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The Cryosphere Discussions

Interactive comment on "Regional Greenland Accumulation Variability from Operation IceBridge Airborne Accumulation Radar" *by* Gabriel Lewis et al.

Gabriel Lewis et al.

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Comment: This is a very nice study and it is good to see the accumulation radar datasets being put to use. We have just published a similar study also using Operation IceBridge data and a comparison between our two results would be very interesting. It could certainly give some insights into the robustness and reproducibility of this method for reconstructing past accumulation rates. For example, we retrieved higher than average accumulation rates during the past 100yr – does this dataset show the same? Our article can be found here: http://journal.frontiersin.org/article/10.3389/feart.2016.00097/full and the data here: http://www.iceandclimate.nbi.ku.dk/data/ or on the Pangaea website. Feel free to con-

tact me if you need additional data for comparison.

Response: We have added a section in the manuscript comparing our results to those in Karlsson et al. (2016). We find very similar values across the transect from NEEM to NGRIP, however we find slightly higher values during the 19th century (instead of the 20th century) than the 1712-2014 average. These differences are very small (<0.01 m w.e. a-1) and are most likely due to differences in our estimated depth-density profiles. We have added a figure comparing our accumulation measurements to the Karlsson et al. (2016) measurements.

"Comparison with Karlsson et al., 2016 A study by Karlsson et al. (2016; hereafter Karlsson16) uses a very different method to calculate accumulation from IceBridge Accumulation Radar data near NEEM and NGRIP. We compare data from their study, representing flight lines in 2011 and 2012, to a repeat flight during the 2014 IceBridge season analyzed using our method. In Figure 10 [reproduced below], the 1921-2014 accumulation rates (this study) are plotted against 1911-2011 Karlsson16 accumulation rates and the RCMs used for comparison in this study. On average along the 350 km flight line, the accumulation rates calculated in this study are 0.002 $\pm$ 0.005 m w.e. a-1 higher than in Karlsson16, well within calculated error, and in better agreement than the RCMs. Our accumulation values agree better with Karlsson16 from 150 km along the transect to NGRIP (underestimate of 0.002 $\pm$ 0.002 m w.e. a-1) than they do along the first half of the transect (overestimate of 0.007 $\pm$ 0.004 m w.e a-1). The average 1817-1921 measurements are 0.01 m w.e. a-1 higher than the 1811-1911 Karlsson16 values, and the 1712-1811 measurements are 0.0081 m w.e. a-1 higher than the 1711-1811 Karlsson16 values. Thus, our results are nearly identical with Karlsson16 over the time domain of this study, despite the two studies using different methods to calculate accumulation, analyzing different IceBridge flights from different years, and tracing IRHs from different ice cores."

Comment: Additionally, I would welcome some comments from the authors on a few points. Age assignment The IRHs are dated using an age-depth scale from a Summit

core drilled in 2007. Presumably, when transferred to the radar data, this age-scale is corrected for the fact that 6-7 years of accumulation has been added in the time between the core was drilled and the radar data were acquired. However, this is not stated explicitly. Furthermore, it would be worth mentioning how far from the radar flightline this core was drilled. We found that even a few kilometres of distance between the radar data and our dated ice core (the NEEM 2011 S1 core) meant that the radar data had to be offset by 50ns due to snow accumulated around camp. At Summit, the snow has been moved around extensively due to camp activities and I would assume that a direct transfer from the Summit timescale to the radar data is not possible. Since our tests indicate that an error in dating of the order of +/- 15yr could lead to large changes in resulting accumulation rate (upwards of 20%) a more rigorous treatment/discussion of the dating of the IRHs is called.

Response: We added the following sentences: “These ice cores are 3 and 7 km from the closest IceBridge radar trace, so we assume similar accumulation rates across this small distance. We correct for the 7-year difference between ice core collection and IceBridge radar flights by extrapolating the depth-age curve.”

Comment: Density profiles The calibrated Herron-Langway model is only briefly described and the paragraph raises a few questions. E.g., where are the in-situ measurements of surface density located that were used to calibrate the model? How spatially variable are the densities in the data domain? The adjustment of +/- 5% to accumulation rates and surface density for testing the sensitivity of the final accumulation rates also seems a bit low. In our study, we retrieved the surface density using an inverse method, and found that the surface density varied by 2%. Our study area is in the dry snow zone at the ice divide, and therefore most likely less variable than the surface density closer to the margins. Furthermore, the difference between the IceBridge accumulation rates and the accumulation rates from Burgess et al. 2010 exceed 5% according to Table 2. Increasing the adjustment to 10% probably still returns accumulation rates well within the stated uncertainty but it is worth a mention.

Response: Snow density values are obtained from ice cores at Summit, field measurements at EGIG t-31, and shallow cores at PARCA locations to calibrate Herron-Langway model. Elsewhere we use snow density values from MAR. We have now clarified these data sources in the text.

Comment: Layer thinning It is not explicitly stated but I assume that the thinning of the layers due to downwards advection has been corrected for? If not then the accumulation rates are consistently underestimated for older layers. This would lead to a systematic bias in the result.

Response: We have corrected for layer thinning and added the following paragraph: “The effect of layer thinning is very small for the time domain and region of this study. However, we correct for layer thinning due to downward advection using a Nye (1963) model. For each radar trace, the thinning factor, ïĄň(z), is calculated from the average accumulation, b ÌĞ (m w.e. a-1), age of the IRH, a (year), and thickness of the GrIS, H (m), from Morlighem et al. (2014): λ(z)=eˆ(-b ÌĞ/H a).”

Comment: Ice flow The manuscript contains no discussion on the influence of ice flow on the accumulation estimates. The movement of ice particles from, for example, low accumulation areas to high accumulation areas leads to an underestimation of the accumulation rate in the final measurement point. While 300yr is a relatively short time span and the ice particles have probably not moved very far there are some areas in the study region where ice flow velocities are high enough that it might have an impact. Again, this leads to a systematic over/underestimation rather than a random error.

Response: We added the following paragraph: “We do not correct for ice flow due to advection of the ice sheet since nearly all of the radar traces occur in areas with surface velocities < 50 m a-1. The only areas with higher velocities are across NEGIS and one small area in the southwest. Velocities in these areas are $\sim$ 60-100 m a-1 for the time domain of this study and do not significantly affect accumulation results”

Comment: Comparison with ice core / shallow core measurements The IceBridge ac-

cumulation rates are compared to ice core accumulation "over the time domain of each ice core". Does this imply that the IceBridge accumulation rates are compared to accumulation rates from the entire NEEM core including the last glacial period? I would assume not but a direct indication of which time periods are used for this comparison would be very helpful. I also wonder why cores from the central and northern part of Greenland are not included? For example, accumulation rates from the NGRIP core and from the cores B26 and B29. Accumulation rates from the latter two were recently published by Weissbach et al., 2016, Climate of the Past.

Response: The IceBridge accumulation rates are compared to ice core accumulation over corresponding time domains; we have added a column in Table 1 to more clearly reflect the time ranges. Accumulation rates and trends are also now calculated for B26, B29, and NGRIP and presented in Table 2.

Comment: I realise that some of these effects might lead to smaller uncertainties than the stated uncertainty in accumulation rate of +/- 0.127 m w.e./yr. However, by not mentioning these complications a reader could get the impression that no such complications exist.

Finally, a comparison between the uncertainty with the accumulation rates from Fig. 5 indicates that this corresponds to at least 25% (highest accumulation rate is 0.5 m w.e./yr) or more for lower accumulation rate areas. In that context, how can the % differences in Table 2 be significant even at less than 10% difference? Am I missing something here?

Response: The IceBridge accumulation rates in Figure 5 are statistically indistinguishable from ice core accumulation rates, for each core. Moreover, the uncertainty decreases when IceBridge accumulation rates are averaged over 1957-2014, as used for comparison in Table 2. This uncertainty decreases since small errors in layer tracing become less important when calculating accumulation over longer timespans.

Comment: Figures Figure 2: The label on the colorbar says "Age of oldest layer" but

presumably, it should say date of the IRH (in Common Era)?

Response: We changed the caption to "Date of oldest resolvable IRH" for clarity.

Comment: Figure 3: This figure implies that the accumulation rate was calculated as an average for the period 1712-2014 but from Figure 2 parts of these lines do not have layers that go that far back in time.

Response: The accumulation rates for Figure 3 are averaged over the entire time domain for each radar trace. The caption has been corrected to "Average accumulation over the temporal domain of each radar trace calculated from IceBridge. . ."

Comment: I apologise if this echoes any comments from reviewer #2. I wrote this before the second review had been posted.

Response: Thank you for your comments.

Figure 10: (Top) Comparison of 1921-2014 IceBridge accumulation rates (this study) to 1911-2011 accumulation rates from Karlsson et al. (2016) along a transect from NEEM to NGRIP. On average, our measurements are 0.002 $\pm$ 0.002 m w.e. a-1 higher than Karlsson16. (Bottom) Accumulation results (this study) compared with PolarMM5, RACMO, MAR, Box13, and Bales09 along the same transect.

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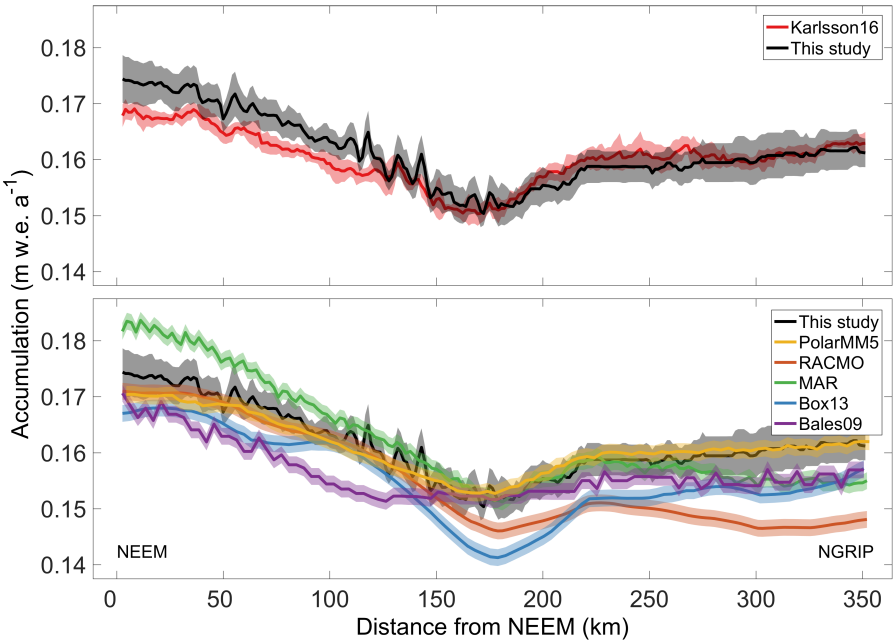
Karlsson16
This study
This study
PolarMM5
RACMO
MAR
Box13
Bales09
NEEM
NGRIP
Accumulation (m w.e. a-1)
Distance from NEEM (km)
0.14
0.15
0.16
0.17
0.18
0
50
100
150
200
250
300
350

Fig. 1.