Review of: Vandecrux et al., Brief communication: Firn data compilation reveals the evolution of the firn air content on the Greenland ice sheet, The Cryosphere 172, https://doi.org/10.5194/tc-2018-172, 2018.

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Introduction

In this paper authors describe the pore space in the upper 10 m of snow and firn (= Firn Air Content or FAC10) of the Greenland Ice Sheet. They specifically focus on quantification of:

- spatial extent of firn,

- spatial distribution of the FAC10 values and

- temporal dynamics of the FAC10.

The pore space can accommodate a certain amount of liquid water which would, otherwise, almost immediately contribute to surface or subglacial runoff and reach the ocean. Firn layer can thus moderate the response of runoff rate to the changes in water supply rates at the surface. Accurate estimation of the FAC is important for understanding of the feedbacks to be expected from the Greenland Ice Sheet to a changing climate, both in the past and in the future.

The FAC10 estimate is based on a comprehensive compilation of subsurface density profiles measured in cores and published either earlier or for the first time in the present manuscript. The FAC10 values derived from individual cores are inter- and extrapolated for the entire firn area (derived using AWS and MODIS remote sensing data) using functions of the mean annual air temperature (Ta) and net surface accumulation (bn). Different approaches are used for three climatological domains defined in terms of Ta and bn. This is a novel approach providing an alternative to FAC estimates derived using multi layered models describing subsurface processes such as IMAU-FDM, CROCUS and SNOWPACK. Apart from its inherent simplicity another obvious advantage of the approach is a more direct use of empirical data from firn cores to constrain the FAC estimate. This, however, comes at the expense of the versatility and detalisation provided by the layered models. The approach can be applied elsewhere as similar data is available for other glaciated areas.

General comments

Physical geography.

Authors use the mean annual air temperature and net surface accumulation as arguments in functions describing the spatial distribution of FAC10. The functions are fitted to minimize the misfit with empirical estimates of FAC10 from cores. One important

thing that is missing in the text is a detailed description of the physical (or may be practical) motivation for the choice of the above mentioned arguments.

Both characteristics (net annual surface accumulation and mean annual air temperature) integrate the effects of processes occurring during the cold and warm parts of a year. Net annual surface accumulation is the result of mass accumulation in winter and surface melt in summer. While the first one can be expected to be positively linked with FAC (more accumulation in winter -> more pores), the second one can be expected to be negatively linked with FAC (more melt -> thinner snow layer by the end of summer with less pores, more water available for refreezing). Mean annual air temperature can be also separated in two parts: temperature in winter and in summer. The principal difference between the two is the likely range of values: significantly negative in winter and close to melt point in summer. High winter temperatures can be expected to result in a lesser cold content of the subsurface profile, leading to a less active refreezing during consecutive summer and larger FAC values. Air temperature during the warm part of a year is commonly used as a proxy for melt rate (e. g. Ohmura, 2001). High air temperatures in summer lead to faster melt and larger potential for refreezing as there is more water available with the effect of smaller FAC values.

As noted above the melt rate (as a contribution to the net annual accumulation) and air temperature in summer (as a contribution to the mean annual air temperature) are closely correlated and probably interchangeable for the purposes of FAC parameterization. There are, thus, 3 proxies left: precipitation rate, winter air temperature and summer air temperature (or melt rate). Along with gravitational settling liquid water refreezing is one of the two contributors to the density increase over time. It can be limited by one of the three parameters: availability of liquid water, pore space or cold content. Subsurface temperature and density, defining the FAC, are heavily dependent on the relation between the three parameters.

In the course of a temporal or spatial transition towards a warmer climate, air temperature increases. The associated rise in melt rates will deliver more water. Depending on whether the potential of pore space or cold content will be exhausted first, two different scenarios can be applied to a subfreezing firn profile: transition towards superimposed ice nourishment or development of a warm firn pack, possibly, with perennial firn aquifers in case runoff is impeded. This is exactly what happens in Greenland and what the authors of the manuscript, probably, attempted to reproduce by introducing three different domains: DSA, LAWSA and HAWSA.

The above presented logic goes back to the theory of glacier zones presented in (Shumskii 1955). English translation was published in 1964 (see ch. 18 and 20). Definitions of glacier zones are also given in Cogley et al. (2011). One can also address the project report Marchenko (2012) and the phd thesis (2018) for a detailed description of the logic and Braithwaite et al. (1994) of some aspect thereof. The approach was applied by Pfeffer et al. (1991, see appendix there) and Janssens and Huybrechts, (2000) for

estimating refreezing rates in Greenland. The idea of geographical patterns in Greenland firn pack development was recently expressed by Michael MacFerrin the his PhD thesis (see ch. 5.2.3), perhaps, worth citing in ch. 2.4 along with the other above published sources.

One option is to use the three above mentioned parameters as arguments in functions for extrapolating and interpolating observed FAC values. That could be precipitation rate and mean temperatures during summer and winter months. The latter two can be replaced by either the annual sums of positive and negative degree-days or mean annual temperature and some continentality index. It is also possible that precipitation expresses continentality to some extent with higher values associated with more maritime climates. It is impossible to say without testing, but it may be possible to adequately describe the FAC10 values from cores around all of the Greenland ice sheet by a sum of three piecewise-linear functions of the earlier mentioned three parameters.

These were just some suggestions and authors are, of course, free to choose the logic used for FAC10 estimates. In any case choice of arguments used for the spatial distribution of the empirical FAC10 values has to be motivated.

<u>Comparing results with earlier published data</u>

I suggest a more extensive referencing of published FAC estimates for the Greenland Ice Sheet. There is, apparently, a considerable spread in values of both FAC10 and total FAC. This is noted in ch. 3.5 of the manuscript, but should, preferably, appear much earlier, already in the Introduction chapter. An overview of the published values would provide one important motivation point for undertaking this kind of studies. Furthermore, comparisons of results with published estimates could make an interesting discussion as the present study suggests an alternative approach to calculation of the firn air content.

For example, Ligtenberg at al. (2018) make a reference to the dataset containing results of simulations on which the publication is build - https://doi.org/10.1594/PANGAEA.884617. A rough calculation of the total FAC in Greenland gives the value of 26300 Gt (please see the code used for the exercise in the appendix of the review), That is 20 times more than value from Harper et al. (2012) referenced in ch. 3.5, p. 8, ln. 8 of the manuscript. Full simulation results are available from Ligtenberg et al. and FAC10 value can be also calculated. The earlier study by van Angelen et al. (2013) is not referenced at all. It would also be interesting to compare the FAC10 values presented in the manuscript with corresponding output from the subsurface component CROCUS of the regional climate model MAR, surface data from which is used in the manuscript. Steger et al. (2017) also have figures showing FAC estimates for different areas in Greenland derived using the another layered model – SNOWPACK.

Scale of the manuscript

One of the shortcomings of the manuscript is that the reader is forced to refer to supplementary material while going through the methods chapter. At the same time the suggested approach to deriving distributed FAC values is elegant, novel and promising.

In case authors decide to introduce a more extensive discussion based on comparison of the results with earlier published values and relocate the "methods" figure from the supplementary material (S3) to the main paper text, the paper can be reclassified to a "research article" instead of "brief communication", which it is now.

In case authors will prefer to keep the manuscript as "brief communication", the number of references has to be greatly reduced. The list of references now contains 55 entries, while only 20 are allowed for this type of manuscripts according to the The Cryosphere protocol (https://www.the-cryosphere.net/about/manuscript_types.html). I would also suggest to:

- transfer the table from the main manuscript to the supplement,
- reduce the number of panels in fig 2 and 3
- merge panes from fig 3 in fig. 2,
- add the "methods" figure in the main text.

Specific comments

N	address	Comment
1	Abstract	Include the estimate of the total FAC in Greenland in Gigatonns. The reader see the firn area, the absolute and relative values of FAC10 decrease in LAWSA, but both values would be more informative if the Gt estimate would be found somewhere not very far.
2	Ch. 1, p. 2, ln. 5-6	The phrase "for that depth range" seems to be out of place.
3	Ch. 1, p. 2, ln. 9-11	Add the quantitative estimates of FAC from Ligtenberg et al., 2018, van Angelen et al., 2013, Steger et al., 2017
4	Ch. 1, p. 2, ln. 12-21	Bring the sentence on deep water percolation evidences from Humphrey et al., 2012 earlier, so that it appears second in the paragraph. This will group together the evidences of shallow percolation from Machguth et al. (2016) and Heilig et al., (2018).
5	Ch. 1, p. 2, ln. 13	Heilig et al., (2018) had their installation at 2120 m asl, not at 2300 m.
6	Ch. 1, p. 2, ln. 23	How does this collection of core data relate to the data from Fausto et al., 2018 in Frontiers? They at least partly overlap, as is seen on the maps of core locations.
7	Ch. 2.2, p. 3, ln. 2	Same as above
8	Ch. 2.2., p. 3, ln. 3	"...as part of the FirnCover campaigns..." It is not obvious what is "FirnCover campaigns", are these field activities affiliated with a University or some other organization? Either a reference or a description of the routines applied in the field has to be given.
9	Ch. 2.2, p. 3	I encourage a more extensive use of density data. FAC values are secondary with respect to the density-depth profiles. • Instead of extrapolating FAC values from too shallow cores, one can extrapolate the density profiles. This will make it possible to include the description of the extrapolation technique (ch. 2.3, p. 3, ln. 15-19) in ch. 2,2, right after the first sentence, which seems more logical. • Describe the "upwards extrapolation" technique (the 315 kg m^-3 value) before describing how gap filling is done. • I guess that the data from all cores was resampled to a common grid. If yes, then what is the spacing between neighboring nodes? Do not let readers guess!)
10	Ch. 2.3, p. 3	I recommend more descriptive explanation of what FAC is. That also includes

		reformulation of equation [1]. A few tips: • Use references! FAC values were calculated earlier. • Express FAC values through porosity, which is a widely applies and more basic concept – that will make it more understandable for an unprepared reader • Use [m] for units! It is more straightforward than [m^2 m^-3] and more descriptive. • Using the threshold of 873 kg m^-3 for FAC calculation contradicts the very definition of FAC as firn AIR content and also the below stated scope of the manuscript (ch. 2.3., p. 3, ln. 13-14). I assume that authors prefer to avoid the discussion of permeability of firn to water, if this is the case, in has to be stated. The value from Machguth et al. (2016) is a result of study in western Greenland. In this manuscript geographical differences in the firn pack are one of the main points and using the value seems not logical. Ligtenberg et al. 2018 used the physically motivated value of pure ice density, 917 kg m^-3, in their FAC assessment for the entire Greenland. One can even argue that the value of 1000 kg m^-3 is valid: water fills all the pores and then expands, increasing the bulk volume. That is known as frost heave and is widely spread in permafrost areas. Pingos can be higher than 50 m suggesting that lifting 10 m of firn is well possible for frost heave action.
11	Ch. 2.3, p. 3, ln. 23	What is "sites" here? Is that 1*1 km spatial domains, or "clusters" with core data? It also remains not clear why are cores grouped according to the original publication? Would you not unite in one group cores that are close by (less than 1 km) but come from different publications?
12	Ch. 2.4, p. 4, ln. 1	"all locations": what is the grid spacing for FAC10 extra- and interpolation and, consequently, for bn and Ta?
13	Ch. 2.4, p. 4, ln. 10	The slope of FAC10 against Ta is not much different between HAWSA and DSA as it is evidenced by Fig. 1d.
14	Ch. 2.5.1., p. 4, ln. 28	What does the Arthern et al., 2010 model take as arguments?
15	Ch. 2.5.1., p. 5, ln. 2	Perhaps, a better place to describe the uncertainty quantification logic (UQ) for the DSA is here, not in ch. 3.2. At least for other domains UQ is described in ch. 2.5.
16	Ch. 2.5.2., p. 5, ln. 6	What is the spacing between Ta bins in the "decreasing piecewise-linear function"?

16	Ch. 2.5.2., p. 5, ln. 7	"to resolve the FAC10 distribution each year": is this expected at all? Reader likely does not expect that, since earlier in ch. 2.5.1. data from different years was lumped together.
17	Ch. 2.5.3., p. 5, ln. 25-27	From Fig. 1b it is obvious that Ta and bn are strongly correlated. It is most probable that this fact above and not the amount of measurements explains the poor correlation between bn and residuals of the air temperature fit. In other words, adding more data will, likely, not help.
18	Ch. 2.5.3., p. 6, ln. 5	Are any routines applied to ensure a smooth transition of the FAC10 model between HAWSA and DSA? Earlier in ch. 2.5.2. such a routine is described for LAWSA-DSA transition.
19	Ch. 3.1., p.6, ln. 13	"...average from 18 years of data" – comparing this with what is given in ch. 2.1. suggests that "average" is not a valid word here.
20	Ch. 3.1., p.6, ln. 15-16	"...we do not believe that..." is not a valid expression. The low significance of the FAC in patchy firn just above the equilibrium line can be motivated by its likely small thickness.
21	Ch. 3.2., p.6, ln. 22	"...absence of temporal trend...": it would have been good to show that in a figure.
22	Ch. 3.3., p.7, ln. 6	Where is 180 +-78 km^3 coming from? 690-520 =170... How is the uncertainty value of the difference (+-78) calculated?
23	Ch. 3.3., p.7, ln. 7-8	I assume that 150 +-68 Gt comes from multiplying 180 km^3 by the assumed ice density (843 kg m^-3) and dividing by the density of water (1000 kg m^-3). If that is the case, it needs to be explicitly said. This logic is in direct contradiction with the phrase "...if we assume that all the air content can be used to store meltwater...". Also see the comment n. 9 above.
24	Ch. 3.3., p.7, ln. 17-19	Perhaps, residuals of fits, widely used in this manuscript, could be of help here as well...? Are the differences between the empirical fit and FAC10 from cores drilled after high melt seasons in 2010 and 2012 show larger values than other cores?
25	Ch. 3.4., p. 7, ln. 25	An observation: the stated mean FAC10 value in HAWSA of 2.4 m seems rather low, when visually comparing panels b and c in Fig. 2. It is considerably lower than in LAWSA for both periods. Check the value!
26	Ch. 3.5, p. 8, ln. 5-11	As mentioned higher up a more extensive comparison of results of the manuscript with previously published FAC values is expected here. The fact that Harper et al., 2012 report Greenland-wide FAC10 value that is 17 times less than

		presented here deserves a wider discussion. It is claimed that their data had a lesser spatial coverage. But from that it does not follow that the FAC10 value should necessarily be less. Then again, results from van Angelen et al., 2013, Steger et al., 2017 and Ligtenberg et al., 2018 are of high relevance for the discussion. The authors are also using MAR data, which, most probably was run alongside with the subsurface model CROCUS. What FAC10 values does these simulation yield?
27	Ch. 3.7., p. 8, ln. 26	Who measured the FAC10 in 2006-2007?
28	Ch. 4, p. 9, ln. 16	"...21% decrease of FAC10...": in ch. 3.3, p. 7., ln. 2 an increase of 23% was reported
29	Ch. 4, p. 9, ln. 21-25	"FAC10 observations also indicated that meltwater may percolate deeper than 10 m from the surface making FAC10 insufficient to describe the retention capacity of the firn there.": is this a result of the present manuscript? "*In a similar way*, Machguth et al. (2016) showed that *under conditions not completely understood*, ice formation may prevent meltwater from accessing the entire top 10 m of firn.": there is no similarity between this statement and the preceding one, rather opposition. What conditions are not completely understood here? It looks like authors intend to say here that depending on the subsurface conditions (temperature, density, stratigraphy, water permeability, slope of the impermeable layers with respect to horizontal) a different fraction of the FAC may be effectively used for storing the melt water. So, FAC10 is good, but, perhaps, not good enough and more research is needed to close the question here...
30	Fig. 1	Few suggestions: • Panel a: It is possible to show not only the spatial but also the temporal distribution of the core data by color-coding the year individual cores were drilled. • Panel b: may be do not use white-centered markers. Use color shading right from the center and add a white border around for higher contrast with the background. Try a different color bar, white-blue for example: more intuitive and in larger contrast with the background. In the caption add description so that it is more obvious

		that the black line is the domain of the Greenland Ice Sheet firn area in the Ta-bn domain. • Panels c and d: combine the two panels and show LAWSA and HAWSA cores using different colors for the markers.
31	Fig. 2	It is possible to combine some panels. Panel a and panel c can be combined. Panel b (when considered together with c) and panel d essentially overlap. When the temporal difference is shown (panel d) the significance of panel b drops and, perhaps, the panel can be left out.
32	Fig. 3	Combine panels a and c
33	Fig. S3	3D graphs give a poor representation of the 3D reality. Try contour plots for the fitted surfaces with contour lines color-coded in the same fashion as empirical markers – FAC10 value. Or may be try 2D plots with one parameter on the horizontal and FAC10 on the vertical axis. Several sets of fit curves plus empirical FAC10 values for different ranges of bn will give an understanding of how the fit relates to empirical data.

Technical corrections

N	address	Comment
1	Literature list	Distinguish between Fausto at al. 2018 in Frontiers (6) and in Geol. Surv. Denmark Greenland Bull. (41) by introducing ”a” and ”b” in the year of publication. Ambiguity in interpretation of short references along the text is now possible as it is (Fausto at al. 2018) in both cases.
2	p. 1, ln. 35	“...contribute to THE sea-level rise...”
3	p. 2, ln. 3	“...end-of-summer snowlineS but did...”
4	p. 2, ln. 4	”simple” is not a valid term here
5	p. 2, ln. 8	“...in spite of the diversity *of firn structures* across the ice sheet...”: replace italic by “in characteristics/properties of the firn profile”
6	p. 2, ln. 23	We then calculate the FAC10 using a set of 344 firn cores collected between 1953 and 2017. We finally present the spatial distribution and where possible the temporal evolution of FAC10. Rephrased: Using a set of 344 firn cores collected between 1953 and 2017 we calculate the spatially distributed FAC10 and where possible present the its temporal evolution.
7	p. 2, ln. 29	Rephrase: “Using these data, we *determine* the firn area, *defined* as the region where only snow has been detected during the entire 2000-2017 period.”
8	Ch. 2.2., p. 3, ln. 3	”...as part of the FirnCover campaigns...” It is not obvious what is “FirnCover campaigns”, are these field activities affiliated with a University or some other organization? Either a reference or a description of the routines applied in the field has to be given.
9	p. 3, ln. 10	Replace ”section” by ”layer”
10	p. 3, ln. 16, 18	”10+ m core” is not a valid expression. Use ”deeper than”.
11	p. 3, ln. 16	”...with THE lowest Root...”
12	p. 3, ln. 16	Rephrase: ”We therefore *attach* to any...”
13	p. 3, ln. 17	Replace ”masurement” by ”estimate”. FAC10 is not measured directly.
14	p. 3, ln. 28	Shorten the sentence to have: “We extract each core site’s long-term (1970-2014) average net snow accumulation (bn) and air temperature (Ta)...”
15	p. 4, ln. 3-11	Avoid double referencing to the color and figure number (“amber area in Figure 1a”). Is amber=yellow?
16	p. 6, ln. 6	What are the ”well-known dry-firn compaction equations”? References are needed here.

17	p. 6, ln. 7	TowardS
18	p. 4, ln. 20	Replace: ”from our” -> “using the” “observations” -> “firn cores”
19	p. 4, ln. 21	Replace: “to predict FAC10 anywhere in the firn area” -> “to interpolate and extrapolate FAC10 for the whole firn area”
20	p. 4, ln. 24	Form of the functions is not *arbitrary*. The authors make an attempt to bring in physics in the extrapolation of the empirical FAC10 estimates.
21	p. 4, ln. 28	Remove “we” before “tuned the surface snow density”
22	p. 4, ln. 29	Add “a” after the reference to Figure S3.
23	p. 5, ln. 4	Add “b” after the reference to Figure S3.
24	p. 5, ln. 23	Replace ”...as additional measurements where FAC...” by ”...as an additional proxy of FAC...”
25	p. 5, ln. 26	Replace: “meaning” -> “suggesting”
26	p. 5, ln. 28	Replace: “We can make three estimates...” -> “Three principal assumptions are possible ...”
27	p. 6, ln. 12	Replace: “Spatial heterogeneity in melt and snowfall leave...” -> “Spatial heterogeneity in snowfall and melt leave...”
28	p. 6, ln. 13	Replace: “missed by the method of Fausto et al. (2018).” -> “missed by the method applied by Fausto et al. (2018).”
29	p. 6, ln. 19-20	Remove the unnecessary paragraph
30	p. 6, ln. 21	Replace ”Assuming a normal distribution of errors, 95% of...” -> “Assuming a normal distribution of errors with zero mean, 95% of...”
31	p. 7, ln. 1	Subscript in FAC10 symbol
32	p. 7, ln. 5	“Summing the FAC10 and its uncertainty indicates that...” I assume that lateral integration across the domain covering the Greenland Ice Sheet is meant here. The phrase, as it is now, can be misinterpreted, one might think that you are summing actual values and their assumed uncertainties.
33	p. 7, ln. 5-6	Replace: ”...of air is contained within...” -> ”...of air was contained within...”
34	p. 7, ln. 28	Add ”b” after ”Figure 1”
35	p. 8, ln. 2	Rephrase: “...occur at deeper than 10 m” -> “...occur below the depth of 10 m”
36	p. 8, ln. 13	Rephrase: “...impactS our FAC10 maps...” -> “...impact our FAC10 maps...”
37	p. 8, ln. 16	Rephrase: “...Since Box et al. (2013) giveS 2 m air temperature...” -> “...Since Box et al. (2013) give 2 m air temperature...”
38	p. 8 ln. 24	Rephrase: ”...provide insight on *how* the FAC10 *might have been* at a given place and time.”. For example “what were the properties of...”. Also add either “an” before or “s” after “insight” – “an insight” or “insights”,

		but not just “insight”.
39	p. 9 ln. 2	“...systematically different *than* our calculated FAC10...” -> “...systematically different FROM our calculated FAC10...”.
40	p. 9, ln. 3	“*A last* measurement raises questions...” -> “One more measurement raises questions...”
41	p. 9, ln. 12-13	”...to 10 m depth (FAC10) *could be* calculated” -> “to 10 m depth (FAC10) WAS calculated”
42	p. 9, ln. 13	“...three regions *on* the firn area *in which FAC10* where we *could* fit empirical...” -> “...three regions WITHIN the firn area where we fit empirical...”
43	p. 9, ln. 17	“This decreas*ing* FAC*10* translates into the loss of...” -> “This decreasED FAC_{10} translates into the loss of...”
44	p. 9, ln. 18	“...of meltwater retention capacity 1998-2008 and 2011-2017.” -> “...of meltwater retention capacity BETWEEN 1998-2008 and 2011-2017.”

Literature list

van Angelen, J., Lenaerts, J., van den Broeke, M., Fettweis, X. and van Meijgaard, E., Rapid loss of firn pore space accelerates 21st century Greenland mass loss, GEOPHYSICAL RESEARCH LETTERS, VOL. 40, 2109–2113, doi:10.1002/grl.50490, 2013;

Braithwaite R. J., Laternser M., Pfeffer W. T. Variations of near surface firn density in the lower accumulation area of the Greenland ice sheet, Pâkitsoq, West Greenland, J. of Glaciology V. 40, No 136, 1994;

Cogley, J., Hock, R., Rasmussen, L., Arendt, A., Bauder, A.., Braithwaite, R., Jansson, P., Kaser, G., Moller, M., Nicholson, L. and Zemp, M., Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCOIHP, Paris, 2011,

Janssens I. and Huybrechts P. The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet, Ann. Glaciol., 31, 133–140, 2000;

Ligtenberg, S., Kuipers Munneke, P., Noël, B., and van den Broeke, M., Brief communication: Improved simulation of the present-day Greenland firn layer (1960–2016), The Cryosphere, 12, 1643–1649, https://doi.org/10.5194/tc-12-1643-2018, 2018;

MacFerrin, M., Rapid Expansion of Greenland's Low-Permeability Ice Slabs in a Warming Climate, PhD dissertation, University of Colorado at Boulder, https://scholar.colorado.edu/cgi/viewcontent.cgi?article=1001&context=cires_gradetds, 2018;

Marchenko, S., Internal accumulation on glaciers: qualitative description and quantitative estimates, SVALI project report, http://ncoe-svali.org/xpdf/svali_rep_1_sergey.pdf, 2012;

Marchenko, S., Subsurface fluxes of mass and energy at the accumulation zone of Lomonosovfonna ice cap, Svalbard, PhD dissertation, Uppsala University, http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1159174&dswid=-6047, 2018;

Pfeffer W., Meier M., and Illangasekare T. Retention of Greenland runoff by refreezing: implications for projected future sea level change, J. Geophys. Res., 96, 1991;

Shumskii, P.., Osnovi strukturnogo ledovedeniya (Principles of structural glaciology), Akademia Nauk, Moscow (in Russian), 1955;

Shumskii, P., Principles of structural glaciology, translation by David Kraus, Dover Publications, Inc., New York, 1964;

Steger, C., Reijmer, C. and van den Broeke, M., The modelled liquid water balance of the Greenland Ice Sheet, The Cryosphere, 11, 2507–2526, https://doi.org/10.5194/tc-11-2507-2017, 2017;

Appendix

Matlab code for calculating the total FAC of the Greenland ice sheet basing on data from (Ligtenberg et al., 2018)

```
clear

clc


dir = ['...'];

flnm1 = [dir 'IMAU-FDM_GrIS_FAC_1960-1979.nc'];

flnm2 = [dir 'IMAU-FDM_GrIS_FAC_1980-1999.nc'];

flnm3 = [dir 'IMAU-FDM_GrIS_FAC_2000-2016.nc'];


% finfo = ncinfo(flnm1); open finfo


l1 = ncread(flnm1, 'FirnAir'); t1 = ncread(flnm1, 'time');

l2 = ncread(flnm2, 'FirnAir'); t2 = ncread(flnm2, 'time');

l3 = ncread(flnm3, 'FirnAir'); t3 = ncread(flnm3, 'time');


lat = ncread(flnm1, 'lat'); lon = ncread(flnm1, 'lon');


%%

fac = cat(3, l1, l2, l3);

t   = cat(1, t1, t2, t3);

clear l1 l2 l3 t1 t2 t3 flnm*


%%

factmp = fac(:,:,end);

m = isfinite(factmp);

a = nan(size(factmp));

Ee = referenceSphere('earth','km');
```

```
for r = 1:size(factmp,1)

for c = 1:size(factmp,2)

    if m(r,c) == 0

        continue

    else

        a1 = areaquad( lat(r,c), lon(r,c), lat(r+1,c+1),
lon(r+1,c+1), Ee );

        a2 = areaquad( lat(r,c), lon(r,c), lat(r-1,c+1), lon(r-
1,c+1), Ee );

        a3 = areaquad( lat(r,c), lon(r,c), lat(r+1,c-1), lon(r+1,c-
1), Ee );

        a4 = areaquad( lat(r,c), lon(r,c), lat(r-1,c-1), lon(r-1,c-
1), Ee );

        a(r,c) = mean([a1 a2 a3 a4]); clear a1 a2 a3 4

        facm(r,c) = a(r,c).*1000.*1000.*1000.*factmp(r,c)/1000;

    end

end

end

M = nansum(facm(:)) / 10^9;

disp(['Greenland total FAC is ' num2str(M) ' Gt'])


%%

close all; figure;

for ti = 1:10:size(t,1)

    factmp = fac(:,:,ti);

    scatter(lon(:), lat(:), 25, factmp(:), '.');

    colorbar('southoutside')

    caxis([0 50])

    title(['total FAC [m], year ' num2str(t(ti,:))])


    pause(1)

    cla

end; clear ti
```