Interactive comment on "A representative density profile for the North Greenland snowpack" *by* C. F. Schaller et al.

Anonymous Referee #2

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General comments:

This paper presents a new technique for efficiently retrieving shallow snow and firn cores from polar regions. Those cores can then be returned to a lab for high-resolution analysis using a micro-CT scanner. These types of measurements are needed to better understand the evolution of firn, which in turn will lead to more accurate estimations of mass-balance changes on the ice sheets. The authors apply a technique that was developed for speech recognition, Dynamic Time Warping (DTW), to analyze changes in snow and firn properties along a 450-km traverse in northern Greenland. Additionally, the authors examine variability in annual accumulation rates and relationships between water isotopes (a temperature proxy) and accumulation rates.

The paper makes a valuable contribution to the glaciological community and will be

of particular interest to those who study snow and firn related surface-mass-balance processes and ice-core delta age estimation. The "liner" technique combined with DTW could easily be adopted by the snow-hydrology and snow-avalanche communities to investigate snow properties on smaller spatial scales. I have 2 general comments and numerous specific comments that I would like to have addressed before publication.

"Matching" snow and firn properties. The authors use DTW to "match" the firn properties along the traverse. The first step of the alignment is to match the d18O data, which identifies snow/firn from a particular summer or winter. This seems to me to be the most valuable use of the DTW technique because it gives an idea of how accumulation is varying seasonally and annually over a large distance (temporal and seasonal variabililty).

Their next step is to align high-resolution density features in the snow/firn. However, I am left unsure what information this high-resolution matching or alignment is providing. What is the end goal in aligning the high-resolution density data? Is it to track layers deposited during individual weather events? Or to provide a common depth-age profile along the traverse? Related to this question: What does the "fine fit" in Figure 4b mean physically, and why is that a useful metric? Likewise, what is the physical meaning of the color bands in Figure 6? Would those be layers of snow with the same age?

I believe that using DTW on the high-resolution density data includes an a priori implicit assumption that stratigraphic features (layers) and are continuous (or at least correlated) over hundreds of kilometers, but the authors have not convinced me that this is or should be true. Why do you expect the depth-density profiles to be related? Does this argument hold up if this assumption is not true? Recent work by Proksch and others (2015, e.g. Fig. 12) showed significant stratigraphic variability in the near-surface snow in Antarctica. I would expect some amount of coherence on the 10's-of-kilometers scale, but it is surprising to hear that stratigraphic features (and coherence in density) persist over hundreds of kilometers and over a divide, where temperatures and accumulation rates vary on daily to annual time scales. If the authors are assum-

ing that layers persist over these distances, at what layer resolution would they expect this assumption to break down? Can you be confident that the algorithm is matching real layer correlations and not just recognizing stochastic layering that all happens to fall near some mean density?

The authors do discuss verification of their method using surrogate density profiles. However, I do not follow their reasoning – this could be a place to clarify their language.

Ultimately, the authors do not make a strong case to me that the layers they are fitting are spatially extensive and not stochastic noise. I request that the authors justify the assumption that the layers are spatially extensive. Additionally, they should clarify the language of what the alignment using high-resolution depth-density data means. An example of somewhere to clarify: Page 5 Line 4 says, ". . . the continuous depth scale agrees. . ." Perhaps specifying what a continuous depth scale means would help me understand – is that a continuous depth-age scale? Alternatively, the authors could focus on the DTW using the d18O data.

Uncertainty and application to mass balance. The authors point out in the introduction the importance of knowing firn properties for mass balance calculations, and they derive a representative depth-density profile. How much uncertainty is associated with using this representative profile? I suggest that it would be useful to compare the representative depth-density profile to measurements and model predictions. A metric of interest for the mass-balance community is the depth-integrated porosity (DIP), or the amount of air in the snow and firn. I think it would be a useful exercise to compare the DIP that is observed in the cores to the DIP that is predicted by the representative profile. Additionally, it could be compared to the DIP predicted by assuming some constant density for the top 2 m and perhaps to density profile predicted by a firn-densification model.

Specific comments:

- Page 2, Line 4: thereby measurements of what? - P2, L10: what individual param-

eters? - P2, L20: How do you know in which cases the snow might be compacted? - P2, L28: Are you confident that no metamorphism occurs during transport, e.g. due to temperature gradients? - P2, L31: "Amongst others,. . ." amongst other what? Other corrections? If so, state what those are. - P3, L24: a shift in what? - P3, L26: what do you mean by event? - P3, L26: what do you mean by align? (related to general comment above) Snow of a certain age? - P3, L30 – P4: DTW is a complicated concept to read through for the first time – perhaps you can provide an example in this section – e.g. what "assigning the values of" means, what "proceeding through the matrix" means, etc. - P5, L3: Combine all of the available information: are you using anything besides d18O and density? - P5, L9/Table 2: How did you come up with you maximal/minimal offset values? (Should that be maximum/minimum?) - P5, L12: These aren't really continuous, are they? You have discrete measurements from every ∼25 km along the traverse. How do you interpolate between those? - Section 3.2: Are the statistics informing the creation of the surrogate density profiles taken from the bulk of all geographic locations (i.e. sigma_base is the standard deviation from all sites) or from single sites? - P5, L24: Do you calculate the surrogate profiles for each site individually using that site's statistical properties, or the bulk statistical properties of all sites? - P6, L12: How do you define a "layer"? - P7, L9: How is 0.1m chosen as the maximum allowed shift? - P7, L10: What does "all combinations of 2 liners" mean? Do you mean that you are comparing the 2 meters of data from each site to each other site? - P7, L11-12 and P9, L1: Can you further elaborate on why that change occurs? Going over the divide, you lose some coherence, but not all? Which signals are lost going over the divide, and which are maintained? Is there also a change at the $\frac{1}{2}$ way mark? - P7, L15: It is unclear to me: was the representative density profile created by stacking the raw depth-density data, or by using the "aligned" profile from DTW? - P8, L9: Do the high and low accumulation years correlate spatially? I.e. does a high-accumulation year at NEEM also mean high accumulation at EGRIP? - P8, L12: Is this spread in isotopic coldest year surprising? Are those data corroborated by reanalysis (e.g. RACMO) data? - P8, L18 and Figure 10: What is the source of those

outliers? Sampling/instrument error? Please elaborate on how you identified them as such. - P8, L20-21 (and P10,L16): I think it would be appropriate to elaborate on why the summer snow has a lower density. - P9, L12: Why do you not expect significant compaction? Reference or justify. - P10, L6: Why is the winter picture less clear? - P10, L9: You show that warmer sites have more accumulation. For a given site, does a warmer winter, summer, or year correlate with higher accumulation at that site? - Figure 3: Does not clarify the constraints on stepping to me. - Figure 6: The densities that are plotted do not have labels, scales, or units. Are those the centerline values and scales same for each? It might be helpful to mark the mean density and standard deviation of each of depth-density profile. - Figure 7: What are your x and y directions? Can you elaborate on how you get the standard deviation error band, e.g. is it comparing the raw data from each site to the representative profile?

Technical corrections: - Numerous places in text the authors use vague language: e.g. "profile" (depth-density profile, depth-age, density-age profile, "depth profile" is still vague), "position" (position could refer to some point on the firn core rather than a geographic location, and I suggest a change to "site" or similar) - Throughout: The authors use the language "the liners show" or similar (e.g. P5L12); the "liners" are the instruments/tools used to gather their data and are not what actually show anything. I suggest language such as "the data from each of the sites show" - There are numerous instances throughout the manuscript where (1) commas are misused or lacking and (2) hyphens are needed. - Several places in the text change tense (past vs. present, e.g. section 2.1) and voice (active vs. passive). I suggest choosing one. - Page 1, Line 5: empirical based empirically-based - Page 1, Line 11: impact impacts - Page 2, L1: causing creating - P2, L25-26: probing sampling, "that technique" "the liner technique" - P3, L3: measurement time increases with resolution? (rather than accuracy) - P3, L5-6: "Then, the raw…CT images." Unclear sentence - P3, L7: weight mass - P3, L15-16: clarify that is it 3-5 years worth of accumulation contained in the 2-m sample; specify "winter-to-winter accumulation rates" - P3, L21: renowned well-known - P4, L23: what does the "maximal ratio of the respective accumulation rates" mean? Repective to

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what? Two sites next to one another? - P6, L3: Perhaps use z_i since you are talking about depth. The x dimension (to me) indicates a direction on the surface (e.g. along your traverse). - P7, L15: Change to "The previously-calculated depth-scale density records were stacked to obtain…" - P8, L6: Increasing to 140 where? - P9, L1: fourth liner? Do you mean location/site? - P9, L15: The statistics in this paragraph were already reported on page 7; did you intentionally do that? - P9, L21: is are, summer of 2012 - P9, L27: sommer summer - P10, L20: accustic acoustic - Figure 8: y-axis does not have scale or units labeled - there are numerous instances of typos and challenging-to-read sentence structure that I have not indicated here; I recommend having a copy editor review the manuscript for those.

Reference:

Proksch, M., Löwe, H., & Schneebeli, M. (2015). Density, specific surface area, and correlation length of snow measured by high‐resolution penetrometry. Journal of Geophysical Research: Earth Surface, 120(2), 346-362.

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