

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

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We thank anonymous referee 2 for comments and recommendations. Please find the response to specific remarks below. All changes/corrections will be shown in the final draft.

By recommendation of two reviewers the paper title has changed to “Changes in the firn structure of the western Greenland Ice Sheet caused by recent warming”.

Response to general comments:

1. The section has been renamed ‘Methods and Observations’, and now includes a definition of firn-ice content, a short description on the measurements made to ice cores, and details on estimates of refrozen meltwater from RACMO. 2. Sites J1 to J4

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are referred as J-sites. Sites along the EGIG line are referred as T-sites. Reference to J-line in Figure 2 has been changed to J-sites. 3. Most of the changes observed were reported to have occurred in western and southern Greenland (west of the ice divide and above the equilibrium line, as stated in the section “Melt intensity and extent of the percolation zone”), and the actual estimated ice content increase is only calculated for this region. However percolation area is estimated for the whole ice sheet based on RACMO2.3 results. We have added discussion of the limitations of this. Snowpack conditions are likely to be different in the North and in the high accumulation areas of southeast Greenland, but for the whole ice sheet we are only estimating the expansion of the area covered by percolation facies, that is, areas where surface melt and subsequent refreezing exist. 4. The paper places emphasis in the unusually warm years, such as 2012. However, increase in modeled melt rates can be seen for most of the 21st Century, as discussed in the section “Melt intensity and extent of the percolation zone”. As can be seen in Figure 2, the sharp increase in firn-ice content was observed after 2013 as well, a cooler year than 2012 but still well above average. In this context, what was found in 2013 (after the 2012 melt) is not isolated, but rather the most dramatic example of changes that are occurring due to the above-average warming in western Greenland in the last decade.

Response to specific comments.

1. Title has been changed as suggested. 2. The sentence now reads as follows: “Here we present field and airborne radar observations of buried ice layers within the near-surface (0–20 m) firn in western Greenland obtained from campaigns between 1998 and 2014”. The use of the model is implicit later in the Abstract. 3. Changed to ‘near-surface firn’ as suggested. 4. Changed to ‘modeled annual melt and refreezing rates’. 5. Sentence has been removed. 6. The sentence now reads as follows: “Here, we use snowpit data and airborne radar and laser remote sensing observations”. 7. Corrected. It now reads as follows: “output from regional climate model of melt, runoff, and snow accumulation”. 8. Corrected. It now reads as follows: “widespread ice layers formed by

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meltwater percolation and refreezing". 9. Phrase removed. 10. We added clarification to place emphasis on the role of RACMO in our analysis. It now reads as follows: "Additionally, output from the Regional Atmospheric Climate Model (RACMO2.3/GR, van Meijgaard et al., 2008; Ettema et al., 2009; van den Broeke, 2009) are used to assess, at a regional scale, the intensity and extent of the abnormally strong 2010 and 2012 melt seasons in Greenland's accumulation zone that led to the sharp increase in the observed firn-ice content." 11. Removed. 12. This sentence has been removed. The paragraph now only describes that for the Greenland Ice Sheet, RACMO2.3 is coupled with a multilayer snow model (up to 100 layers), which calculates melt, percolation, refreezing and runoff of meltwater. 13. The instrument used in Fettweis et al. (2011) is the passive Scanning Multichannel Microwave Radiometer (SMMR). The document has been corrected. 14. The part of the sentence that reads "due in part to the lack of remote sensing capability of assessing melt and runoff rates" has been removed. 15. Corrected. 16. Swapped Figures 2 and 3. 17. Changed to "since 2010". 18. Corrected. 19. For completeness, authors believe that it is important to state the exact length of each core as collected. 20. Sentence describing dating of cores has been moved to 'Observations and Methods'. 21. Corrected. 22. Figure improvements were made as suggested. The sentence now reads as suggested. 23. Average thickness for each campaign was added. 24. It is important to quantify winter accumulation and snow density in the context of the altimetry results presented, since variability in any of these may contribute to a surface elevation displacement. The 2012 elevation change observations made by ATM is clearly of a larger magnitude than what accumulation variability may introduce. 25. Corrected as suggested. 26. Surface elevation change in this region is caused by a combination of dynamic thinning, firn compaction, and accumulation. Variability in annual snow accumulation is not large enough to cause the drastic elevation change noted in 2012-2013 (there are also firn compaction monitors in the sites, so it is also known that compaction variability is not causing the large displacement), and there is no evidence to suggest that dynamic thinning increased so much during 2012. Thus, we conclude that at least most of the differences in elevation

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change in 2012-2013 compared to the previous years shown is caused by a change in the volume of the firn resulting from converting snow to ice. 27. We replaced 'compaction' with the word 'densification', which is more accurate. 28. Figure 6 has been updated to show 1958-2013. 29. The following reference has been added: Bell et al., (2008). Spatial and temporal variability in the snowpack of a High Arctic ice cap: Implications for mass-change measurements, *Ann. Glaciol.*, 48, 159–170. Morris et al., (2014). Field-calibrated model of melt, refreezing, and runoff for polar ice caps: Application to Devon Ice Cap. *JGR*, 10.1002/2014JF003100. 30. Corrected as suggested. 31. As addressed in the response to point 4 of the general comments, our aim is not to report on the formation of thick ice layers in 2012 as an isolated event. Discussion on changing melt rates is intended to illustrate how melt intensity (and extent) has changed in the last few years, and why firn-ice content has increased in the last years, not only 2012. 32. Changed 'predicted' to 'simulated'. 33. The percolation zone is part of the accumulation zone. 34. The 'Methods and Observations' section has been updated with more details regarding the use of the model to estimate ice content. Specifically, a description was added detailing the estimates of refrozen ice, which is a percentage of the total modeled melt. This percentage, which decreases with elevation, is based on the actual field measurements. Given the variability of this, we acknowledge that there is a relatively large uncertainty in the estimates of the total refrozen meltwater, which is included in the estimates ( $\pm 25$  Gt for 2012). We have left some of the discussion highlighted (page 552 first paragraph) since it contains references to previous discussion in the same section. 35. The statement in P. 552, line 24-25 does not contain the words "in the form". We found no other statements with such words that would require such change. 36. The statement has been replaced with the following: "Furthermore, according to RACMO2.3, if current warming trends continue, the percolation zone will potentially extend to most areas above the equilibrium line." 37. Figure 1 corrected. 38. Figure 2 corrected. 39. Figure 3 corrected.

All technical corrections were corrected as suggested.

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