in the western lower accumulation area. Focusing on meltwater percolation area., Langen et al. (2017) also compared how the output of HIRHAM5 RCM compared against 75 firn density profiles while its FAC has not been investigated.

The depth to which meltwater may percolate, and therefore the depth range overto which FAC must be integratedcalculated to constrain the firn's meltwater retention capacity, varies with melt intensity and firn permeability (e.g. Pfeffer et al., 1991). This makes the maximum depth of meltwater percolation both temporally and spatially variable, as highlighted by the following studies. Braithwaite et al. (1994) and Heilig et al. (2018) reported meltwater refreezing within the top 4 m of the firn in western Greenland respectively at ~1500 m a.s.l. during summer 1991 andwhile Heilig et al. (2018) did not observe meltwater percolation below 2.3 m from the surface throughout 2016 melt season, at 2120 m a.s.l. during the 2016 melt season.also in west Greenland. Both studies indicate that, at specific sites and years, meltwater is stored inonly the near-surface FAC. was being used to store meltwater. However, firn temperature measurements in 2007-2009 ~400 km to the north and at 1555 m a.s.l. in west Greenland (., Humphrey et al., 2012) as well as the presence of firn aquifer at depth greater than 10 m in southeast Greenland (Miège et al., 2016) both show that meltwater can percolate below 10 m depth in the firn. This deep . (2012) observed percolation impliesbelow 10 m, meaning that, for certain firn conditionstemperature and stratigraphy and given sufficient surface meltwater, the FAC of the totalwhole firn column, from the surface to the firn-ice transition, maypore close-off depth, might be used for meltwater retention. FinallyNevertheless, Machguth et al. (2016) showshowed that percolation depth may not increase linearly with meltwater production, and insteadthat low-permeability ice layers can limit meltwater, even if abundant meltwater, from percolating intoaccessing the entirefull firn column. Given the complexity of meltwater percolation and the paucity oflimited observations to map percolation observationsdepth on the Greenland ice sheet, reasonable upper and lower bounds of the meltwater retentionfirn's capacity of firn can be estimated by determining both the FAC throughin the top 10 m of firn (FAC_{10}) and the total firn columnFAC (FAC_{tot}) and within the uppermost 10 m of firn column (FAC_{10}), respectively (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; Simonsen et al. 2013;, Kuipers Munneke et al. 2015a).

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

In this study, we first compile a dataset~~estimate the firn area extent using remotely-sensed end-of-summer snow extent maps from Fausto et al. (2018a). We then use a set~~ of 360 firn observations, collected between 1953 and 2017, and quantify the observed FAC. We then extrapolate these point-scale observations across the entire ice-sheet firn area as empirical functions of long-term mean air temperature and mean snow accumulation. The point observations are thereby used to resolves the spatial distribution of FAC, but also,~~ to calculate the spatial distribution of FAC_{10} and~~ where possible,~~ present~~ its temporal evolution. We use a~~A~~ simple extrapolation ~~is introduced~~ to estimate ~~the~~ FAC_{tot} from FAC_{10} where firn cores do not extend to the firn-ice transition. Spatial integration of~~the FAC_{10}. By spatially integrating~~ FAC_{10} and FAC_{tot} over the firn area permits estimating~~, we calculate the~~ lower and upper bounds, respectively, of the Greenland firn's meltwater~~firn~~ retention capacity. Finally, we evaluate the FAC simulated by ~~performance of firn simulations in~~ three ~~regional climate models (~~RCMs, that are~~),~~ commonly used to evaluate ice-sheet wide firn meltwater retention capacity, but that have never been compared to ~~validated with~~ such extensive firn dataset~~data collection~~.

2. Data and methods

2.1. Firn core dataset and firn area delineation

We compiled 340 previously~~gathered 324~~ published Greenland ice-sheet firn-density profiles of ~~from cores that were~~ at least 5 m in depth~~long~~ (Table 1). To these, we added an additional~~add~~ 20 cores extracted in ~~April-May~~ 2016 and 2017, for which firn~~the~~ density was measured at 10 cm resolution following the same procedure as Machguth et al. (2016~~(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 centimetre~~cm~~ and interpolated~~interpolate~~ over the remaining gaps in density profiles 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	Morris and Wingham (2014)	66
Clausen et al. (1988)	8	Mosley-Thompson et al. (2001)	47

Formatted: Normal

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted Table

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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

Formatted: Normal

We~~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 detected during~~, which are~~ the 2000-2017 period. This 1 ~~,~~405 ~~,~~500 km^2 area, where snow is always detected during the 2000-2017 period, is taken to represent the ice sheet's current firn area.~~,~~ Moving this firn line 1 km inward or outward, ~~(~~the resolution of the product from Fausto et al. (2018a), suggests~~)) suggest~~ an uncertainty of ±17 ~~,~~250 km^2 (~1%). Additional~~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 inherent~~likely~~ thinness of firn at the ~~accumulation area~~ lower elevation boundary of the firn area, we expect these omitted firn patches to~~the boundary does not~~ play a negligible role in the overall meltwater retention capacity of the firn area.

2.2. Calculation of FAC_{10}

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

For a discrete density profile composed of N sections and reaching a depth z, the FAC in meters~~m~~ is calculated as:

$$FAC_z = \sum_{k=1}^{N} m_k \left(\frac{1}{\rho_k} - \frac{1}{\rho_{ice}}\right) \quad [1]$$

where, for each depth interval k, ρ_k is the firn density and m_k is the firn mass. ρ_{ice} is the density of the ice, assumed ~~set~~ to be 917 kg/m^3.

With 121 cores shorter than 10 m in our dataset, we extrapolate shallow measurements to a depth of 10 m. We do this by finding the longer than 10 m ~~long~~ core that best matches the FAC-versus-~~vs.~~ depth profile of the shorter than 10 m~~shallow~~ core, with the lowest root mean squared difference~~Root Mean Squared Difference~~ (RMSD) amongst all available cores. We then,~~, and~~ append the bottom section of this longer than 10 m~~'twin'~~ core to the FAC profile of the shorter than 10 m~~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 an~~a~~ RMSD of 0.15 m.

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

We assess the~~The~~ accuracy of the firn density measurements, 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 standard deviation below 0.15 m is found in the majority of the co-located and contemporaneous FAC_{10} observations (20 of 27 groups of comparable observations). We correspondingly assign ~~to FAC_{10} measurements~~ an uncertainty of ±0.3 m, ~~i.e.,~~ twice this~~the~~ standard deviation, to FAC_{10} measurements.

2.3. Zonation of firn air content

The FAC_{10} is calculated from ~~the~~ firn density, which depends, among other parameters, on the local near-surface air temperature and snowfall rate (Shumskii, 1964). Air~~The site's air~~ temperature is a proxy for summer melt and subsequent refreezing within the firn, as well as firn temperature and compaction rates. Through these processes, increasing air temperature acts to decrease FAC (Kuipers Munneke et al., 2015b).~~has a lowering effect on FAC_{10}.~~ On the other hand, snow accumulation introduces low-density~~porous~~ fresh snow at the surface. Increasing snowfall thus acts to increase FAC~~ and has an increasing effect on FAC_{10}~~. To put our FAC_{10} measurements in their climatic context, we extract the long-term (1979-2014) average annual net snow accumulation $\bar{\dot{c}}$ ~~$\bar{\dot{b}}$~~ (snowfall – sublimation) and air temperature $\overline{T_a}$ for each FAC_{10} measurement location from the nearest 5 km^2 cell of~~in~~ the Modèle Atmosphérique Régional (MARv3.5.2; Fettweis et al., 2017). ~~) available at 5 × 5 km horizontal resolution.~~

Following~~In accordance with~~ the terminology of~~from~~ Benson (1962), we define three regions where FAC_{10} shows distinct regimes~~behaviour~~: (1) the dry snow area (DSA, yellow area in Figure 1a); (2) the low accumulation percolation~~wet snow~~ area (LAPA~~LAWSA~~, red area in Figure 1a); (3) the high accumulation percolation~~wet snow~~ area (HAPA~~HAWSA~~, green area in Figure 1a). The DSA encompasses low temperature regions of high altitude and/or latitude where melt is uncommon and where FAC_{10} can be related by a linear function of $\overline{T_a}$ (yellow markers in Figure 1c). Two distinct firn regimes emerge towards~~Towards~~ higher $\overline{T_a}$, meaning~~i.e. at~~ lower altitude and/or latitude.~~, two patterns are visible in Figure 1c.~~ Firstly, towards~~at~~ lower $\bar{\dot{c}}$, ~~$\bar{\dot{b}}$ sites,~~ in the LAPA~~LAWSA~~, more scatter appears in FAC_{10}~~,~~ and the~~a~~ slope of~~change occurs in~~ the FAC_{10}~~FAC_{10}'s~~ temperature dependency changes.~~(Figure 1c).~~ Secondly, towards~~at~~ higher $\bar{\dot{c}}$, ~~$\bar{\dot{b}}$ (~~in the HAPA,~~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 HAPA~~HAWSA~~ are up to five times higher than at locations with similar $\overline{T_a}$ in the LAPA~~LAWSA~~ (Figure 1c).

The boundary that delineates ~~between~~ the cold (DSA) and warm regions (LAPA~~LAWSA~~ and HAPA~~HAWSA~~) can be defined as the temperature where an inflection occurs in the linear dependency of FAC_{10} on~~to~~ $\overline{T_a}$ (Figure 1c). We interpret the slope break in the temperature dependence of FAC_{10} as the upper limit of frequent meltwater percolation and refreezing within the firn which Benson et al. (1962) defined as the dry snow line. While the ~~The~~ transition between cold and warm

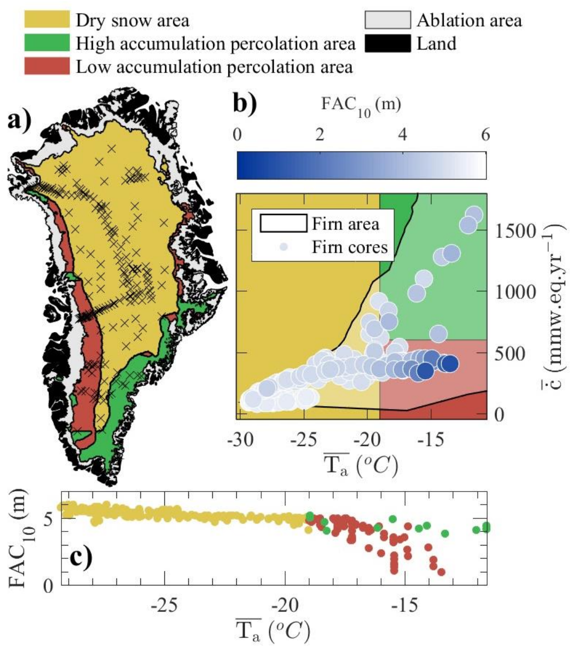
Formatted: Normal

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

areasareas, just as between the facies described by Benson et al. (1962), is gradual in practice,, but for our analysis, we set this boundary to $\overline{T_a}$ = -19 °C. Our LAPA and HAPA here stretch from the dry snow line to the firn line and therefore also include the so-called wet snow facies defined by Benson et al. (1962). The snowfall boundary that delineates the low and high accumulation percolation areas°C. No firn observation is more difficult to characterize. There are insufficient firn observations available alongin the transition from LAPAthe LAWSA to HAPA. The snowfallthe HAWSA. A boundary could be anywhere between 543 mm w.eq. ./yr^{-1} (the (core with highest accumulation LAPA corein the LAWSA, Figure 1b) and 647650 mm w.eq. yr^{-1} (thecore with lowest accumulation HAPA corein HAWSA, Figure 1b). Acknowledging this uncertainty, we We chose the roundrounded value of $\bar{c}\bar{b}$ = 600 mm w.eq. yr^{-1} to separate LAPA and HAPA.LAWSA from HAWSA. The spatial delineations of the DSA, LAPALAWSA and HAPAHAWSA are illustrated in Figure 1a.



Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

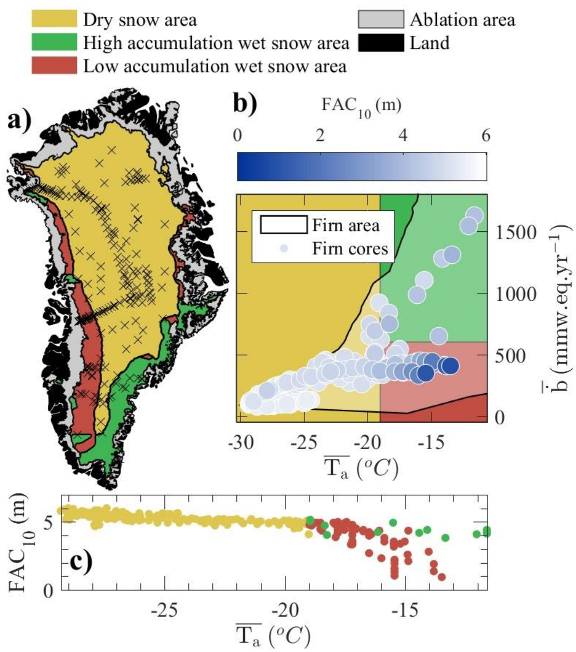


Figure 1. a) Spatial distribution of the FAC_{10} dataset. The DSA, HAPA~~LAWSA~~ and LAPA~~HAWSA~~ are indicated respectively using yellow, green and red areas. b) Distribution of the dataset in the accumulation-temperature space (~~$\bar{c}$~~$\bar{b}$ and $\overline{T_a}$). FAC_{10} value is indicated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

2.4. FAC_{10} interpolation

To interpolate point-scale observations of~~Firn air content mapping~~

~~To map~~ FAC_{10} over the entire ice-sheet firn area, we describe FAC_{10} observations using~~fit~~ empirical functions of long-term mean air temperature ~~to the FAC_{10} observations~~ and net snowfall.~~use these functions to spatially interpolate and extrapolate FAC_{10}.~~ The derivation~~construction~~ of these empirical functions is described in the following sections and an overview of their general form as well as the~~and their associated~~ data used to constrain them are~~is~~ presented in Table 2.

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

Area	Period	Form	Observations used for fitting

Formatted: Normal

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Normal, Space After: 10 pt, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font color: Black

Formatted Table

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

DSA & upper HAPA	1953 - 2017	Linear function of $\overline{T_a}$ (Eq. 2)	259 from the DSA 19~~11~~ from the HAPA~~HAWSA~~
LAPA & HAPA~~LAWSA~~ ~~& HAWSA~~	2010 - 2017	• Smoothed bilinear function of $\overline{T_a}$ and $\bar{c}$ ~~$\bar{b}$~~. • Cannot exceed the FAC$_{10}$~~FAC~~ estimated with Eq. 2.	25 from the LAPA~~LAWSA~~ 10 from the HAPA~~HAWSA~~ 6 selected from firn line in the HAPA~~HAWSA~~
LAPA~~LAWSA~~	1998 - 2008		38 from the LAPA~~LAWSA~~ 1 from the HAPA~~HAWSA~~ 6 selected from the firn line in the HAPA~~HAWSA~~

2.4.1. Dry snow area

~~**Dry Snow Area**~~

In the DSA, the 259 FAC$_{10}$ observations obtained between 1953 and 2017 can be approximated by a linear function of ~~depend linearly on~~ their local $\overline{T_a}$ (Figure 1c). This dependency is the same for the 19~~11~~ FAC$_{10}$ observations from the upper HAPA available between 1981 and 2014.~~HAWSA.~~ We consequently include these observations so that~~use a linear function of $\overline{T_a}$ fitted using least squares method to~~ the linear relationship remains valid in the upper HAPA (Section 2.4.2). These 278 FAC$_{10}$ observations are then~~observed in both DSA and HAWSA (Figure 2a)~~ binned into four equal $\overline{T_a}$ ranges ~~(~~to avoid the overrepresentation of clustered data (Figure 2a). Eventually, a linear function of $\overline{T_a}$ is fitted to the bins' average FAC$_{10}$ using least squares method to ~~) to~~ estimate the FAC$_{10}$ in the DSA:

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

We assign to any FAC$_{10}$ estimated in the DSA using Eq. 2 an uncertainty equal to twice the regression's RMSD: 0.4 m. Although FAC$_{10}$ is also dependant on $\bar{c}$, the residuals from Eq. 2 do not present any correlation with their respective $\bar{c}$ values. It indicates that because of the intrinsic co-variability of $\bar{c}$ and $\overline{T_a}$, most of the variations in observed FAC$_{10}$ can be explained using either $\bar{c}$ or $\overline{T_a}$. Insufficient data are available to disambiguate the role of $\bar{c}$ and $\overline{T_a}$ in FAC$_{10}$ variations in the DSA. We therefore choose to use only $\overline{T_a}$ in Eq. 2.

Formatted: Normal

Formatted: Indent: Left: -0,78 cm, Hanging: 1,28 cm, Outline numbered + Level: 1 + Numbering Style: Bullet + Aligned at: 0,65 cm + Indent at: 1,28 cm

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Auto

Formatted: Indent: Left: 0,07 cm, Hanging: 0,25 cm, Outline numbered + Level: 1 + Numbering Style: Bullet + Aligned at: 0,65 cm + Indent at: 1,28 cm

Formatted: Indent: Left: 0,07 cm, Hanging: 0,25 cm, Outline numbered + Level: 1 + Numbering Style: Bullet + Aligned at: 0,65 cm + Indent at: 1,28 cm

Formatted: Indent: Left: -0,78 cm, Hanging: 1,28 cm, Outline numbered + Level: 1 + Numbering Style: Bullet + Aligned at: 0,65 cm + Indent at: 1,28 cm

Formatted: Font color: Auto

Formatted: Outline numbered + Level: 3 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 2 cm + Indent at: 2,89 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

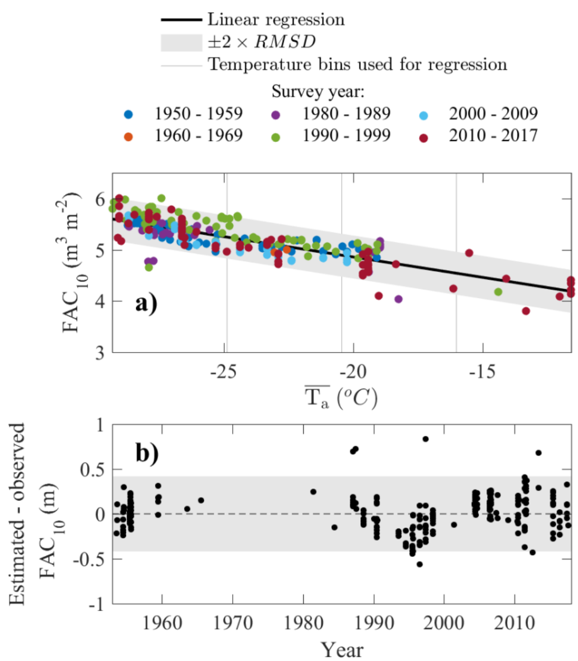


Figure 2. a) Linear function of $\overline{T_a}$ fitted to FAC_{10} observations from the DSA and upper HAPA. b) Residual between estimated (using linear regression) and observed FAC_{10} as a function of survey year.

2.4.2. Percolation areas

~~**Wet Snow Areas**~~

In the LAPA~~LAWSA~~ and in the HAPA~~HAWSA~~, FAC_{10} observations exhibit a more complex dependency on $\bar{c}$~~to $\bar{b}$~~ and $\overline{T_a}$ (Figure 1b and 1c). Additionally, observations are unevenly distributed in space and time. Thus ~~which forces us~~ to reveal the temporal trends in~~group~~ FAC_{10}, the observation dataset is divided ~~measurements~~ into two time ~~-~~slices that each 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 LAPA, stretching~~LAWSA,~~ from the upper boundary of~~transition with~~ the LAPA~~DSA~~ down to the vicinity of the firn line. During that same period, 10 firn cores were collected in

Formatted: Normal

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Normal, Space After: 10 pt

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Font: 9 pt, Bold

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

the HAPA~~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 how the FAC_{10} decreases in parts of the HAPA~~HAWSA~~ closer to the firn line. We consequently complement these firn cores with 6 sites, selected on the remotely ~~-~~sensed firn line, where FAC_{10} is assumed to be null (Figure S3). FAC_{10}

~~We define our empirical function, valid~~ in the LAPA~~LAWSA~~ and HAPA during~~HAWSA for the~~ 2010-2017 is then described by~~period, as~~ a smoothed bilinear function of $\overline{T_a}$ and $\bar{c}$ ~~$\bar{\dot{b}}$~~ 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 upper HAPA (Eq. 2)~~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~~.

Prior to~~In the years preceding~~ 2010, insufficient data are available to document the FAC_{10} in the HAPA~~HAWSA~~. In the LAPA~~LAWSA~~, however, 35~~34~~ observations were made between 2006 and 2008 and three cores were collected in 1998. These~~We group these~~ measurements are used to describe the ~~spatial distribution of~~ FAC_{10} in LAPA~~the LAWSA~~ during the 1998-2008 period by a ~~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 $\bar{c}$. ~~$\bar{\dot{b}}$.~~ To ensure that our empirical function has realistic values towards the transition with the HAPA~~HAWSA~~, we also include one core collected in the HAPA~~HAWSA~~ in 1998. We also include ~~and~~ the previously described six locations from the firn line ~~in the fitting process~~ (Figure 3a). Although observation locations in 1998-2008 and 2010-2017 can be different, few samples available at the same sites (e.g. Crawford Point, Dye-2) in both time slices ensure that FAC_{10} changes are more likely due to a temporal evolution rather than from the different spatial coverage of each period's constraining dataset.

The empirical functions used to estimate the FAC_{10} in the LAPA and HAPA (Figure 3), when compared to FAC_{10} observations, have a RMSD of 0.28 m in the LAPA over the 1998-2008 period, 0.27 m in the LAPA over the 2010-2017 period and 0.17 m in the HAPA over the 2010-2017 period.

We investigate the robustness of our empirical functions in the HAPA~~HAWSA~~ and LAPA~~LAWSA~~ using, for each period separately, the following sensitivity analysis. For 1000 repetitions, we apply four types of perturbations to the FAC_{10} observations and then re-fit our empirical functions.~~function to this perturbed dataset.~~ The effect of the availability of measurements in the LAPA~~LAWSA~~ is tested by randomly excluding four observations in that region (~~respectively~~ 16% and 11% of ~~the~~ observations in ~~1998-2008 and~~ 2010-2017 and 1998-2008, respectively).~~).~~ The effect of uncertainty in the firn line location in the $(\overline{T_a}, \bar{c})$ ~~$(\overline{T_a}, \bar{\dot{b}})$~~ 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

Formatted: Normal

Formatted: Font: 10 pt, Not Bold, Font color: Auto

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

firn line is assessed by assigning to ~~the points selected from the~~ firn~~-~~-line-derived points 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. Following 1000 repetitions of the above-mentioned four perturbations to the FAC_{10} observations, we then ~~We then~~ calculate the standard deviation of all empirically~~possible~~ estimated FAC_{10} values within the~~at each~~ $(\overline{T_a}, \bar{\dot{c}})$ parameter space. We then ~~$\left(\overline{T_a}, \bar{\dot{b}}\right)$ location and~~ double this standard deviation to approximate~~it to quantify~~ the 95% ~~envelope of~~ uncertainty envelope for empirically~~that applies to any~~ estimated FAC_{10} in the LAPA and HAPA.~~LAWSA and HAWSA depending on $\left(\overline{T_a}, \bar{\dot{b}}\right)$.~~ We do not consider that the uncertainty applying on an estimated FAC_{10} can be smaller than the one of FAC_{10} observations. We consequently set 0.3 m as the minimum possible uncertainty on any estimated FAC_{10}.

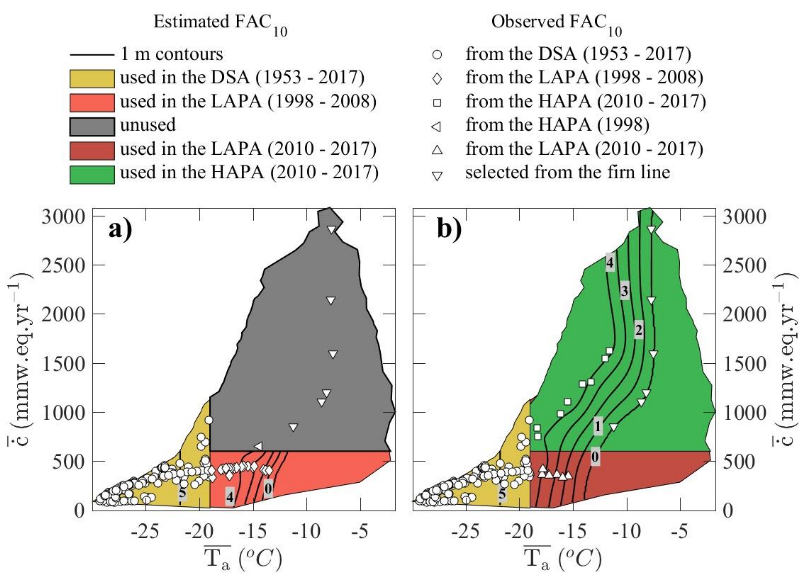


Figure 3. Contours (labelled black lines) of the empirical functions of $\overline{T_a}$ and $\bar{\dot{c}}$ used to estimate FAC_{10} along with the FAC_{10} observations used to constrain the functions. Two functions could be constructed: (a) describing FAC_{10} in the LAPA during 1998-2008 and (b) describing FAC_{10} in the LAPA and HAPA during 2010-2017.

2.5. Estimation of ~~the~~ FAC_{tot}

~~While~~ FAC_{tot} should~~may~~ be integrated~~calculated~~ from the ice-sheet surface down to the~~pore close-off~~ depth where firn reaches the density of ice (Ligtenberg et al., 2018). This depth varies in space and time across the ice sheet but is poorly

Formatted: Normal

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Font color: Black

Formatted: Normal, Space After: 12 pt, Line spacing: Double, Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

documented. Additionally, the RCM ~~), to allow comparison with~~ HIRHAM5 (evaluated in Section 3.3) does~~which sometimes do~~ not reach ice density at the bottom of its column in certain locations. We therefore ~~pore close off, we~~ calculate FAC_{tot} as the vertically integrate FAC from the surface to a standard 100 m depth. Only 29 of our 360 firn observations reach depths greater than 100 m. We therefore ~~, so we~~ complement these core observations with~~them by~~ 13 ground-penetrating radar observations of FAC_{tot} from Harper et al. (2012).Using the least squares method with an intercept of zero, we fit the following linear regression between FAC_{10} and FAC_{tot} (Figure 4):

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

This function infers~~)~~ that FAC_{tot} is approximately 410% FAC_{10}. While we acknowledge this relation is straightforward, we highlight that it is statistically robust. We assign 3.6 m, twice the RMSD of the linear regression, as the typical uncertainty applying on an estimated FAC_{tot} value that can in theory vary between 0 and ~25 m.

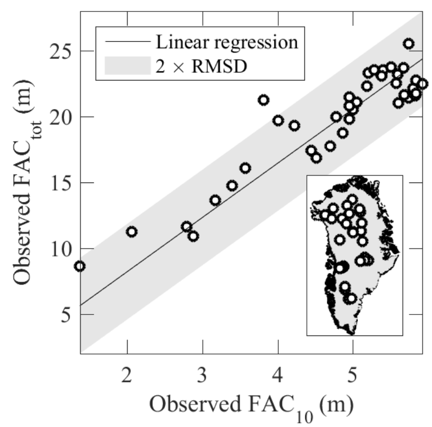


Figure 4. Linear regression ~~at their core sites from ground-penetrating radar. A linear function is fitted to these data and is~~ **used to estimate FAC_{tot} from~~at the rest of our~~ FAC_{10}** ~~observation sites~~.

As a result of deriving FAC_{tot} as a function of FAC_{10} (Eq. 3), any change in FAC_{10} between two dates implies a proportional 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). We therefore note that for a decreasing FAC_{10} (see Section 3.2.1), our estimated change in FAC_{tot} corresponds to the maximum possible change associated with the whole firn column having sufficient time to adapt to the new surface conditions.

2.6. Spatially integrated FAC ~~, uncertainty~~ and retention capacity

We define, for any ice-sheet~~For each~~ region, the spatially integrated FAC as~~is~~ the cumulated~~sum of the entire firn air~~ volume of air~~either~~ within that region either in the top 10 m of firn or for~~in~~ the total~~whole~~ firn column (top 100 m). ~~.~~ The uncertainty

Formatted: Normal

Formatted: Superscript

Formatted: Space After: 10 pt, Line spacing: single

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

associated with the empiricallyapplying on our estimated FAC_{10} and FAC_{tot} at a given location are not cannot be considered independent from other locations because all estimates are made using the same functions of $\overline{T_a}$ and $\bar{\dot{c}}$ are applied across the ice sheet.and $\bar{\dot{b}}$. Consequently, we consider that the uncertainty of the mean of several FAC in a specific regionvalues is the mean of FACeach value's uncertainty values therein and that the uncertainty of spatially integrateda sum or difference of FAC values is the sum of the uncertainty applying on these FAC values in the considered region.

We useFrom the estimated FAC to, we calculate the meltwater firn's maximum retention capacity of the firn., which Harper et al. (2012) defined the firn retention capacity 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 firn saturated by refrozen meltwater measured in firn coresinfiltration ice.

2.7. Comparison with Regional Climate Models

We compare our FAC_{10}FAC observations and spatially integrated FAC estimatesmaps to the available firn products available from three RCMs: HIRHAM5, RACMO2.3p2 and MARv3.9. HIRHAM5 output is available at 5.5 km spatial resolution and isThe two versions of HIRHAM5 presented in Langen et al. (2017). Two versions of HIRHAM5) 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. (2018), provides FAC at a 5.5 km resolution.(2019). MARv3.9 iswas presented in Fettweis et al. (2017), only) and simulates only FAC_{10} because of its shallowa shallower subsurface domain and has a spatial resolution of 15 km..

3. Results and discussionDiscussion

FAC estimation

3.1.1.1.1.1. Dry snow area

3.1. Spatio-temporal distribution of FAC

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

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

weWe 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 unchanging the stability of the FAC_{10} in that areathe DSA between 1953 and 2017. This inference of widespreadThe stable FAC in the DSA is confirmed at point scale by firn cores in our dataset taken decades

Formatted: Normal

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Outline numbered + Level: 3 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 2 cm + Indent at: 2,89 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

apart at the same sites but decades apart,and showing the same FAC (Summit, Camp Century, e.g.). This result is also corroborated.) and by recent firn modelling at weather stations located in the DSA (Vandecrux et al. 2018).

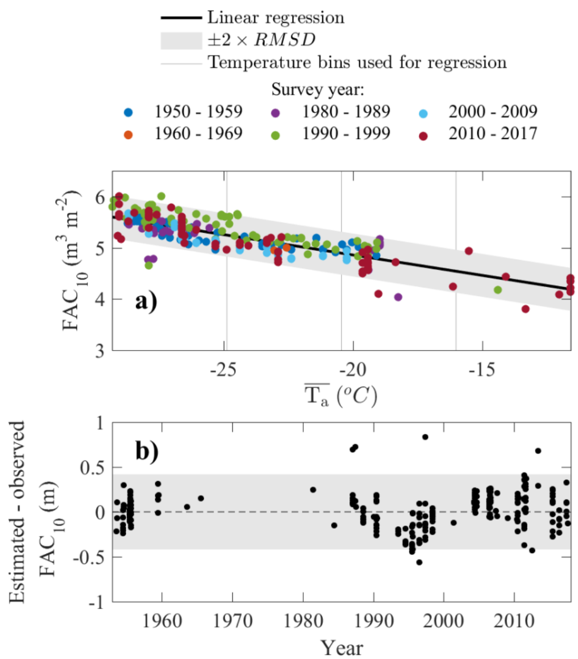


Figure 2. a) Linear function of $\overline{T_a}$ fitted to FAC_{10} observations from the DSA and HAWSA. **b) Residual between estimated (using linear regression) and observed FAC_{10} as a function of survey year.**

Wet snow areas

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 1998-2008 period, 0.27 m in the LAWSA over the 2010-2017 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 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).

Formatted: Normal

Formatted: Font: 9 pt, Bold

Formatted: Font: 9 pt, Bold

Formatted: Normal, Space After: 10 pt

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Font: 9 pt, Bold

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

Formatted: Normal

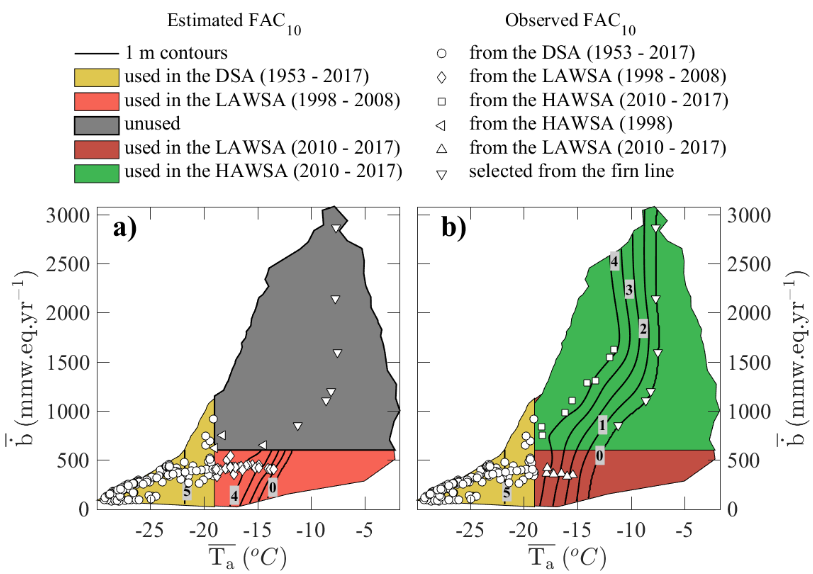


Figure 3. Contours (labelled black lines) of the empirical functions of $\overline{T_a}$ and $\bar{\dot{b}}$ used to estimate FAC_{10} along with the FAC_{10} observations used to constrain the functions. **Two functions could be constructed: one describing FAC_{10} in the LAWSA during 1998-2008 (a)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

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} greater than 20 m but up to 100% of the estimated FAC_{tot} at the firn line.

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

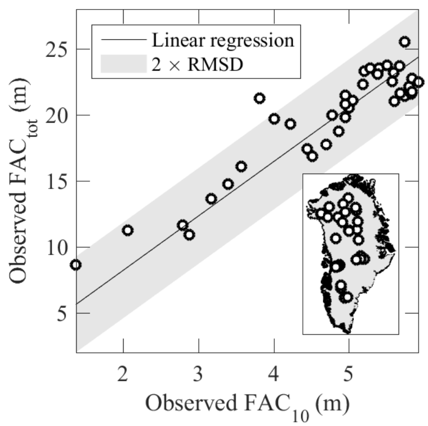


Figure 4. Linear regression used to estimate FAC$_{tot}$ from FAC$_{10}$. Linear regression was fitted using the least squares method with a prescribed intercept of zero.

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.

Spatio-temporal distribution of firn air content

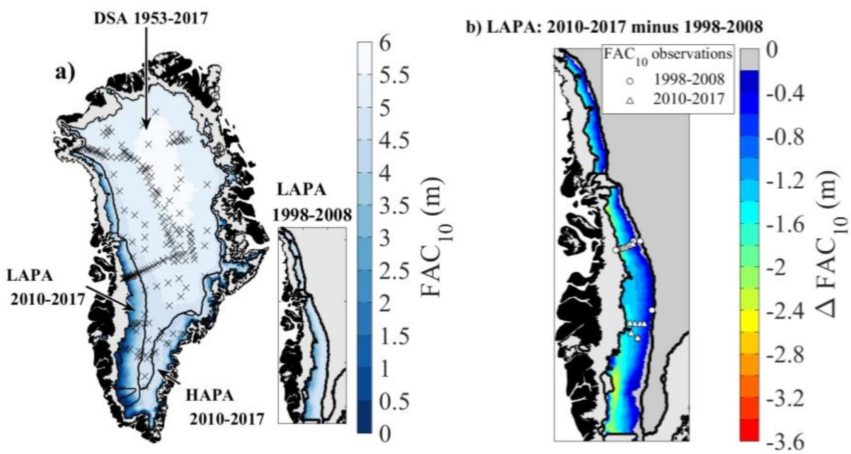
FAC$_{10}$ mapping

Using the 5x5 km $\overline{T_a}$ and $\bar{c}\bar{b}$ 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 maps we calculate an average FAC$_{10}$ of 5.2 1± 0.3 m in the DSA over the 1953-2017 period and of 3., an average FAC$_{10}$ of 2.6 ± 0 ± 0.4.5 m in the HAPAHAWSA during the 2010-2017 period. Within the LAPA, we calculate and an average FAC$_{10}$ of 3.94 ± 0.3 m in the LAWSA during the 1998-2008 period, which decreasesdecreased by 2335 % to 3.02.6 ± 0.3 m byin the 2010-2017 period. Spatially, theThe FAC$_{10}$ loss in the LAPALAWSA is concentrated in a 60 km wide band above the firn line in western Greenland (Figure 5b6).

Formatted: Normal

Formatted: Font color: Black

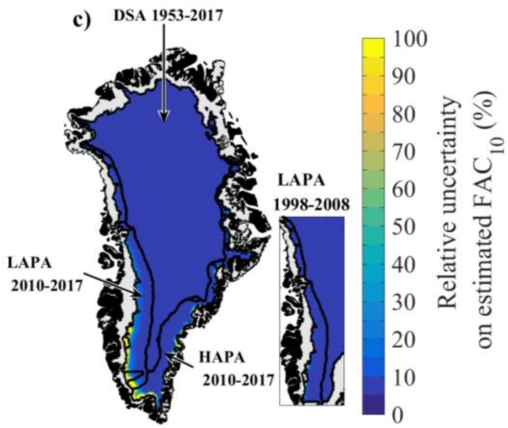
Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right



Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right



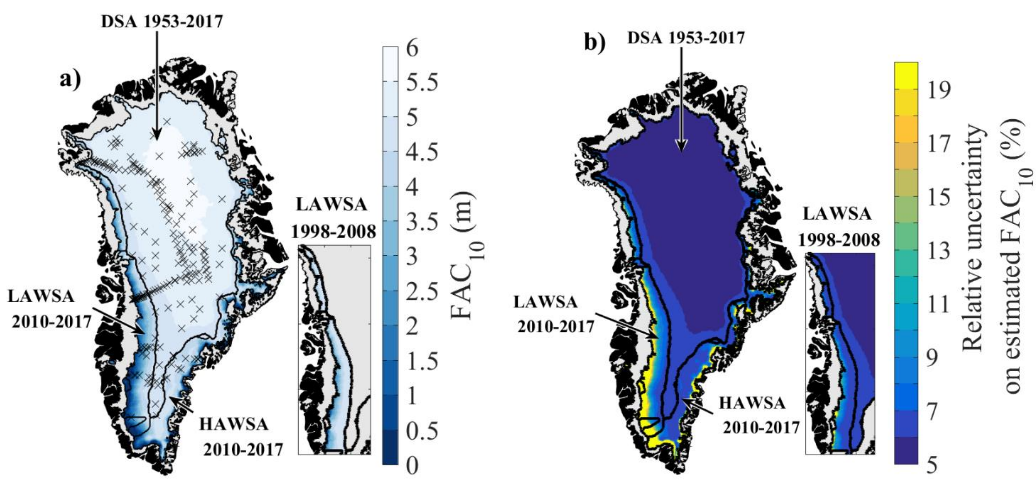


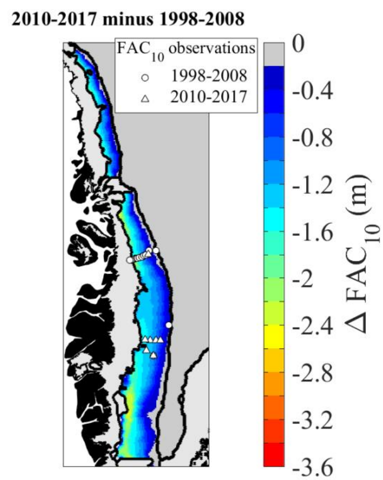
Figure 5. a) FAC$_{10}$ maps and location of the FAC$_{10}$ measurements. b)~~b) Maps of the relative uncertainty of the FAC$_{10}$ map.~~

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

Formatted: Normal



~~Figure 6.~~ Change in FAC_{10} between 1998-2008 and 2010-2017 in the LAPA. c) Maps of the relative uncertainty of the FAC_{10} map~~LAWSA~~.

Formatted: Font color: Auto

~~**Spatially integrated FAC**~~

We find that during the 2010-2017 period, the entire firn area contained~~contains~~ 6 500 ± 450 -km^3 of air content within~~in~~ the top 10 m and potentially up to 26 800 ± 1 840~~850~~ km^3 within~~if~~ the whole firn column ~~is accounted for~~ (Table 3). About 83 ± 5% of this air content is contained in the DSA, which represents 74% of the firn area. The HAPA, covering~~HAWSA, which covers~~ 12% of the firn area, contains ~~about~~ 8 ± 1% of ice-sheet wide firn ~~the firn's~~ air content, both for~~independently of whether we consider~~ the top 10 m and~~10m or at~~ the whole~~entire~~ firn column~~layer~~.

Table 3. Spatially integrated FAC~~FAC_{10}~~ and firn retention capacity~~FAC_{tot}~~ over each ice sheet region.

Area	Period	Spatially integrated FAC (km^3): Upper 10 m~~FAC_{10}~~	Spatially integrated FAC (km^3): ~~FAC_{tot}~~ Total firn column	Firn storage capacity (Gt): Upper 10 m	Firn storage capacity (Gt): Total firn column
DSA	1953 – 2017	5 400 ± 310	22 300 ± 1 280	4 200 ± 290	12 800 ± 1 170
LAPA ~~LAWSA~~	1998 – 2008	750 ± 60	3 100 ± 240~~250~~	550 ± 50	1 490 ± 220

Formatted Table
Formatted: Font color: Auto
Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)
Formatted: Font color: Auto
Formatted: Font color: Black
Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

LAPA LAW SA	2010 – 2017	580570	±	60	2 400	±	250	400	±	50	950	±	220
HAPA HAW SA	2010 – 2017	530	±	80	2 200	±	320330	370	±	70	960	±	290
All	2010 – 2017	6 500	±	450	26 800	±	1 840850	5 000	±	410	14 700	±	1 600

The LAPA, which In the LAWSA, that comprises 14 % of the firn area, contained 9 ± 1% of ice-sheet wide firn air content in the period 2010-2017. Decreasingdecreasing FAC_{10} between 1998-2008 and 2010-2017 yieldslead to a loss of 170180 ± 120 km^3 (23 ± 16%) of air from the top 10 m of firn. The corresponding , equivalent to 24 ± 16% of the 1998-2008 spatially integrated FAC_{10}. The subsequent decrease in FAC_{tot} indicatesindicate that potentiallythe whole firn column lost up to 700 ± 490500 km^3 of air may have been lost from the total firn column. In this we assume that the FAC_{10} decrease propagated to the entire firn column (see Section 2.5), which might not be accurate. Insufficient data are available to determine precisely how much FAC was lost below 10 m and we can only give a hypothetical upper bound to the FAC_{tot} decrease.

Recent studies have identified increasing surface melt and meltwater refreezing as major contributors to increasing 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). However, firn density and FAC are also dependentdependant on annual snowfall, with decreasing and a decrease in snowfall driving increasingcan drive an increase in firn density and decreasing FACconsequently a decrease in FAC_{10} (e.g. Vandecrux et al., 2018). Nevertheless, the lack of widely distributed observation of snow accumulation for the 1998-2017 period and the contradicting trends in precipitation calculatedoutput by the RCMs (Lucas-Picher et al., 2012; van den Broeke et al., 2016; Fettweis et al., 2017) complicate the partitioning ofmake it impossible to precisely partition the melt and snowfall contributions to changes in FACFAC_{10} at ice sheet scale.

Effect of the $\bar{\dot{b}}$ and $\overline{T_a}$ data source FAC_{10} maps

To investigate how uncertainties in $\overline{T_a}$ and $\bar{\dot{c}}$ $\bar{\dot{b}}$ impact our FAC_{10} maps, we repeat our procedure using the 1979-2014 $\overline{T_a}$ and $\bar{\dot{c}}$ $\bar{\dot{b}}$ estimated by Box (2013) and Box et al. (2013) (hereafter referred to as "Box13Box"). The Box13Box-derived FAC_{10} fits equally well (within measurements uncertainty, RMSD < 0.3 m) to the FAC_{10} observations, leading and lead to spatially integrated FAC values within uncertainty offrom the MAR-derived values. (Table 3).

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

However, due to differing model formulations and atmospheric forcings~~forcing~~, the spatial patterns of air temperature and snowfall are different between Box13~~Box~~ and MARv3.5~~9~~.2 (detailed in Fettweis et al. 2017), especially in the southern and eastern regions of the firn area. This~~, which~~ leads to different estimations of FAC_{10} in these regions (Figure S4). Additionally, in these regions no firn observations are available to constrain our FAC_{10} estimates. More observations in the sparsely observed southern and eastern regions would ~~therefore not only~~ improve FAC_{10} estimates and help better~~, but also~~ elucidate which $\overline{T_a}$ and $\bar{c}$ ~~$\bar{b}$~~ source best describes the spatial pattern in FAC_{10}.

~~3.3.~~3.2. Firn retention capacity

The ~~Between 1998-2008 and 2010-2017, the~~ decrease in FAC_{10} in the LAPA between 1998-2008 and 2010-2017 translates to ~~LAWSA indicates~~ a loss in meltwater retention capacity of 150 ± 100 Gt in the top 10 m of firn (Table 3). This is equivalent to a potential sea-level drawdown of~~, 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 total~~entire~~ firn column, we estimate an associated upper bound ~~a~~ loss of ~~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 (171 ± 157 Gt yr^{-1} for 1991–2015 in van den Broeke, 2016~~(~270 Gt/y~~), the impact of reduced retention capacity has an important time-integrated effect, in amplifying meltwater runoff each year. This amplification can be non-linear as when, for instance, ~~, especially in~~ a succession ~~of~~ anomalously high melt years and reduced firn permeability resulted in an abrupt~~as was the case 2007-2012, resulting in a sharp~~ increase in western Greenland runoff in 2012 (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.~~

Harper et al. (2012), using observations from 2007-2009, estimated that ~~the firn located in a~~ 150 000 km^2 of firn residing within the lower percolation area (as delineated in an earlier version of MAR) could potentially store between 322 ± 44 Gt of meltwater in the top 10 m of firn and 1 289 $^{+388}_{-252}$ Gt within~~if considering~~ the entire firn column. We note that the Harper et al. (2012) estimate is based solely on observations in the LAPA, while 68% of the percolation area to which they extrapolate is located in the HAPA. By contrast, we find that the warmest 150 000 km^2 of our firn area in 2010-2017 can retain only 150

Formatted: Normal

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted: Font: Bold

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

± 6667 Gt of meltwater in the top 10 m of the firn. We estimateWhen considering the whole firn layer we find a total storage capacity of 310 ± 270 Gt within the whole firn column in this part of the firn area. Our relatively low estimate of the Gt associated with an uncertainty of 688 Gt. Our lower estimated retention capacity might reflectreflects the recent decrease of FAC in the LAPA but also, for the values derived from FAC_{tot}, our simplifying assumption that this decrease has propagated through the whole firn column (Section 2.5). Yet, beyond these integrated values, our approach allows to quantify 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 corresponding uncertainty at any location of the firn area. Our product can therefore be used in combination with, for instance, remotely sensed melt extent to derive which areas of the firn actively retain meltwater and evaluate the retention capacity there.

Weone of Harper et al. (2012) use the same infiltration ice density as Harper et al. (2012),, 843 ± 36 kg m^{-3} as determined from, which was measured in portions of firn core segmentscores saturated by refrozen meltwater. HoweverIn a later study also in western Greenland, Machguth et al. (2016) measured with similar technique an infiltration ice density of 873 ± 25 kg m^{-3} in western Greenland.. Using the latter 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 remainsremained within the uncertainty intervals of our uncertainty intervals first estimations (Table 34). Additional field measurements arewill be needed to ascertain the spatial and temporal dependence of infiltration ice density on, 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 aquifersaquifer (Forster et al. 2014). Nevertheless, recent work in southeastSoutheast 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). Meltwater On the contrary, the water refrozen within the firn can beis potentially retained for much longer periods,centuries until it is discharged atthrough a marine--terminating outlet glacier or reaches the surface ofin 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.

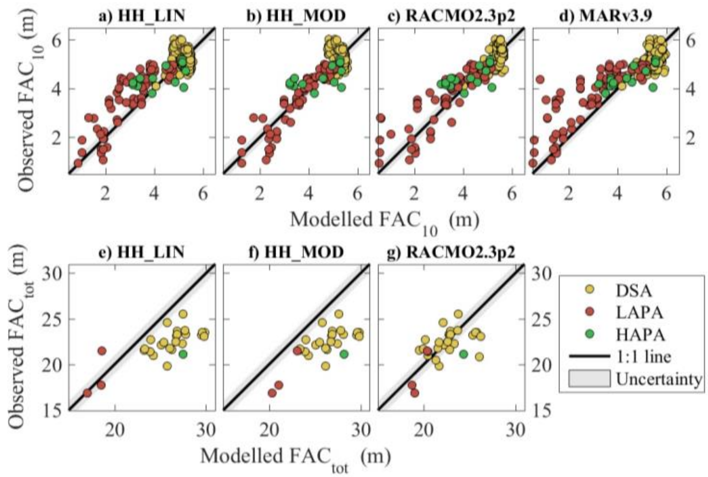
Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

~~3.4.~~3.3. Regional Climate Model evaluation~~performance~~

~~3.4.1.~~3.3.1. Comparison with ~~the~~ FAC observations~~dataset~~



Formatted: Normal

Formatted: Outline numbered + Level: 2 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,76 cm

Formatted: Outline numbered + Level: 3 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 2 cm + Indent at: 2,89 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

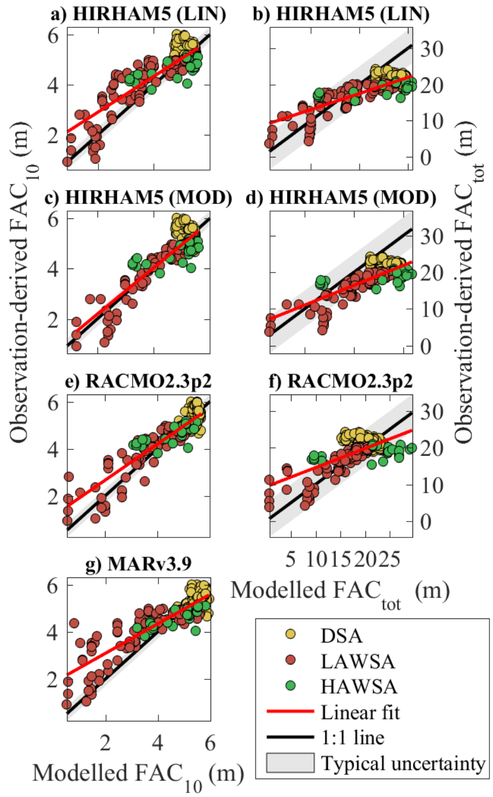


Figure 67. Comparison between the observed observation-derived FAC_{10} and FAC_{tot} and the simulated FAC in the corresponding cellscell of three RCMs.

All models reproduce the FAC_{10} observations in the DSA and HAPAHAWSA with bias -≤ 0.2 m and, RMSD ≤ 0.46 m (Figure 6, Table 5). Nevertheless, RACMO2.3p2, MARv3.9.2, and HH_LIN tend to underestimate the FAC_{10} in the LAPA,LAWSA while HH_MOD doesdid not show a pronouncedany bias therein that area. The RCMs all present a greater biases and RMSD less than 12%regarding FAC_{tot} reflect both the performance of the mean FAC_{10} for our entire dataset. The RCMs are RCM but also evaluated against the 29 directly observed FAC_{tot} (Figure 6, Table 5). Both versions of HIRHAM5 overestimatethe greater uncertainty applying on our observation-derived FAC_{tot} in the DSA (bias > 3 m), while RACMO2.3p2 performs better in that area (bias = 0.1, RMSD = 1.8). HH_LIN . Overall we find that HH_MOD is the best candidate to simulate FAC_{10} and RACMO2.3p2 compare relatively well with the threeto simulate FAC_{tot} observations

Formatted: Normal

Formatted: Font: 9 pt, Bold

Formatted: Normal, Space After: 10 pt, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font: 9 pt, Bold, Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

available in the LAPA, while HH_MOD presents a larger positive bias. These three FAC_{tot} observations are located in the upper LAPA and therefore not including regions where RCMs underestimate FAC_{10}. All models overestimate the only FAC_{tot} observation available in the HAPA by more than 3 m. Compared to all FAC_{tot} measurements, RACMO2.3p2 gives a RMSD equivalent to 9% of the mean observed . Nonetheless, it appears that none of the RCMs can simultaneously FAC_{tot} when HIRHAM5's RMSD reaches 20% with HH_MOD. None of the RCMs therefore 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} in terms of bias (. Bias is the average difference between model and observations) and observation. RMSD stands for Root Mean Squared Difference (RMSD).Error. Intercept and slopes are calculated from the linear fit between simulated and observed FAC (red line in Figure 7).

		DSA		LAPALA WSA		HAPAHA WSA		All firn areaGrIS				
	RCM	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Bias (m)	RMSD (m)	Intercept (m)	Slope (-)	
	N_{obs}	259		82		19		360				
FAC_{10}	HH_LIN	-0.014	0.4	-0.53	0.87	0.1	0.6	-0.2	0.6	1.5	0.7	
	HH_MOD	-0.014	0.4	0.1	0.4	0.2	0.6	0.0	0.4	0.4	0.9	
	RACMO2.3p2	0.1	0.3	-0.32	0.6	0.0	0.5	0.0	0.5	1.1	0.8	
	MARv3.9.2	0.2	0.3	-0.63	1.0.9	0.2	0.5	0.0	0.6	0.01.8	0.6	
	N_{obs}	25		3		1		29				
FAC_{tot}	HH_LIN	3.76.4	47.1	1.02.7	35.3	5.6	8.3	4.9	6.46	-8.6	30.4	4.1
	HH_MOD	6.5	7.2	5.3.8	4.16.2	3.7.0	8.9	46.1	7.10	-5.6	3.90.5	4.3

Formatted: Normal
Formatted: Font color: Auto
Formatted: Space After: 10 pt, Line spacing: single, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)
Formatted: Font: 9 pt, Bold, Font color: Black
Formatted: Font: 9 pt, Bold, Font color: Black
Formatted: Normal, Space After: 10 pt, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)
Formatted: Font: 9 pt, Bold, Font color: Black
Formatted: Font color: Black
Formatted Table
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single
Formatted: Font color: Black
Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

RACMO2.3p2	-0.14	1.83.3	-0.3	3. 1. 0	12.6	6.2	-0.1	3. 3 6	-	0 9 . 4	1.9 0.5

3.4.2.3.3.2. Comparison with the spatially integrated FAC

Agreement between RCM-simulated and observation-derived spatially integrated FAC is model- and region-dependent (Figure 7). RCMs simulate a spatially integrated FAC$_{10}$ within the uncertainty of our observation-derived estimation in the DSA. Models also show lower spatially integrated FAC$_{10}$ in the LAPA and higher values in the HAPA compared to our estimate (Figure 7b-d). These regional differences cancel out when spatially integrating FAC$_{10}$ over the entire firn area (Figure 7a). Our estimation of spatially integrated FAC$_{tot}$ is subject to more assumptions as uncertainty is introduced in our conversion of FAC$_{10}$ to 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.

FAC$_{tot}$ (Section 2.5). In the DSA, HH_MOD simulates a spatially integrated FAC$_{tot}$ 20% higher than our estimation while RACMO2.3p2 simulates spatially integrated FAC$_{tot}$ within our uncertainty range (Figure 7e). In the LAPA, the decrease in spatially integrated FAC$_{tot}$ is more pronounced in our estimate than in the RCMs. This might indicate that, in the RCMs, the FAC loss is concentrated in the near-surface firn and has not yet propagated through the entire firn column. Our estimate assumes that any change in FAC$_{10}$ immediately propagates to the entire firn pack (see Section 2.5). In the HAPA, RCMs show higher spatially integrated FAC$_{tot}$ values than our estimate (Figure 7h), contributing to the higher spatially integrated FAC$_{tot}$ across the entire firn area in the RCMs compared to our estimation (Figure 7e). This is partly due to the fact that in our estimation, FAC decrease with elevation and is set to zero at the firn line. In the RMCs, modelled FAC remains higher than our estimate in the lower HAPA and in the vicinity of the firn line. No FAC observations are available in the lower HAPA to confirm this. Future measurements will help to quantify FAC in the surrounding of the firn line, allowing to better evaluate our assumptions and further assess the RCMs' performance in that area.

Formatted: Normal

Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single

Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single

Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single

Formatted: Right, Indent: Left: 0,18 cm, Line spacing: single

Formatted: Outline numbered + Level: 3 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 2 cm + Indent at: 2,89 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

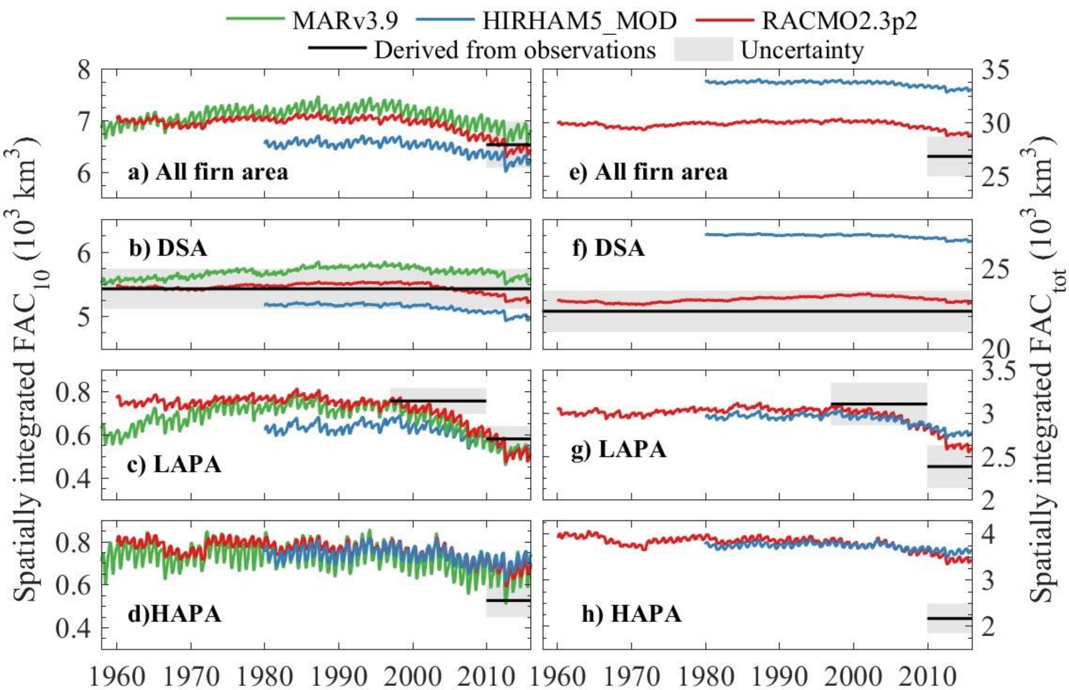


Figure 7. Spatially integrated FAC in the RCMs and from observation-derived estimates.

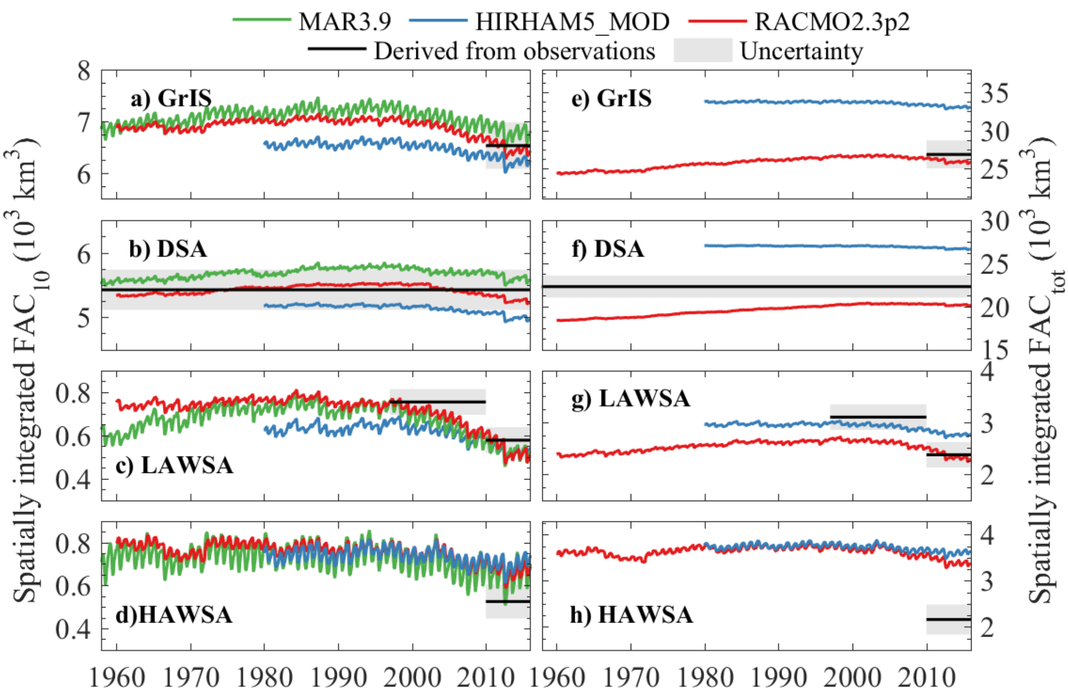
The differences between RCM outputs may stem from their respective surface forcings. As an illustration, HH_MOD uses a higher albedo than HH_LIN, thus ~~and therefore~~ calculates less surface melt and refreezing and, as a consequence, higher FAC_{10} in the LAPA. Noël et al. (2018) found that the ~~LAWSA. 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 in the accumulation area was on average slightly lower than observations,~~(Noël et al. 2018),~~ indicating excessive sublimation or runoff~~melt~~ relative to snowfall in the model. This surface bias ~~,~~ could ~~also~~ explain the model's underestimation of FAC_{10} in the LAPA at point scale (Figure 6, Table 5) and on spatially integrated values (Figure 7). On the other hand, ~~LAWSA. Counterintuitively, HH_MOD, HH_LIN and~~ MARv3.9 has slight positive biases in surface mass balance compared to observations (Fettweis et al. 2017). And although the RCM simulates ~~.2 have in common a slight positive bias SMB (~~too much precipitation relative to melt, it~~)~~ ~~but~~ also underestimates~~underestimate~~ FAC_{10} in the LAPA. Surface forcing is therefore not the only factor influencing the FAC estimates by the RCMs~~LAWSA~~.

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

Differences in RCM-simulated FAC_{10} can also be explained by the~~The~~ way firn densification is treated in the snow model of each RCM. For instance, the overestimation of FAC_{tot} in the DSA by ~~models can also explain differences in simulated FAC_{10}:~~ HIRHAM5 potentially arises from~~and MARv3.9.2 uses~~ the use of a firn ~~same snow~~ compaction law originally developed for seasonal snow ~~scheme~~ (Vionnet et al.~~,~~, 2012). RACMO2.3p2~~) 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, most likely~~potentially~~ because the densification law it uses has been tuned to match~~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 deep firn density observations (Kuipers Munneke et al., 2015a). It is nevertheless difficult to disentangle the roles of surface forcing and model formulation in the performance of RCMs. ~~**Temporal evolution of the FAC in the RCMs compared to the observation-derived FAC_{10} maps**~~.

Formatted: Normal

Formatted: Space After: 0 pt, Line spacing: 1,5 lines

Formatted: Font: 10 pt, Not Bold

Formatted: Font: 10 pt, Not Bold

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

In agreement with our observation-derived ~~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$_{10}$ estimates, the RCMs calculate a ~~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 LAPA (Figure 7c) initiating~~LAWSA as observed (Figure 8b). The RCMs indicate that this loss of air content was initiated~~ in the early 2000s and accelerated during the extreme summers of ~~in~~ 2010 and 2012. In the DSA, RCMs show a FAC$_{10}$ decrease ranging from -120 km^3 in MARv3.9 to -282 km^3 in RACMO2.3p2 between 1998 and 2017. These decreases contradict with our conclusion that FAC has not changed significantly~~All RCMs show a decreasing FAC$_{10}$~~ in the DSA over that period (~~the last two decades which contradicts with our observations (~~Section 3.1). The different FAC$_{10}$ dynamics in our dataset and in RCMs~~.1, Figure 2). This decreasing FAC$_{10}$~~ could be due to: i) the RCMs not capturing~~RCM missing for example~~ an increase of snowfall in the DSA which could in theory counterbalance the densification expected from~~would compensate~~ the recent warming ~~seen~~ in the firn area (McGrath et al., 2014); ii) an overestimated response~~; Graeter et al., 2018). Another possibility would be that the models overestimate the sensitivity~~ of firn compaction rates~~rate~~ to increasing temperatures in the models; iii) the spatial heterogeneity and uncertainty of FAC observations leading to spurious conclusions from our dataset. Yet, finding identical firn density profiles decades apart at several sites (e.g. Summit, Camp Century) adds confidence to our findings.

4. Conclusions

Using a~~A~~ collection of 360 firn density profiles spanning 65 years we quantified~~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 $\bar{c}$). For ~~$\bar{b}$). During~~ the 2010-2017 period~~,~~ we calculate that the Greenland firn ~~layer~~ contained 26 800 ± 1 840 km^3 of air, of which 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~~Dry Snow Area~~ (DSA, where $\overline{T_a}$ ≤ -19°C). We note that the vast majority of the ice sheet's FAC (83 ± 5 %) resides within the DSA, and represents a potential meltwater storage volume of 12 800 ± 1 170 Gt.~~≤ -19°C).~~ In the low accumulation percolation area (LAPA~~Low Accumulation Wet Snow Area (LAWSA~~, where $\overline{T_a}$ > -19°C~~19°C~~ and $\bar{c}$ ~~$\bar{b}$~~ ≤ 600 mm w.eq. yr~~-~~1), we calculate that the FAC decreased by 23 ± ~~24 ±~~16 % between 1998-2008 and 2010-2017. This decrease~~decreased FAC$_{10}$~~ translates into the loss of

Formatted: Normal

Formatted: Not Superscript/ Subscript

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Not Superscript/ Subscript

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

meltwater retention capacity of 150 ± 100 Gt (0.4 ± 0.3 mm sea level equivalent) in the top 10 m~~10m~~ of the firn and potentially up to 540 ± 450 Gt (1.5 ± 1.2 mm sea level equivalent) in the entire vertical extent of the firn layer. This decreased FAC and meltwater retention capacity is focused in the lower accumulation area of central western Greenland. Thus, in contrast to the relative stability of the DSA, the LAPA is the focal area of the firn's response to recent climate change.~~firn layer.~~ The firn in the high accumulation percolation area (LAPA, where $\overline{T_a}$ > -19°C and $\bar{\dot{c}}$ > 600 mm w.eq. yr-1) has the capacity to store 370 ± 70 Gt in its top 10 m and up to 960 ± 290 Gt in its entire vertical extent. Yet, this area is covered by fewer observations and would highly benefit from future field surveys.

The outputs~~output~~ from three regional climate models (HIRHAM5, RACMO2.3p2 and MARv3~~MAR3~~.9~~.5~~) indicate that our calculated decrease in FAC may have been initiated in the early 2000's and accelerated after~~in~~ 2010. The RCMs also provide estimates of FAC in regions where no measurements are available.~~ and 2012.~~ But the mismatch between RCMs and our firn core dataset illustrates~~reminds~~ that RCMs should be used with caution when assessing meltwater~~used to calculate the firn~~ retention capacity, or when converting ~~the~~ ice sheet~~sheet's~~ volume changes into mass changes in the firn area.~~.~~ Finally, our study highlights the importance of assimilating in situ firn density measurements to document the climate response~~evolution~~ of~~ the Greenland~~ ice~~-~~sheet firn as a non-trivial component of the ~~and to improve models and~~ sea~~-~~level budget. More broadly, this work illustrates~~projections. We also illustrate~~ how new insight~~knowledge~~ can be gleaned~~gained~~ from the synthesis of historical~~multiple~~ data sources, and thus emphasizes the tremendous value of open-access data within~~ and encourage~~ the scientific community.~~ to make both recent and historical data available.~~

5. Acknowledgement

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). The~~ FirnCover~~ field campaigns were funded by the NASA grant NNX15AC62G in collaboration with the Greenland Analogue Project (GAP).~~.~~ Achim Heilig was supported by DFG grant HE 7501/1-1. We thank Hubertus Fischer from the Department of ~~(~~Climate and Environmental Physics at~~,~~ University of Bern (Switzerland),~~)~~ 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.

Formatted: Normal

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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.

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, D.: A new programme for monitoring the mass loss of the Greenland ice sheet, Geol. Surv. Denmark Greenland Bull., 15, 61-64, pdf, 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.

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

Bader, H.: Sorge's law of densificationdensication of snow on high polar glaciers, J. of Glaciol. , 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, 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

Formatted: Normal

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Outline numbered + Level: 1 + Numbering Style: 1, 2, 3, … + Start at: 1 + Alignment: Left + Aligned at: 0 cm + Indent at: 0,63 cm

Formatted: Font color: Auto

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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, 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, 2013.

Box, J., Cressie, N., Bromwich, D. H., Jung, J.-H., van den Broeke, M. R., van Angelen, J.,Forster, R.R., Miège, C., Mosley-Thompson, E., Vinther, B., 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, 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.

Charalampidis, C., Van As, D., Box, J. E., van den Broeke, M. R., Colgan, W. 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, 2015.

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.

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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. 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, 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.: 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.

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.

Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., 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, 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.

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Indent: Left: 0 cm, Hanging: 1,27 cm, Space After: 12 pt, Line spacing: Double, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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 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, 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, 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, 2012.

Hawley, R. L., Courville, Z. R., Kehrl, L., Lutz, E., Osterberg~~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, 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, 2018.

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, 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.

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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, 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, 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, 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.

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, 2012.

Formatted: Normal

Formatted: Default Paragraph Font

Field Code Changed

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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, 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, 2016a2016.

Mayewski, P., and Whitlow S.: Snow Pit Data from Greenland Summit, 1989 to 1993. NSF Arctic Data Center. https://doi.org/10.5065/D6NP22KX, 2016b2016.

McGrath, D., Colgan, W., Bayou, N., Muto, A. and Steffen, K.. Recent warming at Summit, Greenland: Global context and implications. Geophys. Res. Lett. 40, 2091-2096, https://doi.org/10.1002/grl.50456, 2013.

Miège, C., Forster R.R., BoxC., B. J.E., 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, 2013.

Miège, C., Forster, R.R., Brucker,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.

L., Koenig, L.S., Solomon, D.K., Paden, J.D., Box, J.E., Burgess, E.W., Miller, J.Z., McNerney, L. and Brautigam, N.: Spatial extent and temporal variability of Greenland firn aquifers detected by ground and airborne radars. J. Geophys. Res.-Earth, 121, 12, 2381-2398, https://doi.org/10.1002/2016JF003869, 2016.

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

Formatted: Normal

Formatted: Font color: Auto

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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 Greenland iceGreenlandice sheet from PARCA cores, J. Geophys. Res., 106, 33839–33851, https://doi.org/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, 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.

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, 2014.

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

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

Formatted: Normal

Formatted: Font: 10 pt

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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.

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, 2011.

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.

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, 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.

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right

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.! 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, 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, 2001.

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

Formatted: Normal

Formatted: Font color: Black

Formatted: Normal, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border), Tab stops: 7,96 cm, Centered + 15,92 cm, Right