

Response to referee #1:

Response to Scientific Comments:

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”.

REFEREE: The selection of the 2011 IceBridge line needs further justification as well as the exclusion of other Snow Radar data in the area. Additional information should also be provided on what causes the tracking algorithm to stop at ~2500 m. Figure 4 seems to show the strong reflection going up to higher elevations in the radar data. What determined the high elevation stopping point of the ice layer? This information should be included on page 549 for clarity.

In regards to the selection of Operation IceBridge data, the Snow Radar transect overlaps the ATM data presented, and it is the only transect that goes from the ablation zone to the ice divide repeatedly between 2011 and 2014 that also overpasses close to the research sites. Snow Radar observations in 2013 after the warm year of 2012 may have been a better selection but unfortunately there are errors in the data that year and can't be used. The retracker was only used below 2450 m on purpose. At this elevation, isochrones can be observed to a depth greater than 5 m, evidence that no significant amount of ice is present in the snowpack to prevent radar signal penetration. The goal of this is to show the signal from the layer of ice (and a proxy for the extent of the area where ice layers are found), not the signal caused by hoar as seen in the dry snow zone. This has been clarified in the text (section 3, paragraph 3, as indicated by referee).

REFEREE: The statement on page 551 line 20 that if melt continues to exceed total accumulation is likely to lead to lateral transport needs further references or explanation. The processes that lead to meltwater pathways and ponding versus percolation are still unknown and this statement needs further justification if included.

We have added to the statement referred on page 551 line 20 further explanation. We state that in order to have supraglacial transport of meltwater over firn, limited buffering conditions must exist (i.e. seasonal ice layers must inhibit percolation). The sentence is a conditional one, and it is preceded by acknowledgement that evidence of lateral meltwater transport was not found at sites. The full sentence now reads:

“We found no evidence of meltwater pathways or pond formation at our sites. If, however, melt continues to exceed total accumulation and climatological conditions that allow the formation of ice layers that limit the buffering capacity of the firn continue, it is likely that lateral supraglacial transport and eventual runoff of meltwater will reach to 2000 m elevation”.

Response to detailed comments:

1. (p543 ln 7) “*Firn ice*” change to *firn-ice content*. Corrected to “firn-ice content”.
2. (p543 ln 17) “*Mass gain*” this is a bit confusing because melt and refreezing alone would not lead to mass gain in the region unless it was transported/routed

*from some other area of the ice sheet. The mass gain is still from snow fall but perhaps you are referring to melt water routing into the region. Please clarify.* The logic is that total snow accumulation, either from direct snowfall or wind redistribution, was subject to melt and later refrozen. The sentences now reads as follows: “modeled annual melt and refreezing rates in the percolation zone at elevations below 2100 m surpass the annual snowfall from the previous year, implying that mass gain in the region is retained after melt in the form of refrozen meltwater.”

3. (p545 ln 1) *Consider adding temporary buffer.* At least until now and at this elevation range, observations show refrozen meltwater that is retained within the firn and subsequently buried by winter accumulation. There is no indication in this region that retained ice is released at a later stage, at least not in liquid form.
4. (p545 ln 1) *Careful with the terminology firn ice throughout. There is either ice or fir or firn-ice content.* Corrected to “firn-ice content”.
5. (p545 ln 25) *Provide approximate snowpit depths to define near-surface.* The text now specifies snow pits are 2-3 m deep.
6. (p546 ln 21) *Provide frequency range of Snow Radar as opposed to bands as it is easier for most readers to interrupt. Also provide the vertical resolution which is important for understanding the ice lenses that can be resolved. Add citation to Panzer et al., 2013 (J. Glac) on Snow Radar.* Added frequency range (2-6.5 GHz), range resolution (~5cm), and citation of Panzer et al., 2013.
7. (p547) *First paragraph please add an additional sentence on if there is a routing scheme for meltwater/percolation implemented in the model and how this relates to the statement about mass gain from the abstract.* 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. There is no routing scheme in the model. This may be an issue when identifying exactly where the runoff/no-runoff limit lies, which has been taken into account in the uncertainty level in the estimates for both the total percolation area and total refrozen meltwater retained. These details have been included in the referred paragraph. This however does not change our statement that mass gain in the percolation zone (in areas with no runoff) below 2100 m in 2012 was mostly in the form of superimposed ice, which is what we found in the field.
8. (p548 ln 22) *You switch units here from giving ice amounts in layer thickness to mass kg/m2. Please make consistent by providing the thickness as well for the J sites for easier comparison.* We have added ice layer thickness as well as mass.
9. (p550 ln 14) *Each site is redundant and can be removed.* Corrected.
10. (p551 ln 17) *Suggests is redundant.* Corrected.
11. (p551 ln 24) *With predicted positive SMB in which year? Average 1958-1999? Please clarify.* Predicted for each period presented – the 1958-1999 average for Figure 7a, and 2012 for Figure 7b. The document has been modified to reflect this more clearly.
12. (p551 ln 28) *It would be more informative/easier to read if km2 was changed to a percentage of the area.* Text now states that the increase in area was of 240%

13. Figure 1. *Increase font size on PARCA, T and J labels and add flight line to zoomed image. It appears to be just outside of the zoomed in box.* The figure has been updated.
14. Figure 4. *Insert should show tracked layer.* The figure inset is meant to show with more detail the variable radar response to the layer retracked shown in the larger image. We believe adding the tracked layer to the inset would partially obscure the details so we would like to live the inset clear, but is easily doable if editor and referee prefer it.
15. Figure 5. *A bit difficult to read with all the data presented. Consider smoothing along track.* The data has been smoothed along-track. The noise observed at low elevations is still present and may be the result of surface roughness.
16. Figure 6. *Unclear from the caption and x-axis if the time series ends in 2012 or 2013. Extend time series through at least 2013 to match in-situ data.* The figure has been updated as suggested, clearly showing data for 2013.
17. Figure 7. *Show the outline of Greenland on this figure and the ice sheet outline for context.* Corrected. Greenland outline is shown for reference.

Response to Referee #2.

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 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.* 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. *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.* Sites J1 to J4 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. *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.* 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, highlighted as well with the change in the paper’s title. However percolation area is estimated for the whole ice sheet based on RACMO2.3 results. Snowpack conditions are 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. We have limited the discussion of the consequences that the increase in firn -ce content may have to western Greenland.
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?* 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 21<sup>st</sup> 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. We have added to the conclusion that “although the melt season of 2012 was unusually warm, rather than an isolated episode it represent 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: 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”.* Title has been changed as suggested.
2. (p. 543, ln 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?* 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. (p. 543, ln 10) *Change “firn” to “near-surface firn”.* Changed to ‘near-surface firn’ as suggested.
4. (p. 543, ln 15) *Specify that annual melt and refreezing rates are derived from model results.* Changed to ‘modeled annual melt and refreezing rates’.
5. (p. 544, ln 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.* Sentence has been removed.
6. (p. 545 ln 15) *Please specify briefly what types of field and remote sensing measurements are used.* The sentence now reads as follows: “Here, we use snowpit data and airborne radar and laser remote sensing observations”.
7. (p. 545, ln 16) *Please specify which regional climate model outputs are used.* Corrected. It now reads as follows: “output from regional climate model of melt, runoff, and snow accumulation”.
8. (p. 545, ln 18) *Please clarify the meaning of “percolation layers”. Are the authors referring to ice layers associated with percolation and refreezing?* Corrected. It now reads as follows: “widespread ice layers formed by meltwater percolation and refreezing”.
9. (p. 545, ln 20-23). *I think this sentence can be removed, as it repeats what is described in the following sentences in more details.* Phrase removed.
10. (p. 546, ln 1-4). *It is unclear from this sentence how the analysis of RACMO data relates to the other sections of the paper. Please clarify.* The use of RACMO data is aimed to put on a regional scale our findings. 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. (p. 546 ln 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.* Removed.
12. (p. 547, ln 5) *What is meant by more realistic? Please clarify.* 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. (p. 547 ln 7). *QuickScat data cannot be used to measure melt rate, only the presence or absence of melting. Please revise.* The instrument used in Fettweis et al. (2011) is the passive Scanning Multichannel Microwave Radiometer (SMMR), not QuickScat. The document has been corrected.
14. (p. 547 ln 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.* 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. It was meant to state that the discrepancies have been found in areas with in-situ data, but that they are difficult to correct due to the limitations of remote sensing platforms.
15. (p. 547 ln 13). *Change “no meltwater runoff” to “no simulated meltwater runoff”.* Corrected as suggested.
16. (p. 546 ln 15-18) *may make more sense to first introduce observations at the cores as shown in Figure 3a, and then to discuss 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.* Swapped Figures 2 and 3 and references in the text.
17. (p. 547 ln 17) *Clarify “the later years”.* Changed to “since 2010”.
18. (p. 547 ln 19) *Change each core’s to “each PARCA core’s” for clarity.* Corrected as suggested.
19. (p. 547 ln 21-22) *Can it simply be said that core 6941 extends back to 1985?* For completeness, authors believe that it is important to state the exact length of each core as collected.
20. (p. 547 ln 22-27) *These sentences describe methods, and can be moved into a separate section detailing methods or into the preceding section.* Sentence describing dating of cores has been moved to ‘Observations and Methods’.
21. (p. 548 ln 7) *Suggest removing “only” from “only 9 cm” as there is no previous discussion of any thicker layers.* Corrected as suggested.
22. (p. 548 ln 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”.* Figure improvements were made as suggested. The sentence now reads as suggested.
23. (p. 548, ln 17) *Please specify the thickness of the layers.* Average thickness for each campaign was added.
24. (p. 548 ln 27 – p. 459 ln 3) *The discussion of accumulation and density seems unrelated to the discussion of the ice layers. Can the authors discuss why these observations are important in the context of the ice layer measurements? 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 and density variability may introduce.
25. (p. 549 ln 13) *Change “over the percolation zone” to “over most of the percolation zone” for consistency.* Corrected as suggested.
  26. (p. 550 ln 4) *I agree that surface elevation drop during 2012-2013 seems to be associated with melting, but can the authors explain their logic in more detail here?* 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 (2012-201), 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 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. This clarification has been added to the last paragraph of Section 3.
  27. (p. 550 ln 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.* We replaced ‘compaction’ with the word ‘densification’, which is more accurate.
  28. (p. 550, ln 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.* Figure 6 has been updated to show 1958-2013.
  29. (p. 550 ln 17-24) *Are there references that can be provided here to support these statements:* 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. (p. 550 ln 26) *Suggest changing “ice layers formed” to “ice layers observed to have formed” for clarity.* Corrected as suggested.
  31. (p. 551 ln 7-16) *What is the purpose of this discussion of changes in melt rates?* 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. (p. 551 ln 23-24) *Change predicted to simulated.* Changed ‘predicted’ to ‘simulated’.
  33. (p. 551 ln 24) *Should this not say “(i.e. the percolation and accumulation zones?)”.* The percolation zone is part of the accumulation zone.
  34. (p. 552, ln 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.* 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). This has been clarified in the last paragraph of Section 2.
35. (p. 552 ln 24-25) Change “in the form” to “solely in the form”. Corrected as suggested.
  36. (p. 554 ln 5-7). *While this statement may be true, it does not seem to be supported by the findings of this study.* 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. *Can the domain of the map showing station locations be expanded slightly to show the locations of the OIB flight line as well? Also please make the font size larger for the station names. In the caption, specify the contour lines shown are surface elevation contours.* Figure 1 has been modified accordingly.
  38. Figure 2. *Note in the caption which core(s) the PARCA average is derived from.* Figure 2 corrected.
  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 in the elevation of the PARCA cores were also included on the figure. What is meant by “2013 melt layer”? It is not clear the “melt layer” lines are pointing to.* Figure 3 was modified as suggested. The following was added to the caption to clarify melt layer: The melt layer dashed lines indicate the position where the top of the ice layer was found in the field at J1 for the J-sites, and at T12.
  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”.* Added the following to the caption after reference to melt layer: (i.e. the top of the ice layer formed after the 2010 melt season).

All technical corrections were corrected as suggested.

Response to Referee #3.

Specific comments reviewer #3:

1. (p. 543 ln 4) “Zones” instead of “regimes”? The phrase ‘melt and percolation regimes’ refers to the processes, not the area affected.
2. (p. 543 ln 4) “ice content” instead of “solid ice”. Replaced “solid ice” with “ice content”.
3. (p. 543 ln 5) “Superimposed ice zone” instead of “equilibrium line”. Not the same. Replaced “equilibrium line” with “superimposed ice zone”.
4. (p. 545 ln 2) “Elevation” instead of “height”. Replaced ‘height’ with the word ‘elevation’.
5. (p. 547 ln 6) *I am not convinced that the referenced comparison justifies your conclusion.* This has been corrected. The instrument used in Fettweis et al. (2011) is the passive Scanning Multichannel Microwave Radiometer (SMMR). This reference confirms that although biases exist in the RACMO data, melt rates in areas with no runoff are consistent with rates derived from satellite observations. The discussion has been modified to reflect that.
6. (p 548 ln 3). *I could not find “Burgess et al.” in refs.* The following reference has been added:  
Burgess, E. W., Forster, R. R., Box, J. E., Mosley-Thompson, E., Bromwich, D. H., Bales, R. C., and Smith, L. C.: A spatially calibrated model of annual accumulation rate on the Greenland ice sheet annual (1958–2007), *J. Geophys. Res.*, 115, F02004, doi:10.1029/2009JF001293.2009, 2010.
7. (p. 548 ln 3) *This statement needs to be qualified. How can you be certain that part of the elevation is not attributed in dynamics or precipitation?* Surface elevation change in this region is caused by a combination of dynamic thinning, firn compaction, and accumulation. Variability in annual snow accumulation (not only from models, but from winter snow accumulation measured in the field) was 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 to cause such a signal at these elevations. Thus, we conclude that at least most of the differences in elevation 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. We have added this to the text.
8. Table 1 *Degrees, minutes, seconds are not displaying correctly.* They should have, but we have converted to decimal degrees to allow more space.
9. Figure 1 *Show flight line on large map, plotting contours over a MODIS image would also be helpful.* Figure 1 has been modified, although a MODIS image was not included since it would not offer any visible information over the study area.
10. Figure 7 *Can you also show the outline of the ice sheet for context.* The figure now shows the outline of Greenland for reference.

1 | **Changes in the firn structure of the western Greenland Ice Sheet caused by recent**  
2 **warming**

3 S. de la Peña<sup>1</sup>, I. M. Howat<sup>2</sup>, P. W. Nienow<sup>3</sup>, M. R. van den Broeke<sup>4</sup>, E. Mosley-Thompson<sup>1</sup>, S. F.  
4 Price<sup>5</sup>, D. Mair<sup>6</sup>, B. Noël<sup>4</sup>, and A. J. Sole<sup>7</sup>.

5  
6  
7 <sup>1</sup>Byrd Polar and Climate Center, The Ohio State University, Scott Hall, 1090 Carmack Road,  
8 Columbus, OH, 43212, USA. santiagodpr@gmail.com

9  
10 <sup>2</sup>School of Earth Sciences, The Ohio State University, 125 South Oval Mall, Columbus,  
11 OH 43210-1002, USA

12  
13 <sup>3</sup>School of GeoSciences, The University of Edinburgh, Geography Building, Drummond Street,  
14 Edinburgh EH8 9XP, UK

15  
16 <sup>4</sup>Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University, P.O. Box 80000,  
17 3508 TA Utrecht, The Netherlands

18  
19 <sup>5</sup>Fluid Dynamics Group, Los Alamos National Laboratory, T-3, Mail Stop B216, Los Alamos, NM  
20 87545, USA

21  
22 <sup>6</sup>The College of Physical Sciences, University of Aberdeen, Fraser Noble Building, King's College,  
23 Aberdeen, AB24 3UE, UK

24  
25 <sup>7</sup>Department of Geography, The University of Sheffield, Sheffield, S10 2TN, UK  
26  
27  
28  
29

30 **ABSTRACT.** Atmospheric warming over the Greenland Ice Sheet during the last two decades has  
31 increased the amount of surface meltwater production, resulting in the migration of melt and  
32 percolation regimes to higher altitudes and an increase in the amount of ice content from refrozen  
33 meltwater found in the firn above the superimposed ice zone. Here we present field and airborne radar  
34 observations of buried ice layers within the near-surface (0-20 m) firn in western Greenland obtained  
35 from campaigns between 1998 and 2014. We find a sharp increase in firn-ice content in the form of  
36 thick widespread layers in the percolation zone, which decreases the capacity of the firn to store  
37 meltwater. The estimated total annual ice content retained in the near-surface firn in areas with  
38 positive surface mass balance west of the ice divide in Greenland reached a maximum of  $74 \pm 25$  Gt  
39 in 2012, compared to the 1958-1999 average of  $13 \pm 2$  Gt, while the percolation zone area more than  
40 doubled between 2003 and 2012. Increased melt and column densification resulted in surface  
41 lowering averaging  $-0.80 \pm 0.39$  m yr<sup>-1</sup> between 1800 and 2800 m in the accumulation zone of  
42 western Greenland. Since 2007, modeled annual melt and refreezing rates in the percolation zone at  
43 elevations below 2100 m surpass the annual snowfall from the previous year, implying that mass gain  
44 in the region is retained after melt in the form of refrozen meltwater. If current melt trends over high  
45 elevation regions continue, subsequent changes in firn structure will have implications for the  
46 hydrology of the ice sheet and related abrupt seasonal densification could become increasingly  
47 significant for altimetry-derived ice sheet mass balance estimates.

## 48 1. Introduction

49 Investigations in the percolation zone of the Greenland Ice Sheet (GrIS) have revealed a highly  
50 variable snowpack structure characterized by the presence of ice lenses, pipes, and layers (Benson,  
51 1962; Scott *et al.*, 2006a; Parry *et al.*, 2007; Harper *et al.*, 2012). The heterogeneous snowpack  
52 characteristic of this region results from periods of relatively high snow accumulation followed by  
53 short melt events during summer. During melt episodes, surface meltwater percolates through the  
54 snowpack and may refreeze at depth. The atmosphere has warmed considerably in the last decade  
55 over the GrIS (van den Broeke *et al.*, 2009; Box *et al.*, 2012; Bennartz *et al.*, 2013), with 2010 and  
56 2012 being the warmest years in western Greenland since records began (Tedesco *et al.*, 2011 and  
57 2013; Bennartz *et al.*, 2013; Tingley and Huybers, 2013). As a consequence, the area of the ice sheet  
58 covered by percolation facies has grown, and the amount of surface melt and subsequently refrozen  
59 meltwater retained in the firn has increased (Tedesco *et al.*, 2008; Fettweis *et al.*, 2011; Harper *et al.*,  
60 2012; Fettweis *et al.*, 2013; van Angelen *et al.*, 2014). Extreme warming events such as in July 2012  
61 (Nghiem *et al.*, 2012; Bennartz *et al.*, 2013) have further intensified melt, but it is unknown whether  
62 increasing meltwater production and subsequent percolation and refreezing at high elevations has  
63 shifted the equilibrium line higher and affected the buffering and transport of meltwater over the  
64 interior of the ice sheet. Furthermore, these processes and their high spatial and temporal variability  
65 have implications for altimetry-derived mass balance estimates.

66 A model-based study by Pfeffer *et al.* (1991) showed that predictions of runoff-induced sea  
67 level rise from Greenland that did not consider meltwater refreezing within the firn could be  
68 overestimating sea level rise by as much as 5 cm over the next 150 years. The importance of  
69 meltwater retention was further highlighted by a study (Harper *et al.*, 2012) based on field  
70 measurements obtained in 2007, 2008 and 2009 along the Expédition Glaciologique Internationale au  
71 Groenland (EGIG) line in western Greenland. Harper *et al.* (2012) estimated that Greenland's firn has  
72 the potential to store between 322 and 1289 Gt of meltwater, confirming its importance as a buffer  
73 between surface melt and runoff. Firn-ice content was greater than 50% by volume at altitudes below  
74 1600 m, decreasing steadily with elevation. At the time, the presence of ice at an elevation of 2000 m  
75 was found to be relatively uncommon. That work added to a series of studies conducted between 2003

Santiago de la Peña 3/16/2015 11:11 AM  
Deleted: solid

Santiago de la Peña 3/16/2015 11:12 AM  
Deleted: equilibrium

Santiago de la Peña 3/16/2015 11:13 AM  
Deleted: line

Santiago de la Peña 3/8/2015 5:43 PM  
Deleted: conditions

Santiago de la Peña 3/3/2015 8:01 PM  
Deleted: is now

Santiago de la Peña 3/3/2015 7:53 PM  
Deleted: . Thus, continuous monitoring of densification, refreezing, and accumulation across the percolation zone (i.e. areas affected by significant melt and refreezing, but with little or no runoff so that all meltwater is refrozen and retained in the snowpack) is important for improving altimetry-derived mass balance estimates and for better understanding of the effects that increased seasonal melt across the ice sheet interior is having on the supra-glacial hydrology of the GrIS.

Santiago de la Peña 3/30/2015 9:22 AM  
Deleted: in the early nineties

Santiago de la Peña 3/30/2015 9:22 AM  
Deleted: (

Santiago de la Peña 3/30/2015 9:22 AM  
Deleted: ,

Santiago de la Peña 3/30/2015 9:23 AM  
Deleted: how

Santiago de la Peña 3/30/2015 3:46 PM  
Deleted: elevation

Santiago de la Peña 3/30/2015 3:46 PM  
Deleted: height

99 and 2006 as part of the first CryoSat Validation Experiment that helped assess near-surface snowpack  
100 and firn conditions at the higher end of the percolation zone (1950-2350 m). The CryoSat validation  
101 work focused on the region's spatially variable stratigraphy, as characterized by the presence of thin  
102 ice layers that were the main source of backscatter of Ku-band altimeter signals (*Scott et al.*, 2006a;  
103 *Parry et al.*, 2007; *Helm et al.*, 2007). Together, these studies can provide a decadal record of ice  
104 content and can be linked with earlier data from [the National Aeronautics and Space Administration](#)  
105 [\(NASA\)](#) Program for Arctic Regional Climate Assessment (PARCA, *Abdalati et al.*, 1998). In the late  
106 1990s, PARCA collected scores of shallow firn and ice cores to quantify spatial and temporal  
107 variability of annual accumulation rates over the GrIS (e.g. *McConnell et al.*, 2000; *Bales et al.*, 2001;  
108 *Mosley-Thompson et al.*, 2001).

109 Here, we use [snowpit data](#) and [airborne radar and laser](#) remote sensing observations from the  
110 percolation zone of western Greenland in conjunction with output from regional climate model [of](#)  
111 [melt, runoff, and snow accumulation](#) to a) quantify changes in percolation conditions after the  
112 unusually warm years of 2010 and 2012; b) identify areas where widespread [ice layers formed by](#)  
113 [meltwater percolation and refreezing](#) are found; and c) assess the state and extent of the percolation  
114 zone of the GrIS given current melt trends over the ice sheet interior. For this, we [estimated](#) the total  
115 ice content and area covered by percolation facies resulting from melting and refreezing patterns  
116 [across a wide elevation range on the western slope of the GrIS](#). Our field sites are all located within  
117 one degree of latitude (69.2°N – 71.1°N) on the western slope of the ice sheet, spanning an elevation  
118 range from 1900 to 2500 m (Figure 1). At each site, snowpits were excavated in April of 2011, 2012,  
119 2013, and 2014 in order to characterize regional near-surface ([~2-3 m](#)) snowpack conditions and  
120 percolation facies in the region following the melt season from the previous year. Extensive melt  
121 layers [were](#) identified and traced using airborne radar to identify areas covered by percolation facies,  
122 and airborne laser altimetry data [were](#) used to estimate annual elevation changes in the region.  
123 Additionally, output from the Regional Atmospheric Climate Model (RACMO2.3/GR, *van Meijgaard*  
124 *et al.*, 2008; *Ettema et al.*, 2009; *van den Broeke*, 2009) are used to assess, at a regional scale, the  
125 intensity and extent of the abnormally strong 2010 and 2012 melt seasons in Greenland's  
126 accumulation zone [that led to the sharp increase in the observed firn-ice content](#).

## 127 2. Methods and Observations

128 We measured firn ice content [by measuring ice layer thickness](#) in snow pits [made](#) during April (pre-  
129 summer melt) field campaigns between 2011 and 2014. The 2011 campaign was part of CryoSat-2  
130 validation activities continuing efforts initiated in 2004 and 2006 (*Parry et al.*, 2007; *Scott et al.*,  
131 2006a and 2006b; *Helm et al.*, 2007). Near-surface density and stratigraphy measurements were  
132 obtained from snow pits at 4 sites in the upper end of the percolation zone, located between 2350 and  
133 2490 m along the EGIG line (named T12-T15 hereafter for historical reasons). The April 2012, 2013  
134 and 2014 campaigns were part of a [study of outlet glacier dynamics](#) and also included snow pit  
135 surveys of winter accumulation and ice layer thickness at four sites in the catchment of Jakobshavn  
136 Glacier (hereafter referred as J1-J4 sites) between elevations of 1935 and 2350 m (Figure 1).  
137 Additionally, we extended the firn-ice content record in this area back in time to 1977 using 3 shallow  
138 firn cores drilled in 1998 at 2000 m, 2500 m, and 2795 m elevation (69°N 45°W; 69°N 43°W; and  
139 69°N 41°W) as part of PARCA. [The cores were dated using a combination of the winter minima in](#)  
140 [the seasonal variations of dust concentration,  \$\delta^{18}\text{O}\$ , and  \$\text{H}\_2\text{O}\_2\$](#)  (*Mosley-Thompson et al.*, 2001).  
141 [Although the thickness of each annual layer \(after being converted to water equivalent using density\)](#)  
142 [can be ascertained using any one of these parameters, for this study the layer thicknesses \(net](#)  
143 [accumulation\) were calculated using the winter minima in dust concentration](#).

Santiago de la Peña 3/30/2015 9:24 AM  
Deleted: 's

Santiago de la Peña 3/3/2015 8:16 PM  
Deleted: field

Santiago de la Peña 3/3/2015 8:19 PM  
Deleted: percolation

Santiago de la Peña 3/4/2015 11:57 AM  
Deleted: we characterized near-surface snowpack structure across a wide elevation range on the western slope of the GrIS, and

Santiago de la Peña 3/30/2015 9:25 AM  
Deleted: are

Santiago de la Peña 3/30/2015 9:25 AM  
Deleted: are

Santiago de la Peña 3/4/2015 12:02 PM  
Deleted: NASA-funded

153 We used remote sensing observations acquired by NASA's Operation IceBridge Snow Radar  
154 and the Airborne Topographic Mapper (ATM). The Snow Radar is a wideband radar that operates in  
155 the 2-6.5 GHz frequency range and can map polar firn internal layers with a range resolution of ~5  
156 cm (Panzer et al., 2013; Leuschen et al., 2014), and is used to trace the ice layers beneath the winter  
157 accumulation in 2011 by identifying internal radar reflections caused by melt layers. The ATM is a  
158 scanning laser altimeter used in this study to estimate annual elevation change between 2010 and 2013  
159 along a frequently repeated transect in western Greenland (Figure 1).

160 Output data from the RACMO2.3/GR model with a horizontal resolution of ~11 km (Ettema  
161 et al., 2009; van den Broeke, 2009) are used in combination with the remote sensing observations to  
162 map the percolation zone extent. For the GrIS, RACMO2.3/GR is coupled to a physical multilayer  
163 snow model that treats surface albedo as a function of melt as well as percolation and refreezing  
164 (Bougamont et al., 2005; Van Angelen et al., 2014). A recent study comparing RACMO2.3/GR results  
165 with melt rates derived from the Scanning Multichannel Microwave Radiometer (SMMR) mission  
166 shows that discrepancies between the model and satellite data occur mainly in areas of high meltwater  
167 runoff (Fettweis et al., 2011), due in part to the lack of remote sensing capability of assessing melt  
168 and runoff rates. There is good agreement at higher elevations, which suggests that assumptions about  
169 snowpack heat transfer and energy balance in the model are well parameterized for the percolation  
170 zone of the GrIS. Thus, the model results used here are limited to regions with no simulated meltwater  
171 runoff. The logic for the estimates for total ice content derived from the model results is as follows: at  
172 the lower elevations of this no-runoff area where modeled melt exceeds total accumulation, with total  
173 firn ice content water equivalent values close to total accumulation. At higher elevations, total firn ice  
174 content measured in the field and presented in Section 3 of this paper represents a percentage of the  
175 total modeled melt. This percentage of the modeled melt in the form of observed firn-ice decreases  
176 with elevation. This is the main cause of the relatively large uncertainty in the estimates of the total  
177 refrozen meltwater presented in Section 4.

### 178 3. Snowpack Structure

179 Figure 2a illustrates the ice layers and lenses present in each PARCA core's visible stratigraphy.  
180 Cores 6945 and 6943 (named for the coordinates where they were acquired) are ~18 m long and  
181 extend back to 1976 while core 6941 is 11.7 m long and extends to a depth equating to 1985's  
182 accumulation. The thickness of the different annual layers is affected by annual snowfall, deflation  
183 and re-deposition by wind, compaction, and melting, and varies on the order of tens of cm from year  
184 to year in western Greenland (McConnell et al., 2000; de la Peña et al., 2010; Burgess et al.,  
185 2010). Small amounts of ice are commonly found in the core, but are not present on an annual basis.  
186 While no ice was observed in core 6945 over the periods of 1977-1979 and 1996-1997, between 1987  
187 and 1991 several thin ice layers were found separated by a few cm. Most layers were found to be 3-4  
188 cm thick, and the thickest (1989) was 9 cm thick. Cores 6943 and 6941 show similar patterns, with  
189 occasional ice layers 1-2 cm thick.

190 Current conditions are represented in the schematic (Figure 2b), made from measurements of  
191 winter snow depth and ice layer thickness for each site visited during spring in 2013 and 2014 and  
192 illustrating the near-surface stratigraphy as found in spring 2014. Ice content measured in 2011 at  
193 T12, a site located at the same altitude as J4 but roughly 10 km north is included as well. The  
194 stratigraphy of the shallow firn cores shows that at least between 1977 and 1997, melt events at higher  
195 elevations were more rare and much less intensive relative to those observed since. The extreme melt  
196 events of 2012 created conditions that facilitated the formation of impermeable ice layers several  
197 times thicker than previously observed across this elevation in the percolation zone of the GrIS. These

Santiago de la Peña 3/8/2015 3:16 PM

Deleted: S-C bands

Santiago de la Peña 3/8/2015 3:17 PM

Deleted: high spatial

Santiago de la Peña 3/8/2015 3:17 PM

Formatted: Font:Not Italic

Santiago de la Peña 3/8/2015 3:17 PM

Formatted: Font:Not Italic

Santiago de la Peña 3/30/2015 2:27 PM

Deleted: , making the model results more realistic

Santiago de la Peña 3/26/2015 11:37 AM

Formatted: Font:Italic

Santiago de la Peña 3/6/2015 9:52 AM

Deleted: QuickScan

Santiago de la Peña 3/8/2015 5:55 PM

Deleted: of

Santiago de la Peña 4/28/2015 12:51 PM

Deleted: .

Santiago de la Peña 3/26/2015 2:41 PM

Deleted: Total annual ice content found beneath the wintertime snow accumulation during each of the campaigns described in the previous section is summarized in Figure 2, revealing an increase in the later years, where the annual ice layers were an order of magnitude thicker in total than the 1977-1997 average from PARCA core 6945.

Santiago de la Peña 3/26/2015 2:42 PM

Deleted: 3

Santiago de la Peña 3/26/2015 1:05 PM

Deleted: The cores were dated using a combination of the winter minima in the seasonal variations of dust concentration,  $\delta^{18}\text{O}$ , and  $\text{H}_2\text{O}_2$  (Mosley-Thompson et al., 2001). Although the thickness of each annual layer (after being converted to water equivalent using density) can be ascertained using any one of these parameters, for this study the layer thicknesses (net accumulation) were calculated using the winter minima in dust concentration.

Santiago de la Peña 3/8/2015 6:09 PM

Deleted: only

Santiago de la Peña 3/26/2015 2:43 PM

Deleted: 3

226 layers were found at all sites visited and appear to be continuous throughout the area surveyed. In  
227 2004, total ice thickness at an elevation of 1950 m averaged 10 cm (Parry *et al.*, 2007), significantly  
228 less than the ice content in 2013 at J4, located 400 m higher on the ice sheet. The total mass of the ice  
229 layers found at the J sites averaged  $441 \pm 12 \text{ kg m}^{-2}$  (0.48 ± 0.013 m thick) and  $306 \pm 118 \text{ kg m}^{-2}$  (0.33  
230 ± 0.128 m thick) in 2013 (related to 2012 melt season) and 2014 (related to 2013 melt season)  
231 respectively. In April 2011 at the higher elevation sites, the total ice layer mass was 285, 255 and 160  
232  $\text{kg m}^{-2}$  for T12, T13 and T14 respectively. Ice content decreased at T15 (h = 2490 m), where an ice  
233 layer just 4 cm thick ( $36 \text{ kg m}^{-2}$ ) was found, suggesting this site was close to the boundary of the dry  
234 snow zone that year. At the J-sites, winter accumulation was measured at  $1.11 \pm 0.17 \text{ m}$ ,  $0.885 \pm 0.08$   
235  $\text{m}$ , and  $1.35 \pm 0.07 \text{ m}$  in the winters of 2011-2012, 2012-2013 and 2013-2014 respectively. The 2010-  
236 2011 winter accumulation measured at the T12-T15 sites was  $1.10 \pm 0.12 \text{ m}$ . Winter snow density was  
237 measured in 2011 and exhibited little variability ( $247 \pm 8 \text{ kg m}^{-3}$ ), consistent with previous  
238 observations (Parry *et al.*, 2007). Total annual ice content found beneath the wintertime snow  
239 accumulation during each of the campaigns described in the previous section is summarized in Figure  
240 3, revealing the sharp increase in firm-ice content since 2010, where the annual ice layers were an  
241 order of magnitude thicker in total than the 1977-1997 average from PARCA core 6945.

242 Measurements in April 2011 by the NASA Snow Radar show the extent of the type of  
243 percolation features as described above that formed during the 2010 melt season (Figure 4). Data for  
244 the years 2012 and 2013 is not available. The ~420 km-long transect extends from the ablation zone  
245 to the ice divide in the dry snow zone and overflights close to our research sites. Radar signals are  
246 partially backscattered from within a stratified snowpack by abrupt changes encountered in snow  
247 density and/or ice structure, such as ice layers in the percolation zone, or 'autumn hoar' in the dry  
248 snow zone. Near surface layering is observed in the 1600-2200 m elevation range and winter  
249 accumulation over the previous summer melt layer is clearly resolved while deeper layers are  
250 obscured by infiltration ice that limits radar signal penetration. The topmost reflection under the  
251 observed winter surface is continuous over most the percolation zone, confirming that ice layers  
252 observed at the J field sites are widespread over an elevation range of 1600 to 2200 m, about 220 km  
253 inland from the ice margin. The ice layer was retraced with a custom-made threshold algorithm  
254 configured to identify strong reflections underneath the surface (shown with a black line in Figure 4).  
255 The retracker was applied up to 2450 m, elevation at which isochrones can be observed to a depth  
256 greater than 5 m, evidence that no significant amount of ice is present in the snowpack to prevent  
257 radar signal penetration. The threshold algorithm tracks continuity between horizontally adjacent  
258 pixels, so that the retraced layer in one individual radar acquisition is not separated vertically by more  
259 than ~20 cm from the next measurement. In some sections the buried signal could not be  
260 differentiated from the surface, and at some points there is discontinuity in the signal. However, for  
261 most of the percolation zone the reflection appears continuous, tracked at a depth of  $0.81 \pm 0.29 \text{ m}$ ,  
262 slightly lower than the field measurements at T sites. The underestimation is likely the result of  
263 tracking on the leading edge of the signal and does not affect our analysis.

264 At higher elevations, annual accumulation layers are clearly seen to depths of at least 15 m,  
265 consistent with previous observations from the dry snow zone (Hawley *et al.*, 2005; de la Peña *et al.*,  
266 2010; Simonsen *et al.*, 2013). While melt has intensified over the last decade, the 2012 melt episodes  
267 had notably bigger impacts on the firm structure, with significant melting and infiltration extending to  
268 the ice divide (Tedesco *et al.*, 2013). Figure 5 shows annual elevation changes over the same transect  
269 shown in Figure 4 obtained from repeat ATM lidar overflights between 2010 and 2013. While snow  
270 accumulation variability and ice dynamics are factors in the observed surface elevation change,  
271 lowering of the magnitude observed in 2012-2013 must be the result of surface melt, infiltration and

Santiago de la Peña 4/28/2015 11:19 AM

Deleted: algorithm

Santiago de la Peña 4/28/2015 4:22 AM

Formatted: Indent: First line: 0.5"

273 densification of the firm, since variability in annual snow accumulation is not large enough to cause  
274 the departure seen in 2012-2013, and there is no indication that dynamic thinning during that year was  
275 significantly different from previous years. Average elevation change estimated across the 1600-2600  
276 m elevation range is  $-0.803 \pm 0.391 \text{ m yr}^{-1}$ , compared to  $-0.112 \pm 0.067 \text{ m yr}^{-1}$  and  $0.031 \pm 0.188 \text{ m yr}^{-1}$   
277 in 2010-2011 and 2011-2012 respectively. This difference does not represent a loss in mass but  
278 rather a rapid densification of the near-surface structure of the firm, with surface lowering observed  
279 almost to the ice divide.

#### 280 4. Melt intensity and extent of the percolation zone

281 Figure 6 presents results from RACMO2.3/GR between 1958 and 2013 for each of the sites visited  
282 between 2011 and 2014, and Table 1 shows modeled melt and accumulation rates for the years 2003,  
283 2010, and 2012. Melt at J1 increased from  $340 \text{ kg m}^{-2}$  in 2003 to  $810 \text{ kg m}^{-2}$  in 2012 (3 times the  
284 1958-1999 average of  $285 \text{ kg m}^{-2}$ ), but as discussed in the previous section, total ice content increased  
285 more than 5 times over the same period. Ice layer thickness does not increase as a simple function of  
286 surface melt. Infiltration of meltwater into firm is complicated by factors including the initial thermal  
287 state and structure of the firm and the timing and duration of melt. For example, more frequent  
288 extreme melt events, such as the event that occurred in 2012, may cause rapid snow saturation and  
289 refreezing near the surface, resulting in the formation of thicker and more extensive ice layers. The  
290 formation of ice reservoirs of this magnitude is thus not only dependent on melt increase, but also on  
291 how melt is distributed during summer. Uncertainties in melt and refreezing rates in RACMO2.3/GR  
292 add to this complexity, and as a result, it is difficult to confidently predict firm changes using only the  
293 model results. For instance, in 2003, the ice layers observed to have formed during the summer at  
294 2000 m elevation accounted for 29% of total modeled melt, while in 2012 discernible ice content was  
295 79% of the modeled melt (52% at the highest site at 2350 m). The 2012 melt season anomaly was  
296 driven partly by extreme, short-lived melt episodes (i.e. *Nghiem et al.*, 2012; *Bennartz et al.*, 2013;  
297 *Tedesco et al.*, 2013), which as discussed may result in more ice content. Increases in modeled melt  
298 rates at higher sites are even more pronounced than at J1, with rates at J4 increasing from less than  
299  $100 \text{ kg m}^{-2}$  over the period from 1958 to 1999, to a rate of 305 and  $580 \text{ kg m}^{-2}$  in 2010 and 2012  
300 respectively (Figure 6). Prior to 2012, the largest modeled melt rates occurred in 2010 at all sites  
301 except at the highest regions (above 2200 m), which registered the largest melt rate in 2007 (second  
302 highest for the lower sites). Large modeled melt rates at all sites occurred during the warm years of  
303 1995, 1998, 2007, and 2010. Melt at J1 increased from less than  $300 \text{ kg m}^{-2}$  between 1958 and 1999,  
304 to  $340 \text{ kg m}^{-2}$  in 2003 and to  $755 \text{ kg m}^{-2}$  in 2010. At J4 there was only an increase of 30% in 2010  
305 with respect to 2003 (from 235 to  $305 \text{ kg m}^{-2}$ ), but this increased to  $580 \text{ kg m}^{-2}$  in 2012. Before 2012,  
306 the modeled melt rate at this site was highest in 2007, in contrast to the 2010 peak melt rates  
307 estimated for most of the western Greenland margin (*Tedesco et al.*, 2011). The mass of ice found in  
308 2013 at sites J1 and J2 exceeds the mass of the total annual accumulation for 2012, a trend that  
309 according to RACMO2.3/GR has been occurring at J1 since 2007. Modeled melt rates in 2013 are  
310 significantly lower than in 2012, but still larger than the 1958-1999 average. We found no evidence of  
311 meltwater pathways or pond formation at our field sites. If, however, conditions impermeable ice  
312 layers keep forming over extensive areas and melt continues to exceed total accumulation, it is likely  
313 that lateral supraglacial transport and eventual runoff of excess meltwater will reach to 2000 m  
314 elevation in western Greenland.

315 Figure 7 presents annual melt predicted by RACMO2.3/GR in areas of the GrIS with  
316 predicted positive surface mass balance (i.e. the accumulation zone) for each time period presented.  
317 The left figure shows the 1958-1999 average, while the right figure is the annual melt rates in 2012,  
318 illustrating the changes in melt intensity and the size of the areas affected by melt over Greenland.

Santiago de la Peña 3/30/2015 3:15 PM

Deleted: compaction

Santiago de la Peña 4/28/2015 4:22 AM

Deleted: -

Santiago de la Peña 3/8/2015 3:30 PM

Deleted: at each site the

Santiago de la Peña 3/30/2015 9:26 AM

Deleted: at each site

Santiago de la Peña 3/8/2015 3:32 PM

Deleted: suggests

324 The predicted average area of the accumulation zone that experienced melt between 1958 and 1999  
325 was about 405,000 km<sup>2</sup>. The extent of this area then increased 240% in 10 years, from 465,000 km<sup>2</sup> in  
326 2003 to a maximum of 1,155,000 km<sup>2</sup> in 2012, more than half the total area of the ice sheet. Although  
327 in 2010 the percolation zone covered a total area of 486,000 km<sup>2</sup>, only a 5% increase with respect to  
328 2003, the intensity of melt increased drastically after 1999, especially in west and southwest  
329 Greenland. To quantify the magnitude of refrozen meltwater in 2012, we estimate total annual ice  
330 content in western Greenland by identifying areas where snowfall and melt rates are sufficiently high  
331 (greater than 100 kg/m<sup>2</sup> per year) to form the stratified snowpack structure described above. We  
332 estimate the total mass refrozen in the snowpack in western Greenland by relating melt rates from  
333 RACMO2.3/GR to the measured ice content found during 2011 and 2013, and subtract the mass of  
334 the snow that occupied the volume where meltwater refroze (total ice content cannot exceed the total  
335 winter accumulation). Based on the field measurements, we assume an average winter snow density  
336 of 250 kg m<sup>-3</sup>. Our estimates indicate that the total 2012 infiltration ice content above the equilibrium  
337 line and west of the ice divide of the GrIS was 74 ± 25 Gt, compared to an average of only 13 ± 2 Gt  
338 between 1958 and 1999. Most of this ice is distributed near the surface solely in the form of thick  
339 layers that appear to be widespread.

## 340 5. Discussion and conclusions

341 Our field observations reveal substantial, recent changes in the structure of high-elevation percolation  
342 facies that differ from those recorded in previous decades. Observations in 2004 and 2006 showed an  
343 increase from the 1977-1997 average ice content, but the lack of significant ice above 2000 m was  
344 evidence that the transition between the percolation and dry snow zones was near this elevation (*Scott*  
345 *et al.*, 2006b). In contrast, the Snow Radar data obtained in spring 2011 reveals that the percolation  
346 zone has risen with the transition in the previous few years occurring at elevations between 2200 and  
347 2400 m. More importantly, the concentration of ice at higher elevations has increased dramatically,  
348 and the formation of thick, widespread continuous ice layers is increasingly common over extensive  
349 areas of the percolation zone causing large changes in the air content of the firn. Furthermore, the  
350 increase in firn ice content raises questions regarding the permeability of the firn column across the  
351 percolation zone, and the effects it could have on meltwater retention and transport and on firn  
352 compaction rates.

353 The formation of percolation facies in the last few decades of the 20<sup>th</sup> Century above 2000 m  
354 was limited, and during some years melt was not even strong enough to form identifiable ice layers. In  
355 this context, the percolation features described here have no recent precedent. Considering, as  
356 measured in the field, an average surface snow density before melt of 250 kg m<sup>-3</sup>, and that meltwater  
357 refreezes in a volume occupied by snow of this density, each meter of winter snow would equate to  
358 layers of ice totaling ~0.35 m thick after refreezing if little or no air remains trapped within. This  
359 process will create the observed seasonal change in the volume of the firn governed by accumulation,  
360 compaction, and melting and refreezing. Even without thermal snow densification, commonly used  
361 steady-state snow density and firn compaction assumptions used for altimetry-derived mass balance  
362 estimates would need to be reconsidered for regions where percolation features become more  
363 impermeable. These ice layers not only significantly limit the total meltwater buffering capacity of the  
364 percolation zone estimated by *Harper et al.* (2012), but also introduce variability in compaction rates  
365 if air is trapped within ice layers. Moreover, and as observed at sites J1 and J2, the winter snow in  
366 these regions of the accumulation zone of the ice sheet completely melted and refroze in 2012,  
367 meaning mass gain in these areas was in the form of superimposed ice. Although the melt season of  
368 2012 was unusually warm, rather than an isolated episode it represent the most dramatic example of  
369 changes that are occurring due to the above-average warming in western Greenland observed in the

Santiago de la Peña 3/31/2015 9:29 AM

Formatted: Superscript

Santiago de la Peña 4/28/2015 4:26 AM

Deleted: (a percentage of the total melt)

371 | [last decade.](#)

372 Melt affecting the GrIS has increased over recent decades, with pronounced departures from  
373 the 1958-1999 mean melt rate during the last few years in regions well within the accumulation zone  
374 of the GrIS. High (and highly variable) accumulation rates play an important role in the surface mass  
375 balance of the ice sheet at higher elevations, but with melt rates increasing faster than snow  
376 accumulation in Greenland (*Fettweis, 2007; Van Angelen et al., 2014*), meltwater excess during warm  
377 years may saturate the already limited firn meltwater storage capacity over large areas (*Van Angelen  
378 et al., 2013*). Although no evidence of extensive lateral hydrological pathways was found at any of  
379 our field sites, it is likely that if melt continues to exceed total accumulation, water will soon be  
380 transported to lower elevations by supraglacial flow, especially during years experiencing extreme  
381 melt. Recent studies show that lakes are increasingly found at higher elevations (*Banwell et al., 2012;  
382 Liang et al., 2012; Howat et al., 2013*), and it is unclear how the percolation zone will evolve if more  
383 meltwater ponds are being formed over firn. Furthermore, [according to RACMO2.3](#), if current  
384 warming trends continue, the percolation zone will potentially extend to most areas above the  
385 equilibrium line. Regardless of the role they will play in the future, these huge ice reservoirs are the  
386 result of an intense melting process of the same order of magnitude as the total mass imbalance of the  
387 GrIS, and the consequences of their formation described here underlines the importance of monitoring  
388 the evolution of Greenland's firn layer in the coming years.

Santiago de la Peña 3/30/2015 3:33 PM

Deleted: facies

Santiago de la Peña 3/30/2015 3:34 PM

Deleted: in the future

Santiago de la Peña 3/30/2015 3:33 PM

Deleted: I cover an even greater extent

Santiago de la Peña 3/30/2015 3:34 PM

Deleted: ing

Santiago de la Peña 3/30/2015 3:34 PM

Deleted: all

394 **Bibliography**

395 Abdalati, W., R. Bales, and R. Thomas (1998). Program for Arctic Regional Climate Assessment. An  
396 improved understanding of the Greenland ice sheet. *Arct. Res.*, **12**, 38-54.

397 Bales, R.C., J.R. McConnell, E. Mosley-Thompson, and B. Csatho (2001). Accumulation over the  
398 Greenland Ice Sheet from historical and recent records. *J. Geophys. Res.*, **106**(D24), 33, 813-33, 825,  
399 doi:10.1029/2001JD900153.

400 Banwell, A.F., Arnold, N.S., Willis, I.C., Tedesco, M., and Ahlström, A.P. (2012). Modeling  
401 supraglacial water routing and lake filling on the Greenland Ice Sheet, *JGR-Earth Surface*, 117,  
402 F04012, doi:10.1029/2012JF002393.

403  
404 [Bell et al., \(2008\). Spatial and temporal variability in the snowpack of a High Arctic ice cap:  
405 Implications for mass-change measurements, \*Ann. Glaciol.\*, \*\*48\*\*, 159–170.](#)

406 Bennartz, R., M.D. Shupe, D.D. Turner, V.P. Walden, K. Steffen, C.J. Cox, M.S. Kulie, N.B. Miller,  
407 and C. Pettersen (2013). July 2012 Greenland melt extent enhanced by low-level liquid clouds.  
408 *Nature*, 496, 83-86, doi:10.1038/nature12002.

409 Benson, C. (1962). Stratigraphic studies of the snow and firn of the Greenland ice sheet. *Res. Rep.* **70**,  
410 U.S. Army Snow Ice and Permafrost Res. Estab.

411 Bougamont, M., Bamber, J. L., and Greuell, W.: A surface mass balance model for the Greenland Ice  
412 Sheet, *J. Geophys. Res.*, 110, F04018, doi:10.1029/2005JF000348, 2005.

413  
414 Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet  
415 albedo feedback: thermodynamics and atmospheric drivers, *The Cryosphere*, **6**, 821-839,  
416 doi:10.5194/tc-6-821-2012, 2012.

417  
418 Burgess, E. W., Forster, R. R., Box, J. E., Mosley-Thompson, E., Bromwich, D. H., Bales, R. C., and  
419 Smith, L. C.: A spatially calibrated model of annual accumulation rate on the Greenland ice sheet  
420 annual (1958–2007), *J. Geophys. Res.*, 115, F02004, doi:10.1029/2009JF001293.2009, 2010.

421  
422 De la Peña, S., Nienow, P., Shepherd, A., Helm, V., Mair, D., Hanna, E., Huybrechts, P., Guo, Q.,  
423 Cullen, R., and Wingham, D. (2010). Spatially extensive estimates of annual accumulation in the dry  
424 snow zone of the Greenland Ice Sheet determined from radar altimetry, *The Cryosphere*, **4**, 467-474,  
425 doi:10.5194/tc-4-467-2010.

426 Ettema, J., M.R. van den Broeke, E. van Meijgaard, W.J. van de Berg, J.L. Bamber, J.E. Box, and  
427 R.C. Bales (2009). Higher surface mass balance of the Greenland ice sheet revealed by high-  
428 resolution climate modeling, *Geophys. Res. Lett.*, **36**, L12501, doi:10.1029/2009GL038110.

429  
430 Fettweis, X., M. Tedesco, M. van den Broeke, and J. Ettema (2011). Melting trends over the  
431 Greenland ice sheet (1958-2009) from spaceborne microwave data and regional climate models. *The  
432 Cryosphere*, **5**, 359-375.

433 Fettweis, X., E. Hanna, C. Lang, A. Belleflamme, M. Erpicum, and H. Gallée (2013). Brief  
434 Communication “Important role of the mid-tropospheric atmospheric circulation on the recent surface  
435 melt increase over the Greenland ice sheet”, *The Cryosphere*, **7**, 241-248, doi:10.5194/tc-7-241-2013.

436 Harper, J., N. Humphrey, W.T. Pfeffer, J. Brown, and X. Fettweis (2012). Greenland ice-sheet

Santiago de la Peña 4/28/2015 12:39 PM  
Formatted: Normal

Santiago de la Peña 4/28/2015 12:38 PM  
Formatted: Font:Italic

Santiago de la Peña 4/28/2015 12:38 PM  
Formatted: Font:(Default) Times New Roman

437 contribution to sea-level rise buffered by meltwater storage in firn. *Nature*, doi:1038/nature11566.

438 Hawley, R.L., E.M. Morris, R. Cullen, U. Nixdorf, A. Shepherd, and D.J. Wingham (2006). ASIRAS  
439 airborne radar resolves internal annual layers in the dry-snow of Greenland", *Geophys. Res. Lett.*  
440 **33**(4), L04502, doi:10.1029/2005GL025147.

441 Helm, V., W. Rack, R. Cullen, P. Nienow, D. Mair, V. Parry, and D.J. Wingham (2007). Winter  
442 accumulation in the percolation zone of Greenland measured by airborne radar altimeter. *Geophys.*  
443 *Res. Lett.*, **34**, L06501, doi:10.1029/2006GL029185.

444 Howat, I.M., de la Peña, S., van Angelen, J.H., Lenaerts, J.T.M., and van den Broeke, M.R.  
445 (2013). *Brief Communication* "Expansion of meltwater lakes on the Greenland Ice Sheet", *The*  
446 *Cryosphere*, **7**, 201-204, doi:10.5194/tc-7-201-2013.

447 Leuschen, C., P. Gogineni, R. Hale, J. Paden, F. Rodríguez, B. Panzer, and D. Gomez (2014).  
448 IceBridge Snow Radar L1B geolocated radar echo strength profiles, version 2 [20110419, 20130405].  
449 Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center.

450 McConnell, J.R., Mosley-Thompson, E., Bromwich, D.H., Bales, R.C., and Kyne, J.D. (2000).  
451 Interannual variations of snow accumulation on the Greenland Ice Sheet (1985-1996): new  
452 observations versus model predictions. *JGR*, **105**, D3, 4039-4046.

453 [Morris et al., \(2014\). Field-calibrated model of melt, refreezing, and runoff for polar ice caps:  
454 Application to Devon Ice Cap. \*JGR\*, 10.1002/2014JF003100.](#)

455 Mosley-Thompson, E., J.R. McConnell, R.C. Bales, Z. Li, P.N. Lin, K. Steffen, L.G. Thompson, R.  
456 Edwards, and D. Bathke (2001). Local to regional-scale variability of annual net accumulation on the  
457 Greenland Ice Sheet from PARCA cores. *J. Geophys. Res.*, **106**(D24), 33, 839-33, 851,  
458 doi:10.1029/2001JD900067.

459 Nghiem, S.V., D.K. Hall, T.L. Mote, M. Tedesco, M.R. Albert, K. Keegan, C.A. Shuman, N.E.  
460 DiGirolamo, and G. Neumann (2012). The extreme melt across the Greenland ice sheet in 2012.  
461 *Geophys. Res. Lett.*, **39**, L20502, doi:10.1029/2012GL053611.

462 Parry, V., P. Nienow, D. Mair, J. Scott, B. Hubbard, K. Steffen, D. Wingham (2007). Investigations of  
463 meltwater refreezing and density variations in the snowpack and firn within the percolation zone of  
464 the Greenland ice sheet. *Annals of Glac.*, **46**, 61-68.

465 Pfeffer, W.T., M.F. Meier, and T.H. Illangasekare (1991). Retention of Greenland Runoff by  
466 Refreezing: Implications for Projected Future Sea Level Change. *J. Geophys. Res.*, **96**(C12), 22,117-  
467 22,124.

468 Scott, J., D. Mair, P. Nienow, V. Parry, and E. Morris (2006a). A ground-based radar backscatter  
469 investigation in the percolation zone of the Greenland Ice Sheet. *Remote Sens. Environ.*, **104**(4), 361-  
470 373.

471 Scott, J., P. Nienow, D. Mair, V. Parry, E. Morris, and D.J. Wingham (2006b). Importance of seasonal  
472 and annual layers in controlling backscatter to radar altimeters across the percolation zone of an ice  
473 sheet. *Geophys. Res. Lett.*, **33**, L24502, doi:10.1029/2006GL027974.

474 Simonsen, S.B., L. Stenseng, G. Adalgeirsdottir, R.S. Fausto, C.S. Hvidberg, P. Lucas-Picher (2013).  
475 Assessing a multilayered dynamic firn-compaction model for Greenland with ASIRAS radar

Santiago de la Peña 4/28/2015 12:38 PM  
Deleted: .

Santiago de la Peña 4/28/2015 12:39 PM  
Formatted: Normal

Santiago de la Peña 4/28/2015 12:38 PM  
Formatted: Font:Italic

Santiago de la Peña 4/28/2015 12:38 PM  
Formatted: Font:(Default) Times New Roman

477 measurements. *J. Glac.*, **59**, 215, doi:10.3189/2013JoG12J158.

478 Tedesco, M., M. Serreze, and X. Fettweis (2008). Diagnosing the extreme surface melt event over  
479 southwestern Greenland in 2007. *The Cryosphere*, **2**, 159-166, doi:10.5194/tc-2-159-2008.

480 Tedesco, M., X. Fettweis, M.R. Van den Broeke, R.S.W. Van de Wal, C.J.P.P. Smeets, W.J. Van de  
481 Berg, M.C. Serreze, and J.E. Box (2011). The role of albedo and accumulation in the 2010 melting  
482 record in Greenland. *Environ. Res. Lett.*, **6**, 014005.

483 Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box, and B. Wouters (2013). Evidence  
484 and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and  
485 reanalysis data. *The Cryosphere*, **7**, 615-630, doi:10.5194/tc-7-615-2013.

486 Tingley, M.P., and P. Huybers (2013). Recent temperature extremes at high northern latitudes  
487 unprecedented in the past 600 years. *Nature*, **496**, 201-205, doi:10.1038/nature11969.

488

489 Van den Broeke, M., P. Smeets, J. Ettema, C. van der Veen, R. van de Wal, and J. Oerlemans (2008).  
490 Partitioning of melt energy and meltwater fluxes in the ablation zone of the west Greenland ice sheet.  
491 *The Cryosphere*, **2**, 179-189.

492 Van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. Van de Berg, E. van  
493 Meijgaard, I. Velicogna, and B. Wouters (2009). Partitioning Recent Greenland Mass Loss. *Science*,  
494 **326**, 984-986, doi:10.1126/science.1178176.

495 Van Meijgaard, E., L. H. van Ulkft, W. J. van de Berg, F. C. Bosveld, B. J. J. M. van den Huri, g.  
496 Lenderink, and A. P. Siebesma (2008). The KNMI regional atmospheric climate model, version 2.1,  
497 *KNMI Tech. Rep.* 302, R. Neth. Meteorol. Inst., De Bilt, Netherlands.

498 Van Angelen, J. H., J. T. M. Lenaerts, M. R. van den Broeke, X. Fettweis, and E. van Meijgaard,  
499 (2013). Rapid loss of firn pore space accelerates 21st century Greenland mass loss, *Geophysical*  
500 *Research Letters* **40**, doi:10.1002/grl.50490.

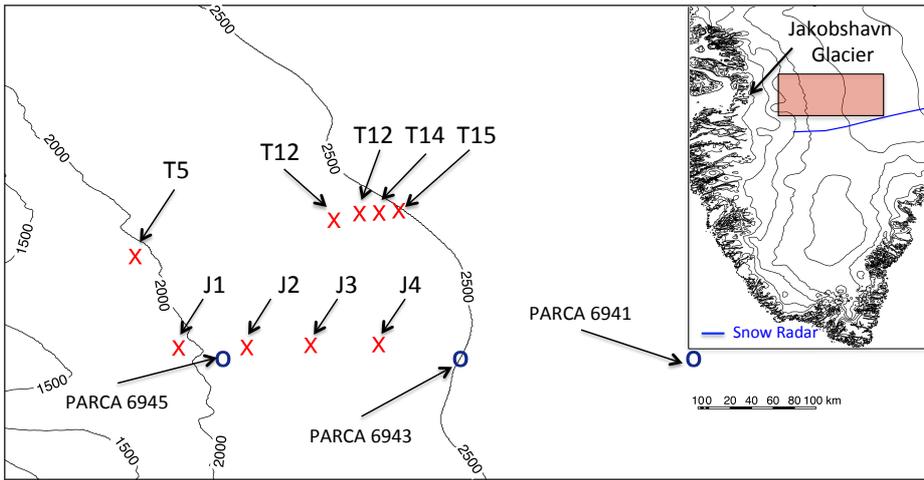
501

502 Van Angelen, J. H., M. R. van den Broeke, B. Wouters and J. T. M. Lenaerts, (2014). Contemporary  
503 (1960–2012) evolution of the climate and surface mass balance of the Greenland ice sheet, *Surveys of*  
504 *Geophysics*, doi: 10.1007/s10712-013-9261-z.

Site	Latitude	Longitude	Elevation (m)	Melt (kg/m <sup>2</sup> ) 2003/2010/2012	Accumulation (kg/m <sup>2</sup> ) 2003/2010/2012
J1	69.212° N	46.152° W	1935	340 / 753 / 808	520 / 497 / 648
J2	69.218° N	45.566° W	2090	250 / 569 / 729	513 / 644 / 500
J3	69.221° N	44.762° W	2245	87 / 341 / 637	505 / 492 / 635
J4	69.221° N	44.089° W	2350	31 / 305 / 580	505 / 480 / 628
T12	70.175° N	45.345° W	2345	37 / 195 / 502	498 / 548 / 599
T13	70.274° N	45.008° W	2455	17 / 178 / 507	501 / 550 / 604
T14	70.302° N	44.757° W	2464	17 / 170 / 455	496 / 546 / 601
T15	70.302° N	44.574° W	2490	13 / 104 / 399	493 / 538 / 601

**Table 1:** Melt and accumulation at each field site as simulated by RACMO2.3/GR.

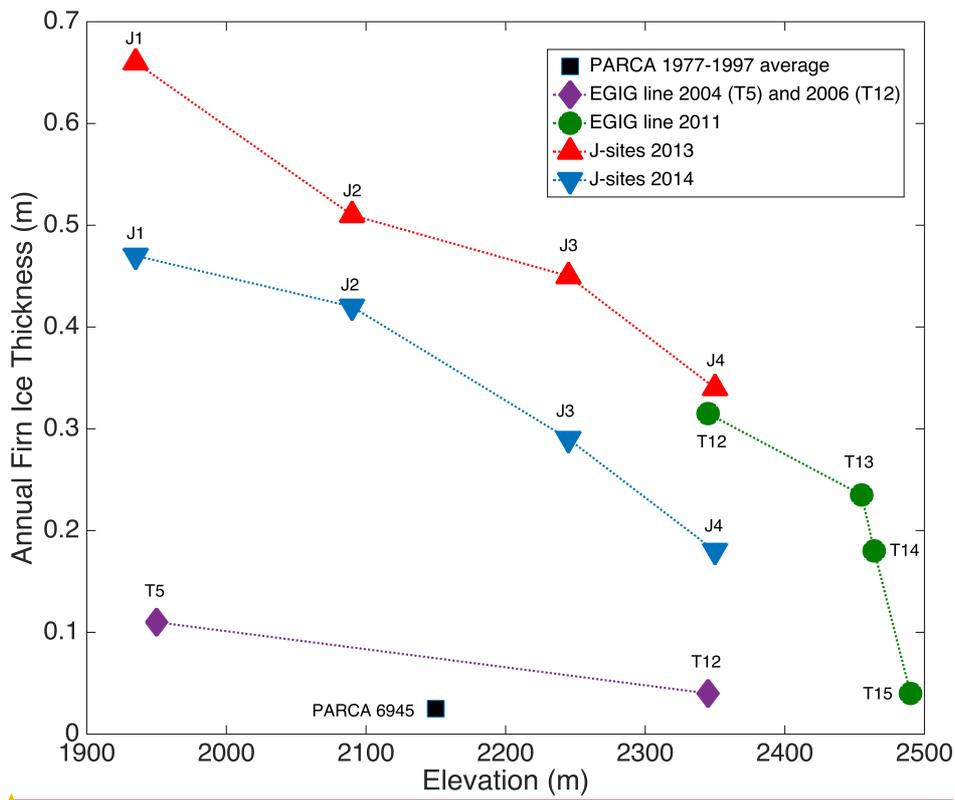
- Santiago de la Peña 4/20/2015 12:21 PM  
**Formatted Table**
- Santiago de la Peña 4/20/2015 10:41 AM  
**Deleted:** 12' 44''
- Santiago de la Peña 4/20/2015 10:42 AM  
**Deleted:**
- Santiago de la Peña 4/20/2015 10:55 AM  
**Deleted:** 09' 07''
- Santiago de la Peña 4/20/2015 10:42 AM  
**Deleted:** 13' 05''
- Santiago de la Peña 4/20/2015 10:55 AM  
**Deleted:** 34' 00''
- Santiago de la Peña 4/20/2015 10:43 AM  
**Deleted:** 13' 16''
- Santiago de la Peña 4/20/2015 10:55 AM  
**Deleted:** 45' 45''
- Santiago de la Peña 4/20/2015 10:43 AM  
**Deleted:** 13' 16''
- Santiago de la Peña 4/20/2015 10:56 AM  
**Deleted:** 05' 19''
- Santiago de la Peña 4/20/2015 10:44 AM  
**Deleted:** 10' 32''
- Santiago de la Peña 4/20/2015 10:57 AM  
**Deleted:** 20' 41''
- Santiago de la Peña 4/20/2015 10:44 AM  
**Deleted:** 16' 27''
- Santiago de la Peña 4/20/2015 10:57 AM  
**Deleted:** 00' 28''
- Santiago de la Peña 4/20/2015 10:45 AM  
**Deleted:** 18' 10''
- Santiago de la Peña 4/20/2015 10:58 AM  
**Deleted:** 45'' 26''
- Santiago de la Peña 4/20/2015 10:49 AM  
**Deleted:** 18' 09''
- Santiago de la Peña 4/20/2015 10:58 AM  
**Deleted:** 34' 25''



523

524 **Figure 1.** Location of research area and research sites (all T-sites are along the EGIG line). Inset: map  
 525 of western Greenland showing the area surveyed. Blue line is the flightpath of the NASA Operation  
 526 IceBridge data shown in Figure 4 and 5. Snowpit sites are shown with an X, while core sites are  
 527 shown with a blue circle. Contour lines represent 500 m surface elevation intervals.

- Unknown
- Formatted: Font:Bold
- Santiago de la Peña 4/22/2015 9:49 AM
- Deleted: Map of Greenland showing the r
- Santiago de la Peña 4/22/2015 9:50 AM
- Deleted: ack
- Santiago de la Peña 4/22/2015 9:50 AM
- Deleted: [Page Break](#)

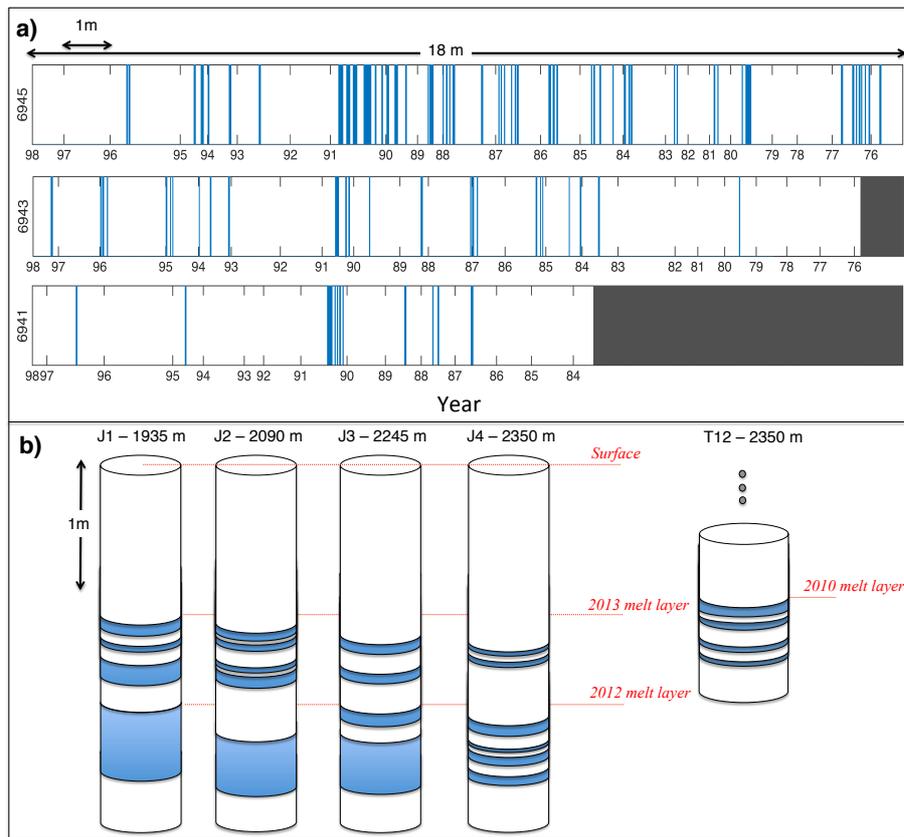


Unknown  
 Formatted: Font:(Default) Times New Roman, Bold

531  
 532  
 533

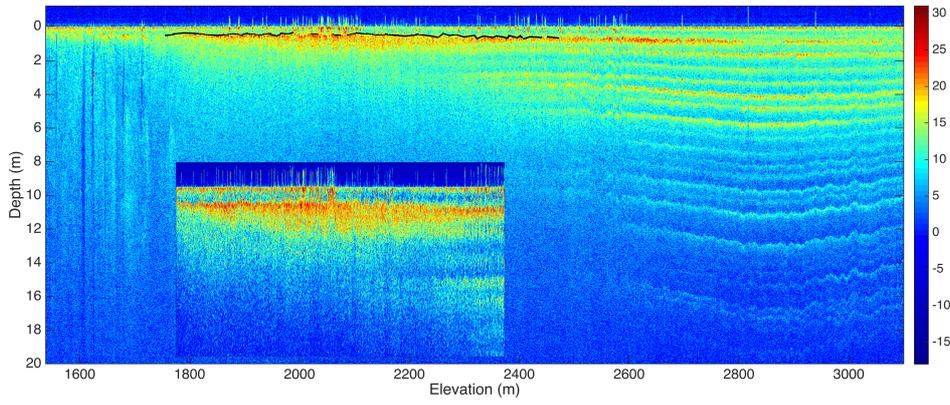
Figure 2. Firn ice content vs. elevation measured in field campaigns between 1998 and 2014. All measurements taken from snow pits except PARCA 1977-1997 average, taken from core 6945.

Santiago de la Peña 4/29/2015 3:59 AM  
 Deleted:



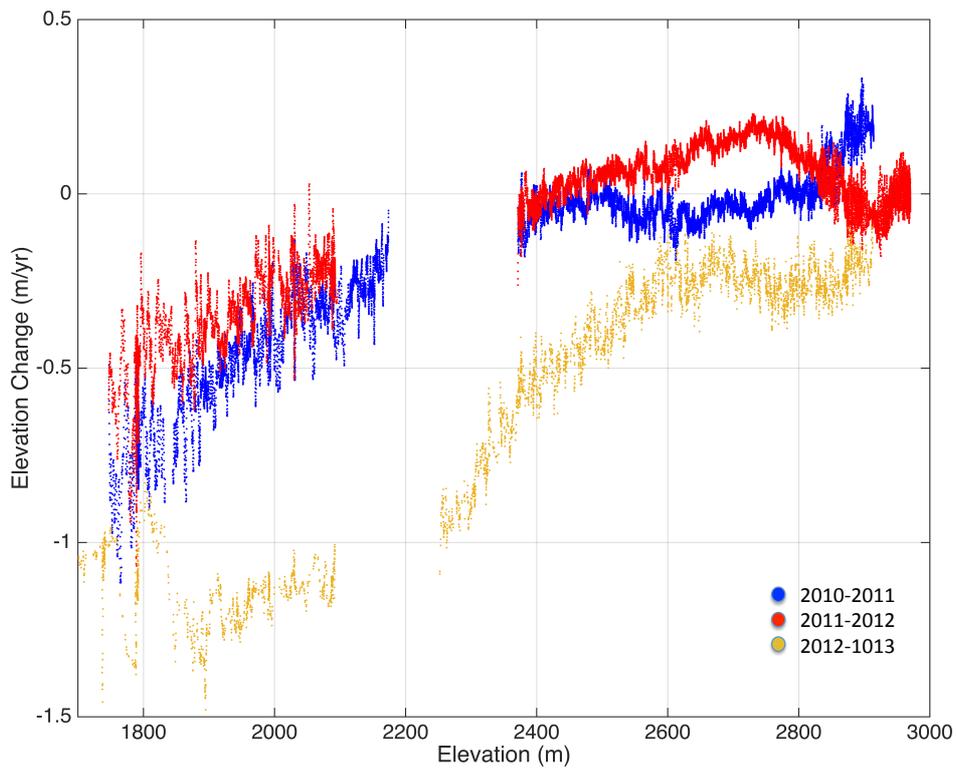
535  
536

537 **Figure 3.** a) Ice layers and ice lenses present in the visible stratigraphy of PARCA firn cores 6941,  
 538 6943, and 6945 drilled in 1998 are plotted with depth in core (m). The deepest core is 18 m long and  
 539 the dates are assigned at the depth (m) of each year's winter minima in dust concentration. b)  
 540 Schematic showing ice layer structure as measured in snow pits excavated between 2011 and 2014.  
 541 The melt layer dashed lines indicate the position where the top of the ice layer was found in the field  
 542 at J1 for the J-sites, and at T12. J-sites are represented as found in April 2014. T12 representation is  
 543 shown as found in 2011.



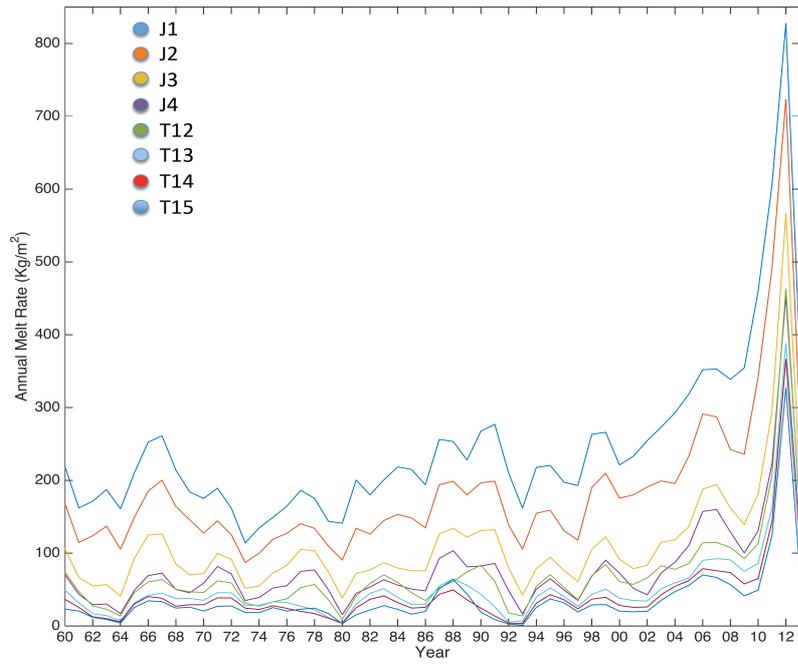
544

545 | **Figure 4.** A transect in western Greenland showing Operation IceBridge Snow Radar response to the  
 546 snowpack in 2011. The aerial survey extends (left to right) from the ablation zone to the dry snow  
 547 zone. The color scale shows the relative power intensity (in dB). The black line shows the position  
 548 | where the melt layer (i.e. the top of the ice layer formed after the 2010 melt season) was retraced.  
 549 Inset shows the upper ~5 meters where the melt layer is located.



550

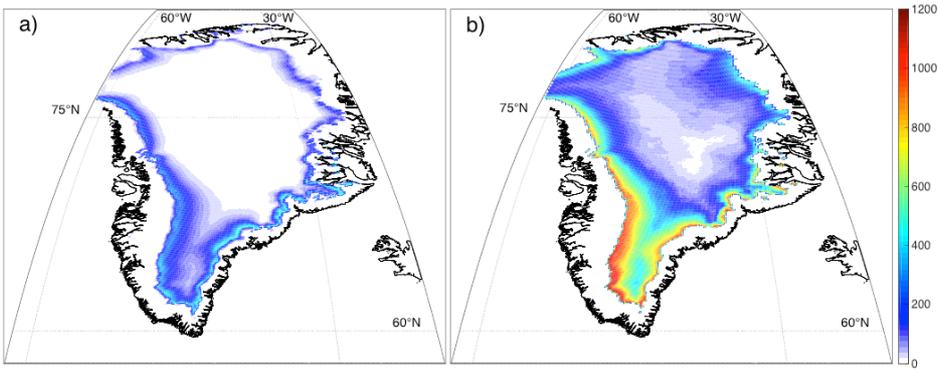
551 **Figure 5.** Elevation change estimated from NASA ATM laser altimeter in western Greenland along  
552 the flight path shown in Figure 1. Estimates are for annual change in 2011 (blue), 2012 (red), and  
553 2013 (yellow).



554

555 **Figure 6.** 1958-2013 Modeled annual melt rates from RACMO2.3/GR for each field site visited  
 556 between 2011 and 2014.

Unknown  
 Formatted: Font:Bold



557 **Figure 7.** Regional Atmospheric Climate Model (RACMO2.3/GR) annual melt rates ( $\text{kg m}^{-2}$ ) shown  
 558 for areas of the GrIS with predicted positive surface mass balance (i.e. above the equilibrium line).  
 559 Annual melt rates shown for a) the 1958-1999 average and b) for 2012.

Santiago de la Peña 4/30/2015 1:18 PM  
 Deleted: -