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# *Interactive comment on* "Changes in the firn structure of the Greenland Ice Sheet caused by recent warming" *by* S. de la Pe na et al.

**Anonymous Referee #2**

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Changes in the firn structure of the Greenland Ice Sheet caused by recent warming S. de la Peña, I. M. Howat, P. W. Nienow, M. R. van den Broeke, E. Mosely-Thompson, D. Mair, B. Noël, and A. J. Sole

Summary The authors detail observations of ice layers obtained from snowpits and ice cores in the western portion of the Greenland Ice Sheet percolation zone. They find thick layers of ice associated with the extreme melting that occurred during 2012. Matching of the layers with a radar transect across the western portion of the ice sheet suggests that the ice layers are widespread. A regional climate model is used to provide estimates of melt volume and its relation to the volume of ice observed. The authors suggest that changes in the near surface properties of the ice sheet may lead to changes in hydrological pathways, and that rapid densification associated with melting



can affect altimetry-derived estimates of ice sheet mass change.

General Comments This manuscript is well written and discusses research that has important implications for our understanding of the mass balance of the Greenland Ice Sheet. The article should be published with minor revisions as discussed below.

1. The authors should provide more details regarding methods within the "Observations" section, or preferably include an additional section after "Observations", describing methods in further detail. Methods to be described should include a description of firn ice content, and methods describing measurements taken at ice cores and snow pits, as well as further details derivations from RACMO model results. 2. Sometimes the terminology used to refer to the field sites is not consistent (e.g. "J-line" "J-sites"). Please try to make this consistent for clarity. 3. I think the authors should be careful about drawing conclusions about the entire percolation zone or ice sheet-wide changes based on measurements in one portion of the western percolation zone. This limitation should be discussed. If the authors do think the conclusions for this region can apply across the ice sheet, their rationale should be explained. 4. The authors discuss the 2012 extreme event, but also mention "current trends". Shouldn't the impact of extreme events like the 2012 event be separated from the less dramatic effect of long term trends? Can some discussion of this be provided in the conclusions section?

Specific Comments

1. Title: The data used in this study are all from the western portion of the Greenland Ice Sheet. Perhaps the title should be changed to "Changes in the firn structure of the western Greenland Ice Sheet caused by recent warming."

2. P. 543, Lines 6-7: Can the authors mention specifically that they are using observations of ice layers from field campaigns in conjunction with radar data and model results?

3. P. 543, Line 10: Change "firn" to "near-surface firn".

4. P. 543, Line 15: Specify that annual melt and refreezing rates are derived from model results.

5. P. 544, Lines 16-21: This sentence seems out of place. Perhaps it can be moved to the discussion and conclusions section. It is also a bit wordy.

6. P. 545, Line 15: Please specify briefly what types of field and remote sensing measurements are used.

7. P. 545, Line 16: Specify which regional climate model outputs are used (e.g. melt volume, etc.)

8. P. 545, Line 18: Please clarify the meaning of "percolation layers". Are the authors referring to ice layers associated with percolation and refreezing?

9. P. 545, Lines 20-23: I think this sentence can be removed, as it repeats what is described in the following sentences in more detail.

10. P. 546, Lines 1-4: It is unclear from this sentence how the analysis of RACMO data relates to the other sections of the paper. Please clarify.

11. P. 546, Line 12: "NASA-funded" seems irrelevant to the discussion of the science. Perhaps this can be mentioned in an "Acknowledgements" section at the end of the manuscript.

12. P. 547, Line 5: What is meant by "more realistic"? Please clarify.

13. P. 547, Line 7: QuikScat data cannot be used to measure melt rate, only the presence or absence of melting. Please revise.

14. P. 547, Lines 8-9: It is not clear how the inability to measure runoff volume using satellite data would lead to discrepancies in the comparison of melt extent or duration in areas of high runoff. There must be other reasons for the discrepancies in these regions. Please clarify.



15. P. 547, Line 13: Change "no meltwater runoff." to "no simulated meltwater runoff."

16. P. 547, Lines 15-18: It may make more sense to first introduce observations at the cores as shown in Figure 3a, and then to discus the total annual ice content as shown in Figure 2, so it is clear where the measurements of ice content come from. If the authors agree with this, Figures 2 and 3 can be switched.

17. P. 547, Line 17: Clarify "the later years".

18. P. 547, Line 19: Change "each core's" to "each PARCA core's" for clarity.

19. P. 547, Lines 21-22: Can it simply be said that core 6941 extends back to 1985?

20. P. 547, Lines 22-27: These sentences describe methods, and can be moved into a separate section detailing methods or into the preceding section.

21. P. 548, Line 7: Suggest removing "only" from "only 9 cm" as there is no previous discussion of any thicker layers.

22. P. 548, Lines 13-15: This is not exactly clear from figure 3. Some improvements to the figure are suggested below. Since there is a gap in the record, perhaps "observed since" should be changed to "for 2011 through 2014".

23. P. 548, Line 17: Please specify the thickness of the layers.

24. P. 548, Line 27 – P. 549, Line 3: The discussion of accumulation and density seems unrelated to the discussion of the ice layers. Can the authors discuss why these observations are importance in the context of the ice layer measurements?

25. P. 549, Line 13: change "over the percolation zone" to "over most of the percolation zone" for consistency.

26. P. 550, Line 4: I agree that the surface elevation drop during 2012-2013 seems to be associated with melting, but can the authors explain their logic in more detail here?

27. P. 550, Lines 8-10: This sentence makes it sound as if the firn compacts due to

a higher densification rate, while the process is actually surface melting followed by refreezing, if I understand the authors correctly. Please make this clear.

28. P. 550, Line 12: It is stated that RACMO outputs for 1958-2013 are shown, but Figure 6 only shows data through 2013. If RACMO outputs for 2013 are available, please include these.

29. P. 550, Lines 17-24: Are there references that can be provided here to support these statements?

30. P. 550, Line 26: Suggest changing “ice layers formed” to “ice layers observed to have formed” for clarity.

31. P. 551, Lines 7-16: What is the purpose of this discussion of changes in melt rates?

32. P. 551, Lines 23-24: Change “predicted” to “simulated”.

33. P. 551, Line 24: Should this not say “(i.e. the percolation and accumulation zones)”?

34. P. 552, Lines 3-11: The details of this method are not clear. I suggest providing a more detailed description of the methods earlier in the manuscript and removing the discussion of methods here.

35. P. 552, Lines 24-25: Change “in the form” to “solely in the form”

36. P. 554, Line 5-7: While this statement may be true, it does not seem to be supported by the findings of this study.

37. Figure 1: Can the domain of the map showing station locations be expanded slightly to show the location of the OIB flight line as well? Also please make the font size larger for the station names. In the caption specify that the contour lines shown are surface elevation contours.

38. Figure 2: Note in the caption which core(s) the PARCA average is derived from.



39. Figure 3: Move the (a) and (b) labels on the figure to the upper left corner and make them slightly larger. The “Year” label for figure 3a is also rather small. Could the authors replace the 18 m scale with a 1 m scale on figure 3a, or also show a 1 m distance? This would allow figures 3a and 3b to be more easily compared. Also, it would be helpful if the elevation of the PARCA cores were also included on the figure. What is meant by “2013 melt layer”? It is not clear what the “melt layer” lines are pointing to.

40. Figure 4: “the melt layer” is a bit vague. Please note which melt layer is being traced. Also change “to snowpack in 2011” to “to the snowpack in 2011”.

Technical Corrections 1. P. 544, Line 22: Suggest changing “A model-based study in the early nineties” to “A model-based study by Pfeffer et al. (1991)...”. Also change “showed how” to “showed that”.

2. P. 545, Line 11: Please define NASA before using the acronym.

3. P. 545, Line 28: Change “layers are” to “layers were”

4. P. 545, Line 29: Change “data are used” to “data were used”

5. P. 546, Line 3: Change “are used” to “were used”

6. P. 550, Line 13: Remove “at each site”

7. P. 550, Lines 20-21: Change “such as occurred in 2012” to “such as the event that occurred in 2012”

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Interactive comment on The Cryosphere Discuss., 9, 541, 2015.