

Review of: “Changes in glacier facies zonation on Devon Ice Cap, Nunavut, detected from SAR imagery and field observations”, by T. de Jong et al., submitted to *The Cryosphere*.

The authors use Envisat Advanced Synthetic Aperture Radar (ASAR) imagery for the period 2004-2011 to outline and study the evolution of glacier facies zones over Devon Ice Cap, northern Canadian Arctic Archipelago (CAA). Glacier facies zonation is validated using a combination of observational data including in situ surface mass balance (SMB), ice cores, ground-penetrating radar (GPR) transects and climatic measurements at automatic weather stations. The technique proves to successfully map the evolution of glacier ice, saturation/percolation and dry snow zone in time (2004-2011). The study highlights a clear inland migration of glacier ice and saturation/percolation facies at the expense of dry snow zone, threatening the sustainability of Devon Ice Cap in the future when increased meltwater runoff at all elevations lead to enhanced mass loss.

This is a sound, well documented study describing a remote sensing technique that successfully map changes in glacier facies zonation over a small ice cap. The paper is of great interest, well written, with clear figures illustrating the methods and main results of the study. Comparison to the results of a climate model providing spatially continuous SMB maps over Devon Ice Cap, more detailed discussion of the SMB response to changes in glacier facies, and some clarifications at places would make the study more robust and appealing for a broader audience. Including model outputs would increase the scientific impact of the paper, combining all available instruments/data (in situ, remote sensing and model) and extending the discussion on the ice cap response to facies changes to 2017. In brief, I deem that the current manuscript requires **minor revisions** before acceptance for publication in *The Cryosphere*. Hereunder, the authors can find my **remarks** listed as **Substantial**, **Point** and **Stylistic** comments, which should be addressed before acceptance.

Substantial comments

1. The authors should better describe the sign convention (positive/negative) of the backscatter intensity measurements (σ^0 in dB) from Envisat ASAR. In addition, a Table listing typical σ^0 values (minimum/maximum thresholds) for the different glacier facies zones (glacier ice, saturation/percolation, pseudo dry snow) would facilitate the interpretation of e.g. Fig. 2. This extra Table should be discussed in **Section 5.1 i-iii**.
2. Mass balance is often used when referring to “surface mass balance” (SMB) i.e. the difference between mass gain from precipitation and mass loss from sublimation and meltwater runoff. This is confusing because “mass balance” quantifies the difference between SMB and solid ice discharge from calving glaciers. To clarify this, the authors could reformulate **L33** as follows: “Surface mass balance (SMB), i.e. the difference between accumulation from precipitation and ablation from sublimation and meltwater runoff, is estimated to have accounted for 48% [...]”. Then “SMB” should be used instead of “mass balance” across the manuscript. At **L36**, the authors could refer to Noël et al. (2018) to estimate present-day SMB (1958-2015) for the northern CAA, highlighting that mass loss from ice dynamics is negligible compared to surface processes.
3. The discussion/conclusions (Sections 6/7) could elaborate on the impact of upward migration of glacier facies zones (bare ice and percolation zone) on the contemporary/projected mass loss of Devon Ice Cap, and the CAA ice masses in general. In line with the current study, Noël et al. (2018) show a progressive saturation of the remaining firn pore space of CAA ice caps caused by intensified melt following the recent Arctic warming. Reduction of the firn zone extent and snow buffer capacity has recently accelerated the mass loss of these ice caps through increased meltwater runoff. The authors should mention these corroborating results in their discussion/conclusions. For the long term perspectives, the authors should refer to model climate projections suggesting drastic reduction in firn retention capacity of CAA ice caps within the next century (Lenaerts et al., 2013). These publications demonstrate that

upward migration of glacier facies **do have an immediate impact** on the ice cap mass balance as opposed to conclusions drawn at L479-480. This statement should be reformulated in the revised manuscript (see also point comment L479-480).

4. In Figs. 4-6, the authors should strongly consider comparing their observational data to a climate model e.g. SMB product at 1 km statistically downscaled from RACMO2.3 that is freely available without conditions (Noël et al., 2018). Including model data would not only make the comparison more robust and comprehensive but also increase the scientific impact of the paper, as it would combine all instruments/data currently available: in situ, model, and remote sensing. This could also enrich the discussion on the SMB response to recent migration of glacier facies, as well as extend trends in ELA migration to 2017 (see also Substantial comment #3). In **Fig. 4a**, contours of annual ELA (SMB = 0; e.g. in yellow) could be outlined and compared to the ELA derived from remote sensing. In **Figs. 5-6**, evolution of modeled ELA could be compared to in situ and remote sensing estimates.

Point comments

L10: “surface mass balance” instead of “mass balance”. This holds for the whole manuscript.

L29-30: The authors should better use “±” instead of “+/-”.

L32: For consistency, the $493 \text{ kg m}^{-2} \text{ a}^{-1}$ estimate could be integrated over northern CAA ice masses to obtain a value in Gt a^{-1} (listed in brackets), comparable to the value mentioned at **L29**.

L32-36: Here the authors could mention mass loss estimates from Noël et al. (2018). Their Table 1 clearly shows that decreasing SMB, governed by increased meltwater runoff, is the main driver of recent mass loss over solid ice discharge (see also Substantial comment #2).

L56: “[...] air temperature and in situ SMB data.”

L80: “NW” is not defined in the main text. While it obviously means “northwest”, the authors should either write: a) “northwest sector (NW)” or b) “northwest sector”. If a) is chosen, the northwest transect/sector should be referred to as “NW” across the rest of the manuscript e.g. **L158, 261**. The same holds for “northeast (NE)” e.g. **L401**.

L84-85: This sentence is confusing; I understand that 58% of the mass loss between 1963-2009 occurred after 2000. Could the authors clarify and reformulate?

L92-93: The authors certainly mean “runoff of meltwater” instead of “surface melting”.

L102-103: I suggest: “Here, meltwater percolates into the firn and further refreezes below the last summer surface, resulting in internal accumulation.”

L104-105: I suggest: “In the percolation zone, meltwater percolates within the annual surface layer where it is retained and refrozen.”

L107: “[...] where (almost) no melt occurs.”

L110: Here a brief description of the meaning of dB unit and sign convention would be instructive; some explanation arises at **L151** which appears to be too late (see also Substantial comment #2).

L124: “SMB” instead of “surface mass balance”.

L154: The filter was used to remove noise in the σ^0 field? Please clarify.

L170: Is “ringing” a jargon word? Does it mean “resonance”? Please clarify and/or reformulate.

L173: “Dev1H (550 kg m^{-3} ; Fig. 1)”. The authors should also add a sentence mentioning the location of ice cores in the caption of Fig. 1.

Section 5.1: Here the authors should include a Table listing typical σ^0 values for each glacier facies, and refer to this Table in subsections i-iii. **L225:** “[...] negative values ($\sigma^0 < 0$). [...]”. **L245:** “This boundary coincided with $\sigma^0 = 0$ in Envisat.”. **L250:** Here a Table listing typical σ^0 values would be appreciated as “ σ^0 values are low” is rather subjective and could mean either a) negative values or b) smaller σ^0 positive values than observed for the percolation/saturation zone. **L261:** To reproduce the author’s technique, the “ELA σ^0 value” is required and should be listed in the additional Table.

L217: The authors should refer to Fig. 2 instead of Fig. 4, since Fig. 3 has not been discussed yet.

L260 and L332-333: Why did the authors estimate a unique σ^0 value based on local in situ measurements instead of spatially varying σ^0 values derived from e.g. ELA (SMB = 0) from a gridded climate model? How would this affect the outlining of glacier facies? Is it reasonable to assume that the σ^0 thresholds are constant in space, or that the SMB transect, on which the σ^0 is based, is representative of conditions over the whole ice cap? Please clarify.

L263-265: Could the authors point to this in Fig. 2?

L284: Add a reference to Fig. 3c as: “0dB σ^0 value (Fig. 3c)”. **L286:** “(Fig. 3a)” instead of “(Fig. 3c)”.

L322: Fig. 5 is described before Fig. 4. The authors should swap Fig. 4 and Fig. 5. **L332, 333 and 337:** “(Fig. 4)”. **L346, 359, 372, 385, 387, 400 and 468:** “(Fig. 5 [...])”.

L356-359: For comparison, the authors should consider showing changes in ELA elevation from e.g. RACMO2.3 at 1 km in Fig. 5, and compare the model-derived ELA migration rate with in situ/remote sensing estimates.

L373: Add “(Fig. 5b)” after “Devon Ice Cap”; remove “(Fig. 4b)” at **L374**.

L382: Add “(Fig. 5)” after “pseudo dry snow zone”.

L395: Could the authors provide a p-value for these regressions?

L412: What do “its” and “there” refer to in this sentence? Please clarify and reformulate.

L439-448: Here the authors could elaborate on the recent and projected response of changes in glacier facies on Devon Ice Cap SMB as mentioned in Substantive comment #3.

L466-469: This sentence is somewhat insubstantial and does not address whether, after the study period 2004-2011, the whole of Devon Ice Cap more frequently experiences surface melt (with a peak in the extreme year of 2012). The author’s statement could be verified using melt and runoff fields from a gridded climate model for the period 2004-2017. While I understand it may be beyond the scope of this study, this question is worth being addressed with more robustness than the current statement. Therefore, I strongly encourage the authors to extend their discussion/conclusions on the SMB response to glacier facies changes after the Envisat period using climate model data (2004-2017; see also Substantive comment #3).

L479-480: The sentence: “While these changes do not have an **immediate impact** on the mass balance of the ice cap” is not supported by Noël et al. (2018). See for instance Fig. 7(c-f) showing how runoff has increased after the mid-1990s due to drastic reduction in retention capacity of the fast retreat of the firn zone for CAA ice caps, including Devon Ice Cap. The authors should, in my opinion, revise their conclusions and reformulate accordingly.

L489-491: To support increased melt after the mid-1990s, the authors should also refer to the recent work of Noël et al. (2018) (see their Fig. 7).

Stylistic comments

L101: Maybe “persisting throughout summer and being”.

L158: “(red line in Fig. 1)”

L184: “ice lenses” instead of “ice layers”.

L189: “[...] of 57 poles (blue dots in Fig. 1) [...]”.

L193: “[...] ~400 m a.s.l. (green dots in Fig. 1).”.

L199: “[...] net balance between year n-1 [...]”.

L203: “[...] from positive (accumulation) to negative (ablation) is identified [...]”.

L284, 306 and 321: “ $\sigma^0 = 0$ line” instead of “0 dB σ^0 value”.

L383: Replace “with σ^0 values < 0 dB” by “($\sigma^0 < 0$)”.

L390: “negative” instead of “< 0dB”.

L391: “positive” instead of “> 0dB”.

L394: “appears”.

L466-469: Remove “which” and “say lie fairly close together” and write “(Braithwaite et al., 1994)”.

Figures

Fig. 1: “surface mass balance” instead of “mass balance”. An additional statement on the location of ice cores should be inserted in the caption. The authors should include longitude/latitude on the map, as well as a second box in the inset to locate the sector of Devon Ice Cap depicted in the main figure.

Fig. 3: “red cross” instead of “+” in the caption; I suggest “ σ^0 (sigma nought)” in the caption.

Figs. 4-5: Swap Fig. 4 and Fig. 5. In new Fig. 4, replace “mass balance” by “SMB”.

Figs. 4-6: See also Substantive comment #3 for including comparison to model data.

Figs. 7b and 8b: For consistency with numbers mentioned in the main text e.g. **L364**, the authors should use “m w.e.” as units on the y-axis.

Additional references

1. B. Noël et al. doi:10.1029/2017JF004304
2. J. T. M. Lenaerts et al. doi:10.1002/grl.50214