We would like to thank Dr. Helm and the anonymous reviewer for the time and care they have taken with their reviews. Their comments are very helpful and will certainly improve the paper. Their contribution, and the help of the editor, Dr. Berthier, will be acknowledged.
We have copied all the comments from both reviewers below, and added our response in italics.

Anonymous Referee #1

Received and published: 9 July 2015

This paper develops estimates of surface elevation change for five Arctic ice caps, using radar altimetry data acquired by the CryoSat-2 satellite since 2010. The authors provide a detailed analysis of CryoSat's capability to measure elevation changes at both a monthly and annual sampling frequency, and evaluate their findings using a range of field and airborne datasets. Particular attention is given to the impact of changing snowpack conditions on the retrieved elevations.
I found the paper interesting, informative and comprehensive. The manuscript is very well written and has clearly been thoroughly proofed by the authors prior to submission.
I would expect the work to be of relevance to a wide audience of The Cryosphere, in particular to readers with an interest in the current evolution of Arctic ice caps and the performance of satellite radar altimeters. More widely, the results are relevant to anyone with an interest in geodetic estimates of ice sheet, glacier and ice cap mass balance. I have no major comments and would therefore recommend the manuscript for publication. I have listed some minor comments below, which I hope will help to clarify certain aspects of the work.

Minor comments
P2822 line 6: Suggest "contribution of subsurface to surface" => "ratio of subsurface to surface".
Wording changed as suggested.

P2823 line 4-6: ICESat and NASA acronyms are not defined.
Acronyms defined.

P2827 line 21: 0.13 m w.e. / yr?
Fixed
P2828 line 6: "indicate" => "indicates".
Fixed

P2829 line 11: "variation in the time history of the illuminated area". Not sure I understand exactly what you mean here. Do you mean variation with time of the area illuminated by the wavefront?
Yes, the wording has been changed as follows to make this clear: … 'This complexity is not entirely unexpected and arises due to the nature of the surface being measured, in particular the possible variation of the illuminated area at the sampling times in the receive window, and the possibility of reflections from sub-surface layers.'

P2829 line 19: Worth noting that Davis's measure of repeatability was based on a single-cycle cross-over analysis and so, as I understand it, his low threshold retracker showed greater repeatability with respect to variations in antenna orientation between the ascending and descending passes (perhaps because of reduced sensitivity to subsurface backscattering anisotropy), but not necessarily improved repeatability with respect to changes in time (as is desirable for elevation change detection).
Thanks for the clarification. The Davis et al. paper has been re-checked and the wording has been changed appropriately… 'The choice of the threshold level retracker used by Helm et al. (2014) for their work in Greenland and Antarctica followed that of Davis (1997), who advocated a threshold retracker to help minimize the influence of subsurface returns on the detected elevation.'

P2832 line 20: By 'better' do you mean that it gives a lower standard error of the mean, because of the larger sample size? This would presumably reflect a better precision on the measured mean elevation change, but not necessarily the most accurate measurement of the actual surface elevation change, because the measured elevation change may include the effects of changes in the dominant scattering horizon? In some cases, when melt occurs every year, then perhaps differencing summer elevations might give a more accurate measure of the real surface elevation change because of the negligible bias between the real and detected surface. I'm not expecting the authors to redo any analysis but I am more interested in their opinion on how to best minimize the impact of time variations in the bias.
Year-to-year surface height change can be achieved, as stated, by differencing summer minimum heights (small sample but, with surface melt, less uncertainty as to the level being measured) or by differencing average winter heights (large sample but now with increased uncertainty as to the dominant reflecting layer). It is dangerous to generalize too much but our results suggest that the latter is normally better as the 30 day averages encompass many fewer points, are consequently nosier, and may not capture the true minimum summer elevation. Perhaps the best approach is to use all available information, including field work and meteorological records. Some wording has been added to help clarify this…

'This is a consequence of the advantage obtained by averaging the many samples obtained over the larger time period in comparison to the fewer acquisitions possible in the 30 day period, which are then noisier and may not capture the true minimum surface elevation.'

P2833 line 13: 'This' => 'These'. *Fixed.*
P2833 line 14 'was' => 'were'. *Fixed.*

P2835 line 12: 'Changing historical meteorological conditions' I don't find particularly clear. Do you mean year-to-year changes in meteorological conditions?
The wording has been changed to clarify this sentence. We were not referring to just year-to-year changes but also the possibility that changes during the winter could influence the bias between the surface and the CS2 detected 'surface'…
'Changing meteorological conditions; accumulation, storms, heavy snow falls, etc., could change the bias between the CS2 detected surface and the true surface, even during the winter. We expect that the magnitude of this variable bias may be dependent on the winter accumulation and the variability in conditions.'

P2835 line 21: 'CryoSat-2' => 'CS2'. *Fixed.*
P2836 line 17: 'Devon Ice Cap and Austfonna'. *Fixed.*

P2837 line 13: If I understand correctly, you are comparing an AWS point measurement with a CS2 spatial average calculated over several thousand square km. Do you think the different sampling scales could explain some of the observed discrepancies, for example through spatial variability in meteorological conditions within the NW sector?
There is certainly a huge scale difference between the essentially point AWS measurement and the CS2 average measurement. Nevertheless, other AWS data and the mass balance pole measurements imply that the spatial variability in conditions across the NW sector is not large, although the local topography around the AWS could (slightly) affect the local accumulation.

P2838 line 17: If the backscatter is dominated by the previous end of summer layer, then could another possible contribution to the decreasing height over winter be from the downward motion of the previous summer layer as a consequence of firn compaction?
Yes, this is a possibility, and we have added text to provide a more complete explanation of the possible causes of the CS2 height decrease…
'It is possible that the changing nature of the winter accumulation reduces the surface reflectivity in relation to the volume component, such that the bias between the surface and the CS2 detected height increases during the winter. If the previous summer melt layer remains as the dominant backscatter layer then the apparent height could decrease because of firn compaction and the additional two-way path length due to the permittivity of the winter snow layer. This could then contribute to the apparent decrease in surface height seen in the 2012/13 winter.'

P2838 line 28: Here you could refer to http://onlinelibrary.wiley.com/doi/10.1002/2015GL063296/full.
Yes, this recently published reference is certainly relevant, and has been added…
'The influence of changing conditions on the apparent CS2 detected elevation was also observed with the low resolution mode (LRM) data in Greenland after the extensive 2012 melt (Nilsson et al., 2015).'

P2839 line 17: These are referred to as height changes and not height decreases, and so the values should presumably be negative?
Yes, the sign has been changed in the text. This problem also existed elsewhere in the text, and has been fixed.

P2840 line 4: Is the trend with respect to elevation significant given the dispersion of the height change data?
Yes, we believe so. Both polynomial fits and segmenting into different elevation bands leads to the same conclusion. This conclusion is also consistent with field measurements.

P2841 line 19: Why July 2010 to Dec. 2011 and not an integer number of years?
This choice is related to illustrating the height loss in basin 3 associated with the surge. The larger the data set (time wise) prior to the beginning of the rapid motion the more likely there will be adjacent pairs of points with which to estimate the average height loss.

P2842 line 8: I can see that a specular surface would increase backscattered power, but wouldn't moisture in the snow result in more microwave absorption and reduced backscattered energy?
Yes, the wording here was poor. As you suggest, we think that moisture in snow would initially lead to a reduction in the backscatter. However, when there is sufficient melt to create a truly wet layer then strong coherent reflection is possible. The

wording has been improved to reflect this…
'On Barnes Ice Cap the relative maximum power of each return waveform shows increased power and dynamic range in the summers (Fig. 13a), which we interpret to be a consequence of significant melt and the possibility of a specular return from a wet surface. Initially moisture in the snow can reduce the backscatter but with continued melt and the creation of a wet surface there is the possibility of relatively strong coherent reflection.'

P2843 line 24: remove 'at'. *Done*

P2844 line 12: I appreciate this probably has no straightforward answer, but I wonder whether the authors have any thoughts on the extent to which their conclusions are specific to their chosen retracker, or are generalizable to other retrackers?
A complete answer to this question would require systematic testing of different retrackers, something beyond the scope of our work. Although some of the details of the seasonal change in elevation, e.g. summer-winter, may change slightly with the form of the retracker (c.f. Ricker et al., 2014, 'Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation'), we suspect that any CS2 detected elevation will be more dependent on the changing conditions than on the detailed form of the retracker. Consequently, we think our conclusion that the bias between the surface and CS-2 detected elevations depends on the conditions of the surface and near-surface is generalizable to other retrackers.

P2844 line 14: 'between the mean CS2 height'?
Changed to '… variable bias between the mean detected CS2 elevation and the surface elevation…'.

P2844 line 25: Might be worth commenting on the value of the length of the time series.
I'd expect that the magnitude of the bias is constrained by the physical properties of the snowpack and microwave penetration, and that the bias varies most over seasonal to annual timescales depending upon changing meteorological conditions. Therefore over longer time periods, would you expect the relative influence of the variable bias on the measured height change to diminish?
Yes, we would expect that over a sequence of winter-to-winter CS2 height comparisons that the effect of a possible variable bias would diminish, but we should still be aware that slowly changing conditions may have an influence on the year-to-year CS2 detected height change. In the light of the comment we have expanded the text as follows…
'Notwithstanding the uncertainty in the bias between the surface and CS2 elevation, the winter-to-winter CS2 height change results can give a credible estimate of the year-to-year ice cap surface height change, particularly as more years are added to the time series. The largest uncertainty in these estimates, and the most difficult to quantify, comes from the fact that the conditions winter-to-winter may change in a manner that affects the bias between the surface and the CS2 elevation. Surface field measurements under cold spring conditions may help identify differing winter conditions that could lead to a changing bias between the surface and average CS2 elevations.
The results for the Canadian ice caps…'

P2844 line 27: 'A change: : : volume change'. This sentence seems a little out of place as the manuscript has focused on elevation change and not mass change.
This is true, so we have removed the sentence.

P2845 line 16. I don't find this final sentence particularly clear. Do you mean the interferometric capability to locate POCA within the beam footprint, or something different?
We believe that the improved resolution and interferometric capability of the SARIn mode of Cryosat allows the user to identify the POCA position more accurately than with previous altimeters, and that the temporal height changes we have shown in this work are only possible thanks to the ability to better geocode the POCA footprint. The text has been expanded to help make this clear…
'In summary, we believe that the improved resolution and interferometric capability of the SARIn mode of Cryosat allows the user to identify the POCA position more accurately than with previous altimeters, and that the temporal height changes we have shown in this work depend to a large extent on the ability to better geocode the POCA footprint.'

Table 1: Consider splitting glacier facies types with commas or new lines.
Commas added.

Table 1: Would be helpful to give a brief description of the data type that each DEM is derived from.
Added as footnotes below table

Table 1. Is 'high temporal resolution' 30 days? If so might be worth mentioning this explicitly.
Done.

Figure 2: Replace CS with CS2 to maintain consistency with acronym used in text.
Done.

Figure 4 Replace CS with CS2 and STD with SD to maintain consistency with acronyms used in text. To avoid any misinterpretation, suggest you define more explicitly, perhaps in the caption, what <delH> is.
Done.

Figure 6 caption: 'stations is indicated' => 'stations are indicated'.
Corrected.

Figure 6: I know 'A' is described in figure 7 but would be helpful to also mention what it refers to here.
Done.

Figure 7: Panels a and b are lacking vertical axis labels to specify units.
Fixed.

Figure 7: My understanding was that the horizontal black dashes in panel a were meant to mark the 30 day sampling periods. However, the Nov-Dec 2011 dash seems to cover a longer time period.
Yes, this is correct. Sometimes the data in any one 30 day period is so small that it was better to reduce the time resolution and amalgamate with adjacent data time-wise. The text both in the paper and the figure caption has been changed to explain this. The caption now includes… 'The short dashed black lines at the top indicate the time periods encompassing the CS2 passes which have been combined for the high temporal resolution plots. In one case (Nov.-Dec. 2011) passes were missing so the two groups were combined.'

Figure 7: I can't work out where the blue AWS B data are from. It doesn't appear to be specified in the caption or visible in Figure 6.
Label added to Fig. 6, and appropriate text to the captions.

Figure 7: Why have you chosen to compute year-to-year height change for AWS A rather than AWS B?
The elevation of AWS 'A' is closer to the average of the elevations used for the average CS2 height change data.

Figure 7: AWS B height change looks extremely stable between Dec 2012 and May 2013. Is this real or have the data been interpolated?
While the plot does looks quite 'suspicious' we have checked the AWS B data and believe it to be real..

Figure 8 caption: 'along the north-south transect shown'?
Fixed.

Figure 8a: Labels on colour bar are difficult to read.
Fixed.

Figure 10: 'has been removed' => 'have been removed'.
Fixed.

Figure 10: Is background image a DEM?
Yes, and this has now been acknowledged in the caption.

Figure 13a: dashed black line is hard to see, consider changing to a more visible colour.
Fixed.

Figure 14: Suggest adding units to elevation ranges in panels a-d.
Units added.

Figure 14 caption: 'The winter-to-winter average height change'.
Fixed.

V. Helm (Referee)
veit.helm@awi.de
Received and published: 12 July 2015
In this paper monthly and inter-annual surface elevation changes of 5 Arctic Ice Caps are presented. The results are derived by a detailed and comprehensive analysis of
CryoSat2 data acquired in the period 2010 to 2014 and evaluated to field, meteorological" and airborne data sets.
Special focus is given to seasonal changing surface conditions causing a shift of the main radar scatter horizon, where the radar elevation is tracked. This is a very important finding, which needs to be considered when estimating elevation change time series from radar altimetry, since it demonstrates that observed elevation change might not necessarily be a true surface elevation change.
C1188
The paper is well written, clear, concise, well-structured and understandable and the data processing and analysis of high quality. I think the paper is of interest to a broader community with interest in evolution of Arctic ice caps and altimetry.
I have no major concerns and would recommend the paper for publication in TC. In the following I have added some comments and questions that came into my mind when reading the paper.

P2827L4: accumulation rates of 0.5m ! m/a
Fixed.

P2827L21: accumulation rate of 0.13m ! m/a
Fixed.

P2829L10-15: I would expect that internal layers are not resolved by CS2 and therefore not show up as single peak. Maybe they broaden the waveform due to increased volume scattering. I would expect that peaks in the later part of the waveform are more due to undulating surface within the CS2 beam width.
Thanks for the comment. We suspect that more studies of different areas will help in understanding the shape of the waveform leading edge, in particular the balance between the influence of the topography and volume backscatter. We agree that the variations in return power beyond the leading edge are related primarily to the surface topography.

P2829L21-24: It would be of great value if you show the results you obtained by the comparison between the two methods. Are they within the error bar of the derived elevation changes or do they differ significantly? From the sentence it seems to me that your new approach using the max gradient in the leading edge to re-track the elevation eliminate the problem of a variable bias between the detected elevation and the physical surface. But in the rest of the paper your findings are clearly showing that this is not the case.
A systematic comparison of retrackers is beyond the scope of this work. Indeed we acknowledge that the sentence referred to implies more testing than was actually done. Consequently we have changed this to… 'Limited tests on some of the ice caps in our study have shown that a threshold retracker also produces satisfactory results but still does not totally eliminate the problem of a variable bias between the detected elevation and the physical surface.'

P2830L12-16: This method is an excellent way to improve the quality of the SIN CS2 elevation data used in the analysis, since you get rid of large outliers without neglecting them. To demonstrate the performance of your method you could add a comparison when using the method with and without a DEM.
Unfortunately, in our code it is difficult to turn off the reference DEM feature, so it isn't straightforward to do as you suggest. However, we know that the official L2 product for these ice caps does include some poor results that are clearly related to 2π phase ambiguities, resulting in the footprint being mapped to the wrong side of the sub-satellite track. With a reference DEM one can usually avoid this situation. Also, the advantage afforded by a reference DEM will be ice cap specific as the potential benefit depends on cross-track slopes. In defense of the ESA L2 product it would be very difficult to include reference DEMs for all the areas covered by the SARIn mode.

P2830L19: Reference DEMs: Could you please add some more details about origin, time of creation, the quality, and resolution (slightly update table 1 should be fine).
Some of these details, and relevant references, have been added to Table 1.

P2830L28: How close are the CS 30 day sub-cycle tracks (are they within 1km or 5km)?
At the latitude of Agassiz or Austfonna (~ 80° N) the 30 day ascending or descending tracks are separated by ~ 5 km but this separation increases as the latitude decreases. At 70° N, the latitude of the Barnes Ice Cap, the separation has increased to ~ 10 km.

P2831L9: How many data points usually fall within a 400m footprint within a 30 day subcycle?
Normally a few hundred, but this varies a lot depending on the size of the area being studied, the latitude, the number of passes in the time window, and the temporal separation of the 2 time windows (the middle of which are usually separated by

a multiple of ~ 30 days). Having both ascending and descending passes helps provide sufficient height comparisons.

Are you averaging all elevations within one footprint of one time period and subtract the averaged elevation of the second period or do you average all possible combinations of height differences for the two time periods within one footprint? Maybe add an equation to make it clearer.
The average CS2 height change for a particular area between the two time periods is estimated as follows: Initially each point (the centre of a CS2 footprint) in one time period is compared to all the points in the other time period on a point-by-point basis. If the distance between the points is within the preset limit (usually 400 m), the height difference is stored and corrected for the slope between the two footprint centres. This is done using the reference DEM. When all the height differences are collected the mean and standard deviation (SD) are calculated and any pair with a height difference greater than ~ 10 m from the mean (which is larger than 3 standard deviations) is discarded. The mean and standard deviation are recalculated and stored. This is done for all the possible time period combinations. This approach has the important advantage that bad height estimates can be identified and discarded easily. In this regard there is no guarantee that 'bad' CS2 points (arising from 2π ambiguities, high slopes, low coherence, etc.) will have the same mean as 'good' values, and it doesn't take too many 'bad' points with the same sign to affect the mean. The disadvantage of the above approach is that it can be computationally tedious. The appropriate text (second paragraph in section 3.2) has been expanded, like the above, to make this clear.

P2831L14 and P2832L9 When you derive an elevation rate (m/a or m/month) for temporal height change analysis (month to month) it is important to know the averaged time tag next to the averaged elevation difference. I could imagine that this difference of the averaged times are not exactly 30 days and could vary from a couple of days.
Are you considering this as well?
Yes, initially the temporal distribution of data is examined and if there are missing passes then the temporal window can be expanded to create a larger data sample. The black lines at the top of lower panel in Fig. 13 illustrates the time periods over which data were acquired for the Barnes Ice Cap. Note that the October - November time period is longer than the others, this is a results of missing passes. Consequently, the date associated with each time period is always the average of the dates of all the data in that time window. Again we have modified the text in the paper to make sure this is clear.

P2832L9: "relatively small number of data samples possible in 30 day periods:" !
What means small number? Do you use any criteria to neglect points with too low coverage?
Typically there are a few hundred points in each '30 day' period depending on the size of the area being studied. If the data set for the height differences between any pair of time periods contains less than 10 values it is discarded. Again some text has been added to clarify this step in the process.

P2833L15: Technical University of Denmark (TUD) acquired the ALS data during the
ESA CryoVex campaign. TUD also processed the GPS and ALS data, which is a lot of work. In the acknowledgments TUD is listed but I think it would be good to add a sentence directly in the text for this effort.
Yes, the contribution made by TUD with the ALS and GPS data (and AWI with ASIRAS) is significant and does warrant further acknowledgement. This has been done.

P2833L25: As mentioned before. Could you show the statistics without using your CS2 SIN processing DEM approach to detect and correct for phase uncertainties? Do you see similar mean and SD when applying the re-tracking at a certain threshold like Helm et. al. 2014 as you discussed before?
As explained above we are reluctant to include results or statistics in a situation where there hasn't been systematic study. We believe that the improvement obtained by including a reference DEM will be ice cap specific, indeed it is likely that the DEM is most important in situations in which the cross-track slope can be close to, or above, the slope that leads to phase 'wrapping' (~ 0.55°).

P2834 Error estimation: This is a good error discussion but I miss the explanation how you derived the uncertainty for the elevation changes. You mentioned 5 points, which need to be considered. It's not clear to me if you have considered those points and if yes, how exactly you did this.
Good comment! Yes, we did consider all the points listed in section 4.2 but admit that the errors included in Table 1 have not been carefully justified. The various uncertainties for each ice cap were all estimated and then root square summed. The trouble is some of our potential errors are very hard to quantify and perhaps are best described as 'best estimates'. While we admit this is less than ideal we have added text to justify the approach. Many papers in this field assume random errors, and then quote an error based on the standard deviation divided by the square root of the number of samples (the 'standard error'). In our case, for some of these ice caps, we believe that this would lead to an optimistic estimate of the errors due to our concern that some of the errors are not random.

E.g. in Fig. 7 and 11 there are no error bars but in Fig. 13 you show the error.
The error bars are shown in Fig. 13 for the temporal height change for the Barnes Ice Cap, because in this case the absence of firn makes the glaciological situation more straightforward than for the other ice caps, and we can use the standard deviation

and number of samples for each height change estimate to define a 'standard error'. The error bars then reflect ± two standard errors, and as there is some variation in this number the error bars are included in the graph. For the other ice caps we feel that this approach could lead to an underestimate of the potential error. Consequently, we estimate one number for the CS2 height change error for each ice cap and add this to Table 1. Adding constant bars to the upper panels in Figs. 7 and 11 would un-necessarily complicate the figures, and we felt the easiest way to document our errors was to include an 'all-inclusive' estimate for the two temporal resolutions for each ice cap in Table 1.

Does your error estimate reflect your assumption of larger uncertainty in winter than in summer?
Except for the Barnes ice cap results the answer is no. However, the error estimate for the high temporal resolution height change does include the potential contribution from the change in the bias between the surface and the CS2 detected elevation in winter.

The scatter in Fig. 5 is pretty large. Are there any assumption why this is the case?
Could medium scale roughness within the CryoSat2 POCA footprint, like sastrugies cause such differences? Could you please add a figure showing the elevation difference versus surface gradient and roughness derived from the reference DEMs. Maybe this could give some more information. Another idea might be to plot the coherence extracted at the retracked bin versus elevation difference.
What you are suggesting is actually part of some on-going work. For those areas where there is good spatial and temporal overlap with surface GPS and/or airborne laser altimeter data we have been comparing the CS2 'height' minus the reference surface height with cross-track and along-track slopes, coherence, and some other parameters related to the waveforms. Your suggestion re roughness and sastrugi is very interesting and would be best approached by looking at the statistics of the ALS and ATM data, and then comparing these with the CS2 data. Again, we feel that this is beyond the scope of this paper but should be addressed in future work.

P2837L5 You mentioned ASIRAS data before and CRESIS Ku band airborne data in this section. Who provided ASIRAS data, who processed it - not mentioned in the acknowledgments? Did you use ASIRAS or only CRESIS in your analysis – not clear to me?
While the paper uses data only from the CReSIS airborne altimeter, our overall work has certainly involved study of ASIRAS data. In Canada we processed it from the raw files (from the aircraft) but the comment is certainly pertinent, and we should have made better specific acknowledgement to TUD (for the ALS and the ESA sponsored CryoVex flights), and to AWI for their efforts to process all the CryoVex ASIRAS data. This has been done.

P2838L14 It would be helpful to add the elevation profile as a subpanel as well as the different glacier facies (like percolation zone) along the profiles.
The primary purpose in including Fig. 8 was to show that the waveforms from the high resolution airborne Ku band altimeter flown over cold spring conditions on Devon varied year-to-year in a way that wasn't directly related to the elevation or surface facies. We doubt that adding an elevation profile for the NS and EW lines illustrated in Fig. 6 would add useful information.

P2839L17 Please add uncertainty of AWS.
The operational accuracy of the AWS acoustic distance ranger is ~ 0.03 m. This has been added to the text.

P2840L14 How does your result for Austfonna compare to McMillan 2014?
Where a comparison is possible the results are quantitatively consistent but the spatial and temporal resolution in our results appear to be better.

P2840L26 elevation change of 1 to 1.5 m
Fixed in 2 places.

P2840L28 you mention AWS temperature data. Could you also add this in Fig 11, as it is used to explain the April/May elevation change?
We think Fig. 11 becomes too busy and complicated with the additional temperature data, see additional comments below.

P2841L4 Why does Duvebreen AWS show an increase in elevation and CS2 a decrease between Sep2012 to March 2013? It seems that CS2 completely penetrates the fresh snow and still tracks the surface of the last summer which densifies and moves down. With the onset of the warm air the new surface is tracked by CS2. Could you comment a bit more on this? Are there density profiles of snow pit data available?
The Duvebreen AWS is on the north coast of Austfonna and does show an increase in surface elevation with the winter snow accumulation. The purple trace in the upper panel of Fig. 11 is the appropriate CS2 line for comparison. This also shows a more modest increase and yes, it is probable that the difference is due to an increasing bias between the surface and the CS2 detected elevation. The decrease in CS2 height for the low elevation southern data set (fawn trace in Fig. 11a) may be due to the strong subsurface component, compaction and the added two-way path component due to the permittivity of the snow.

Note the south coast warm snow event referred to in the text is visible as the small blue spike towards the end of April in the CPDD (cumulative positive degree day) plot in Fig. 11b. Also, at the same time the Basin 3 height sensor (red trace in Fig. 11b) does pick up a height increase due to the snow fall.

P2841L28 Please add uncertainty (0.18 +/_ ?).
This sentence was worded poorly, and has been replaced by…
'The three-year surface height gain at elevations above 600 m was measured by finding pairs of surface GPS points within 1 m of one another where one point was from the spring of 2011 and the other from the spring of 2014 (blue points in Fig. 12). The mean height increase was 1.19 m with a standard deviation of 0.32 m. The CS2 height change was also estimated by using pairs of height estimates adjacent to the GPS transect with time windows Nov. to April in the winters of 2010/11 and 2013/14. In this case the CS2 height increase was 0.96 m with a standard deviation of 1.15 m. Although the approaches are very different this does provide added credibility that the 3-year CS2 height change illustrated in Fig 12 does bare a strong resemblance to the surface height change.'

P2842L25 Which error estimate is used for the other ice caps?
Text has been added to sections 5.1, and 5.2 to justify the errors quoted in Table 1 for the other ice caps.

P2844L12 I think one should add a citation to Ricker (2015) and Nilsson (2015) who also explained the effect of "variable bias between the physical surface and the heights derived from CryoSat-2"
Nilsson, J., P. Vallelonga, S. B. Simonsen, L. S. Sørensen, R. Forsberg, D. Dahl-Jensen, M. Hirabayashi, K. Goto-Azuma, C. S. Hvidberg, H. A. Kjær, and K. Satow (2015), Greenland 2012 melt event effects on CryoSat-2 radar altimetry. Geophys. Res. Lett., 42, 3919–3926. doi: 10.1002/2015GL063296.
Ricker, R., S. Hendricks, D. K. Perovich, V. Helm, and R. Gerdes (2015), Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: An observational approach with buoy data. Geophys. Res. Lett., 42, 4447–4455. doi: 10.1002/2015GL064081.
This would add some more weight to the argument that the so called "penetration bias" need to be considered when deriving elevation change in areas observing summer melt or freeboard change over sea ice. Would you expect that this kind of seasonal variability is important for longer time series as well?
Agreed, and both these references will be added to the paper.

Fig1 - Use larger characters
Done

Fig6 - AWS positions hardly visible. Use different colour.
The AWS positions have been made easier to see.

Where is AWS B located?
Fig7 **–** Labeling of y-axis is missing. Why are you not showing results of AWS 3 and 4
AWS 'B' is identified now in Fig. 6.
The labelling for the y axis in Fig. 7 has been added.
The results from the 2 higher elevation AWSs on the Devon ice cap don't really add relevant information to compare to the CS2 data. AWS 'A' is close to the average elevation of the blue CS2 and provides the best comparison.

Fig11 - Why does CS2 not show the summer melt in 2012 as the AWS are indicating? It is not explained in text. Please add temperature of the AWS - similar to Fig. 7.
There are dips in the CS2 'elevation' for all 3 areas centred at the end of July in 2012. However, as noted by the reviewer, the magnitude of the CS2 detected melt in 2012 is much less than that in 2011, but all 3 AWS show comparable summer height losses in 2011 and 2012. We are not certain why this is but have added the following tentative explanation in the text. … 'In comparing the CS2 and AWS summer height loss data it appears that CS2 indicates less melt in the summer of 2012 than in 2011, but the 3 AWS surface height sensors show comparable melt. It should be noted that the positions and elevations of the AWS sensors (Fig. 10; Etonbreen, E; elevation 369 m, Duvebreen, D; 304 m and Basin 3, B; 175 m) may not be truly representative of the CS2 data. In particular, the average CS2 elevations for the low elevation north and south data sets (459 m and 380 m) are significantly higher than the relevant AWS elevations. Consequently, it is possible that the melt at higher elevations in 2012 was really less than that in 2011.'
We feel that the important surface temperature variation is better captured by the cumulative positive degree day data already present in the graph, and that the temperature variation for the three AWS positions would add little useful information.

Comment:
Maybe it is worth to scale all height changes to a height rate (m/month), because e.g. in Fig. 7 the black bars, which are hard

to identify have different lengths indicating the time used for a monthly average is not constant.
We have added text to better explain the variation in the short time periods used for the high temporal resolution height variation plots (see also the response to reviewer 1). The monthly height change rate would be very noisy, and we feel that the height change plots, using the average time of each data set, is the clearest way to show the temporal evolution of CS2 'height'.

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The Cryosphere Discussions

CryoSat-2 delivers monthly and inter-annual surface elevation change for Arctic ice caps

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Abstract

We show that the CryoSat-2 radar altimeter can provide useful estimates of surface

elevation change on a variety of Arctic ice caps, on both monthly and yearly time scales. Changing conditions, however, can lead to a varying bias between the elevation estimated from the radar altimeter and the physical surface due to changes in the ~~contribution~~ ratio of subsurface to surface backscatter. Under melting conditions the radar returns are predominantly from the surface so that if surface melt is extensive across the ice cap estimates of summer elevation loss can be made with the frequent cov- erage provided by CryoSat-2. For example, the average summer elevation decreases on the Barnes Ice Cap, Baffin Island, Canada were 2.05 ± 0.36 m (2011), 2.55 ± 0.32 m (2012), 1.38 ± 0.40 m (2013) and 1.44 ± 0.37 m (2014), losses which were not balanced by the winter snow accumulation. As winter-to-winter conditions were similar, the net elevation losses were 1.0 ± 0.2 m (winter 2010/2011 to winter 2011/2012), 1.39 ± 0.2 m (2011/2012 to 2012/2013) and 0.36 ± 0.2 m (2012/2013 to 2013/2014); for a total surface elevation loss of 2.75 ± 0.2 m over this 3 year period. In contrast, the uncertainty in height change results from Devon Ice Cap, Canada, and Austfonna, Svalbard, can be up to twice as large because of the presence of firn and the possibility of a varying bias between the true surface and the detected elevation due to changing year-to-year conditions. Nevertheless, the surface elevation change estimates from CryoSat for both ice caps are consistent with field and meteorological measurements. ~~For example, the average 3 year elevation difference for footprints within 100 m of a repeated surface GPS track on Austfonna differed from the GPS change by 0.18 m.~~

1 Introduction

Recent evidence suggests that mass losses from ice caps and glaciers will contribute significantly to sea level rise in the coming decades (Meier et al., 2007; Gardner et al., 2013; Vaughan et al., 2013). However, techniques to measure the changes of smaller ice caps are very limited: satellite techniques, such as repeat gravimetry from GRACE (Gravity Recovery and Climate Experiment), favour the large Greenland or Antarctic Ice Sheets, while surface and airborne experiments sample conditions sparsely in both time and space. Satellite laser altimetry (ICESat; Ice, Cloud, and land Elevation Satellite launched by the US National Aeronautics and Space Administration, NASA) was used between 2003 and 2009

but the results were limited by both laser lifetime and atmospheric conditions. NASA's follow-on mission (ICESat 2, Abdalati et al., 2010) is currently scheduled for launch in 2017, but until then CryoSat-2 (CS2), launched by the European Space Agency (ESA) in 2010, provides the only high resolution satellite altimeter able to routinely measure small ice caps and glaciers. The new interferometric (SARIn) mode of CS2 (Wingham et al., 2006) has important new attributes in comparison to previous satellite radar altimeters: Delay-Doppler processing (Raney, 1998) permits a relatively small ($\sim$ 380 m) along-track resolution (Bouzinac, 2014), while the cross-track interferometry (Jensen, 1999) provides information on the position of the footprint centre. Here we show that the SARIn mode of CS2 can measure annual height change of smaller Arctic ice caps, and even provide estimates of summer melt on a monthly time frame.

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To test and validate the CS2 altimeter, ESA developed the airborne ASIRAS Ku-band (13.5 GHz) radar altimeter. ASIRAS has been operated during field campaigns under the CryoSat Validation Experiment (CryoVex) at selected sites before and after the launch of the satellite. One of the most interesting revelations of the ASIRAS data has been the demonstration of variability in relative surface and subsurface returns in a variety of locations including Devon Ice Cap in Canada, Greenland and Austfonna in Svalbard (Hawley et al., 2006, 2013; Helm et al., 2007; Brandt et al., 2008; de la Pena et al., 2010). The time variation of the ASIRAS return signals from the surface and near surface (the "waveforms") can and does vary significantly from year-to-year at the same geographic position, and in any one year with changing position across the ice cap. During cold conditions in spring, the maximum return need not be from the snow surface, but could be from the previous summer surface, or strong density contrasts within the snow pack such as those manifested by buried weathering crusts or refrozen percolating meltwater (see e.g. Bell et al., 2008). Changes in snowpack

characteristics, dependent on past meteorological conditions, could therefore affect the relative strength of the surface and volume component of the CS2 return signal and affect the bias between the elevation measured by CS2 and the true surface.

In this study we use all available SARIn data from July 2010 to December 2014 to undertake the first systematic measurement by spaceborne radar of elevation change on a variety of ice caps across the Canadian and Norwegian Arctic (Fig. 1) representing a wide range of climate regimes. Emphasis is placed on CS2 results from Devon and Austfonna as both ice caps were selected by ESA as designated calibration/validation sites, and a wide range of ground and airborne validation datasets are available. SARIn data are also used to measure height changes on Penny, Agassiz and Barnes ice caps to illustrate the wide applicability of the method in areas where there is less data available for surface validation. Together with the recent CS2 work on Greenland and Antarctica (McMillan et al., 2014a; Helm et al., 2014), this illustrates the power of the new interferometric mode of the CS2 altimeter to provide useful information in an all-weather, day-night situation.

Our emphasis in this paper is to demonstrate that CS2 can measure elevation and elevation change on relatively small ice caps, even with differing surface conditions, and for some on a monthly time scale. The many complications associated with converting the CS2 elevation change data to an ice cap wide mass balance will be treated in future papers.

2 Study areas

We begin by describing the two ice caps, Devon and Austfonna, which were part of the CryoVex campaigns and which have a wide range of surface reference data. Then we discuss conditions on Barnes, Agassiz and Penny ice caps. Although these ice caps have less surface reference data, they are quite different and represent a good test of the capability of the CS2 system.

2.1 The Devon Ice Cap

Occupying $\sim 12\,000\,\mathrm{km}^2$ of eastern Devon Island, Nunavut, the main portion of the Devon Ice Cap (75° N, 82° W) ranges from sea-level, where most outlet glaciers terminate, to the ice cap summit at ~ 1920 m. While the ice cap loses some mass through iceberg calving (Burgess et al., 2005; Van Wychen et al., 2012), the main form of ablation is through runoff, which is controlled primarily by the intensity and duration of summer melt (Koerner, 1966, 2005). Surface accumulation is asymmetric and can be as much as twice as high in the south-east compared to the north-west due to the proximity to Baffin Bay (Koerner, 1966). Surface mass balance has been negative across the Northwest sector since 1960 (Koerner, 2005), but after 2005 the surface melt rates have been ~ 4 times greater than the long-term average (Sharp et al., 2011). This has led to a thinning of ~ 6 m of the northwest basin since the sixties (Burgess, 2014). The ice cap is characterized by four glacier-facies zones that have developed at various altitudes as a function of prevailing climatic conditions (Koerner, 1970): below ~ 1000 m annual melting removes all winter precipitation, creating the "ablation" zone. Above this (~ 1000–1200 m), the "superimposed ice" zone develops, where refreezing of surface melt results in a net annual mass gain. In the "wet snow" zone (~ 1200–1400 m) the winter snowpack experiences sufficient melt during the summer that meltwater percolates into one or more previous year's firn layers. The highest "percolation" zone typically occupies elevations above ~ 1400 m to the ice cap summit, where surface melt is refrozen within the winter snowpack. It is important to emphasize that the distribution of these facies varies year-to-year, reflecting meteorological conditions and mass balance history.

2.2 Austfonna

Occupying $\sim 8100\,\mathrm{km}^2$ of Nordaustlandet, Svalbard, Austfonna (79° N, 23° E) is among the largest ice caps in the Eurasian Arctic. It consists of a main dome that reaches a maximum surface elevation of ~ 800 m (Moholdt and Kääb, 2012). The south-eastern

basins form a continuous calving front towards the Barents Sea, while the north-western basins terminate on land or in narrow fjords (Dowdeswell et al., 1986a). Several drainage basins are known to have surged in the past (Dowdeswell et al., 1986b), including Basin-3 which entered renewed surge activity in autumn 2012 (McMillan et al., 2014b; Dunse et al., 2015).

Mass balance stakes indicate an equilibrium line altitude (ELA) of ~ 450 m in the NE and ~ 250 m in the SE of Austfonna (Moholdt et al., 2010). This reflects a typical asymmetry in snow accumulation with the southeastern slopes receiving about twice as much precipitation as the northwestern slopes, as the Barents Sea to the east represents the primary moisture source (Pinglot et al., 2001; Taurisano et al., 2007; Dunse et al., 2009).

Despite a surface mass balance close to zero (2002–2008), the net mass balance of Austfonna has been negative at $-1.3 \pm 0.5\,\mathrm{Gt\,a^{-1}}$ (Moholdt et al., 2010), due to calving and retreat of the marine ice margin (Dowdeswell et al., 2008). Sporadic glacier surges, as currently seen in Basin-3 (McMillan et al., 2014; Dunse et al., 2015) can significantly alter the calving flux from the ice cap. Prior to the surge of Basin-3, interior thickening at rates of $\sim 0.5\,\mathrm{m\,a^{-1}}$ and marginal thinning of 1–3 $\mathrm{m\,a^{-1}}$ had been detected from repeat airborne (1996–2002; Bamber et al., 2004) and satellite laser altimetry (2003–2008; Moholdt et al., 2010). The accumulation area comprises an extensive superimposed ice and wet snow zone, and in some years a percolation zone may exist. The distribution of glacier facies varies significantly from year to year, a consequence of large inter-annual variability in total amount of snow and summer ablation (Dunse et al., 2009). Despite mean annual temperatures of -8.3 °C, large temperature variations occur throughout the year and it is not uncommon for temperatures above 0 °C and rain events to occur in winter (Schuler et al., 2014).

2.3 Barnes Ice Cap

Barnes Ice Cap (70° N, 73° W) is a near-stagnant ice mass that occupies $\sim 5900\,\mathrm{km}^2$ of the central plateau of Baffin Island. It terminates at a height of ~ 400–500 m around most of its perimeter, and its surface rises gradually towards the interior, reaching a maximum elevation of ∼ 1100 m along the summit ridge (Andrews and Barnett, 1979). In-situ surface mass balance measurements (1970–1984), indicate winter accumulation rates of ∼ 0.5 m snow water equivalent (s.w.e.), and net balance for the entire ice cap of $-0.12\,\mathrm{m\,a^{-1}}$ (Sneed et al., 2008). Mean mass loss rates have become increasingly negative ($-1.0 \pm 0.14\,\mathrm{m\,a^{-1}}$) up to the present (Abdalati et al., 2004; Sneed et al., 2008; Gardner et al., 2012). In the past accumulation occurred primarily as superimposed ice (Baird, 1952), but more recently summer melt has been extensive and the ice cap has lost its entire accumulation area (Dupont et al., 2012). Similar to glaciers in the Queen Elizabeth Islands (Koerner, 2005), the surface mass balance of the Barnes Ice Cap is driven almost entirely by the magnitude and duration of summer melt (Sneed et al., 2008).

2.4 Agassiz Ice Cap

Agassiz Ice Cap (80° N, 75° W) occupies ∼ 21 000 km^2 of the Arctic Cordillera on north-eastern Ellesmere Island. It ranges in elevation from sea-level, where several of the major tidewater glaciers that drain the ice cap interior terminate, to ∼ 1980 m at the central summit. Ice core records acquired from the summit region indicate that melt rates since the early 1990's are comparable to those last experienced in the early Holocene ∼ 9000 years ago (Fisher et al., 2012). In-situ measurements of surface mass balance indicate a long term ELA of ∼ 1100 m with an average accumulation rate of 0.13 m w.e. a^{-1} over the period 1977–present. Between the summit and the sea level outlet glaciers there is a progression of ice facies similar to that described for Devon.

Repeat airborne laser altimetry surveys conducted in 1995 and 2000 indicate zero change to slight thickening at high elevations, but the ice loss at lower elevations led to an estimate of ice cap wide thinning of ∼ $0.07\,\mathrm{m\,a^{-1}}$ (Abdalati et al., 2004). More recently (2004–2009), model results confirmed by independent satellite observations (Gardner et al., 2011) suggest the ice cap has been thinning by $0.23\,\mathrm{m\,a^{-1}}$.

2.5 Penny Ice Cap

Penny Ice Cap (67° N, 66° W) occupying ∼ 6400 km^2 of the highland region of southern Baffin Island, ranges in elevation from 0 to 1980 m and contains one main tidewater glacier, the Coronation Glacier, which calves into Baffin Bay (Zdanowicz et al., 2012). A historical climate record derived from deep and shallow ice cores (Fisher et al., 1998, 2012) indicates that current melting on Penny is unprecedented in magnitude and duration for the past ∼ 3000 years. Thickness changes derived from repeat airborne laser altimetry surveys in 1995 and 2000 indicate an average ice cap wide thinning rate of $0.15\,\mathrm{m\,a^{-1}}$, with maximum thinning of ∼ $0.5\,\mathrm{m\,a^{-1}}$ in the lower ablation zones (Abdalati et al., 2004). More recent measurements (2007–2011) indicate thinning of ∼ 3–4 $\mathrm{m\,a^{-1}}$ near the ice cap margin (330 m), amongst the highest rates of glacier melt in the Canadian Arctic (Zdanowicz et al., 2012). The current climate regime limits accumulation to elevations above ∼ 1450 m, where it forms as superimposed ice and saturated firn. Recently, the temperature of the near-surface firn (10 m depth) in the summit region has increased by 10 °C as a result of latent heat release due to increased amounts of summer melt water refreezing at depth (Zdanowicz et al., 2012).

3 Methods

3.1 CS2 SARIn data processing

All available SARIn L1b data files (processed with ESA "baseline B" software; Bouzinac, 2014) from July 2010 to the end of December 2014 were obtained from ESA for each ice cap. Although developed independently, our processing methodology to derive geocoded heights from the L1b data is similar to that described by Helm et al. (2014), so the summary below focusses on the differences between the two methods.

Delay Doppler processing (Raney, 1998) has been completed in the down-loaded data and the resulting waveform data are included in the ESA L1b files. However, geophysical results, e.g. terrain footprint height and position, have not been calculated. Our processing for this stage has been developed primarily for the ice cap data acquired above, and the steps are illustrated in Fig. 2. The waveform data for each along-track position (time histories of the power, phase and coherence) include the unique "point-of-closest-approach" (POCA) followed in delay time by the sum of surface and subsurface returns from both sides of the POCA (Gray et al., 2013).

An initial examination of the L1b data showed that the received power waveforms varied in both shape and magnitude, and that the peak return did not necessarily follow immediately after the first strong leading edge of the return signal. This complexity is not entirely unexpected and arises due to the nature of the surface being measured, in particular the possible variation in the time history of the illuminated area at the sampling times in the receive window, and the possibility of reflections from sub-surface layers. The problem is then to identify an optimum algorithm (the "retracker") to pick the position of the POCA ~~(the "retracker")~~ from the waveform. Our approach estimates the POCA position by identifying the maximum slope on the first significant leading edge of the waveform. This is similar to the approach of Helm et al. (2014), who used a particular threshold level on the first significant leading edge of the power waveform.

The choice of the threshold level retracker used by Helm et al. (2014) for their work in Greenland and Antarctica followed that of Davis (1997), who advocated a threshold retracker to help minimize the influence of subsurface returns on the detected elevation ~~dependency of the "retracked" elevation on varying microwave penetration into, and backscattering from, various snow-firn-ice layers~~. Limited tests on some of the ice caps in our study have shown that a threshold retracker also produces satisfactory results but still does not totally eliminate the problem of a variable bias between the detected elevation and the physical surface.~~Our tests on the ice caps in our study have shown that a threshold retracker also produces satisfac- tory results but still does not totally eliminate the problem of a variable bias between the detected elevation and the physical surface~~. In contrast to the interior of Antarctica where near surface melt is very rare, in this study we are dealing with surface and near-surface conditions in which there are significant spatial and temporal variations in surface roughness, near surface permittivity, and microwave penetration. Consequently, it is hard to envisage that any retracker would respond to the physical surface independently of the conditions of the near surface. This issue is discussed further be-

low in the light of the airborne and CS2 results for particular ice caps, but it is doubtful that an optimum retracker exists for all conditions.

Smoothed phase (Gray et al., 2013; Helm et al., 2014) and information on the interferometric baseline are used to estimate the unit vector in the "CryoSat-2 reference frame" (Wingham et al., 2006) pointing towards the POCA in the cross-track swath: initially the phase is used to calculate the look direction with respect to the line connecting the centers of the two receive antennas (the interferometric "baseline") using the calibration provided by Galin et al. (2012). The spacecraft attitude is then used to estimate the look direction to the POCA in the cross-track plane with respect to the nadir direction, perpendicular to the WGS84 ellipsoid. Using the data provided on satellite position and delay times, the latitude, longitude and elevation of the POCA footprints above the WGS84 ellipsoid are then calculated. The results are checked against a reference DEM elevation (Table 1), if the difference is large, typically 50–100 m, then the elevation and position is recalculated with the phase changed by $\pm 2\pi$ radians. If one of these options corresponds satisfactorily to the reference DEM, and the expected cross-track slope, then the original results are replaced. In this way some of the "blunders" which arise with an ambiguous phase error are avoided. Note the criterion for identifying 2π phase errors and subsequent data replacement depends on the quality of the reference DEM (Table 1).

3.2 Determination of temporal change in surface elevation

At the latitude of the Agassiz or Austfonna Ice Caps there is a westward drift of ~ 15 km every two days in a sub-satellite track of ascending or descending CS2 orbits, increasing to 25, 34 and 38 km at the latitudes of the Devon, Barnes and Penny ice caps respectively (Table 1). The repeat orbit period of CS2 is 369 days, with a 30 day orbit sub-cycle (Wingham et al., 2006). Consequently, the passes over the ice caps tend to group such that there is a period in the 30 day orbit sub-cycle with relatively good coverage and a period with no coverage. The shortest practical time period for height change estimation is then the 30 day orbit sub-cycle, and while we refer to a 30 day or monthly height change variation it is important to note that data are acquired only for a fraction of the 30 day period dependent on the size of the area and the latitude. In some cases passes are missing and the data from two groups are combined to provide an adequate sample.

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~~When comparing the average elevation between two time periods the position of the centre of each CS2 footprint in one time period is compared to all the footprints in the other time period. If the separation is less than 400 m, then the height difference is obtained and corrected for the slope component between centres of the two footprints using the reference DEM. The choice of 400 m is rather arbitrary but represents a compromise between the need for a large data sample and the increasing errors that arise as the separation between the two footprints increases. The height differences are then averaged to get the estimated height change between the two time periods for the ice cap. This approach has the advantage that if an unrealistic height difference is encountered it can be easily rejected. In this way we can study the monthly (30 day) av- erage height change, or select a much longer period, e.g. the period from November to May, to study the year-to-year average height change. If the total CS2 data set is large (;::60 000 points) it may be possible to define sub areas, e.g. different elevation bands or areas with different accumulations for the 30 day temporal height change analysis.~~

The average CS2 height change for a particular area between the two time periods is estimated as follows: Initially each point (the centre of a CS2 footprint) in one time period is compared to the positions of all the points in the other time period on a point-by-point basis. If the distance between the points is within the preset limit (usually 400 m), the height difference is stored and corrected for the slope between the two footprint centres using the reference DEM. When all the height differences are collected the mean and standard deviation (SD) are calculated and any pair with a height difference greater than ~ 10 m from the mean (which is larger than 3 standard deviations) is discarded. The mean and standard deviation are recalculated and stored. This is done for all the possible time period combinations. The choice of 400 m is rather arbitrary but represents a compromise between the need for a large data sample and the increasing errors that arise as the separation between the two footprints increases. This approach has the advantage that if an unrealistic height difference is encountered it can be easily rejected. In this way we can study the monthly average height change, or select a much longer period, e.g., the period from Nov. to May, to study the year-to-year average height change. If the total CS2 data set is large (> ~ [illegible]000 points) it may be possible to define sub areas, .e.g., different elevation bands or areas with different accumulations for the monthly temporal height change analysis.

For the ~~short, 30 day,~~ monthlyheight change we can compare all the time periods to the initial time period. However, it is possible to improve on this approach and use all the possible height differences between all the different time periods: when we compare the heights between time periods T_1 and T_2, and T_1 and T_3, we use a different subset of measure-ments in time period T_1. Therefore we can create a new estimate of the average height difference between T_1 and T_2 by calculating the height difference between T_1 and T_3 and adding the height difference between T_2 and T_3 if the time period T_3 precedes T_2, or subtracting if T_3 is subsequent to T_2. With N separate time periods there will be $N-1$ estimates of height difference for any pair of time periods. Combining the different estimates to create a weighted average not only reduces noise but also allows a way of estimating the statistical error. This approach is a variation of the method described by Davis and Segura (2001) and Ferguson et al. (2004).

Summer melt (measured as surface elevation decrease) and winter accumulation (measured as surface elevation increase) are extracted from these time series. We assume that CS2 returns acquired in summer, if melt extends across the entire ice cap,

are dominated by surface backscatter and that at this time the CS2 detected elevation change therefore reflects the true surface height change (it will be seen later that our results support this assumption). In this case summer melt can be estimated by differencing the early and late summer heights; yearly elevation change can be estimated by differencing successive minimum summer heights; and winter accumulation could be estimated by differencing the late summer height in one year with the early summer height the next year. However, the uncertainty in these estimates will be high, particularly because of the relatively small number of data samples possible in 30 day periods.

Finally, year-to-year elevation change is calculated in the same manner but now based on a much larger data sample: typically all the data acquired between November and April or May in one year is compared to all the data in the same time period in subsequent years. Again, each footprint in one winter period is compared to all the footprints in the other winter time period and if the separation of footprint centres is within 400 m the height difference is obtained and corrected for the slope between the footprint centres. This provides a large data set, normally many thousands of height changes, and avoids the effect of the possibly large summer seasonal height variation.

Also, if any particular height change is unrealistically large, greater than ~ 4 standard deviations (SD) from the mean, it can be removed before final averaging. In most cases the winter-to-winter approach gives a better estimate of year-to-year height change compared to differencing successive minimum summer heights, particularly if the winter meteorological conditions are comparable. ~~This is a consequence of the advantage obtained by averaging the many samples obtained over the larger time period. However, a change in the bias between the detected CS2 elevation and the physical surface for the different winters is still a possibility.~~ This is a consequence of the advantage obtained by averaging the many samples obtained over the larger time period in comparison to the fewer acquisitions possible in the monthly time period, which are then noisier and may not capture the true minimum surface elevation. However, a change in the bias between the detected CS2 elevation and the physical surface for the different winters is still a possibility and all the available information, including field and meteorological records, should be considered.

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4 Data validation and error estimation

Before describing the ice cap height change results, we begin in this section by comparing elevations derived from CS2 with surface elevations acquired from airborne scanning laser altimeters and kinematic GPS transects, and then address the accuracy and precision of the CS2 results. Ideally we would like to measure the surface elevation so we treat the difference as a height error and address it on three scales; the accuracy of any one CS2 elevation measurement, the accuracy of elevations averaged over an area and time period, and thirdly, elevation change estimates when averaged and differenced over various spatial and time frames.

4.1 The difference between CS2 and surface elevations

We use data collected over Devon and Austfonna as the surface elevation reference data. In spring 2011 an extensive skidoo-based GPS survey (42 by 6 km) provided detailed surface height data over a relatively wide area on Devon. Th~~is~~ese ground based data w~~as~~ere combined with the spring 2011 NASA ATM (airborne topographic mapper)
and ESA ALS (airborne laser scanner) data to give the Devon reference surface elevation dataset. The airborne datasets were first referenced to the surface GPS data, and in both cases the SDs of the differences were <15 cm. The positions of the surface reference data and the centres of the CS2 footprints collected between January and May 2011 are illustrated in Fig. 3 by black and blue dots respectively. For each CS2 elevation the closest reference height was found. If the distance between the reference point and the centre of the CS2 footprint was less than 400 m, the height difference was obtained and corrected for the slope between the two positions using the reference DEM. Although the CS2 data reflect a relatively large footprint (~ 380 m along-track by 100–1500 m across-track, dependent on slopes) in comparison to the essentially point measurements from the reference data set, the mean of over 700 height differences (CS2 elevation minus the reference elevation) was -0.13 m with a SD of 1.7 m (Fig. 4a). In spring 2012 NASA repeated some of the 2011 flight lines and a similar methodol-

ogy was used to compare the ATM laser elevations against the January to May 2012 CS2 elevations. In this case the mean height difference was -0.22 m with a similar SD (Fig. 4b). All of the CS2 data were acquired when the surface temperatures were below zero so we expect that, if calibrated correctly, the CS2 detected elevation would be lower than the actual surface elevation due to the expected volume component to the CS2 returns.

Similar results were obtained in the comparison of surface and CS2 elevations for Austfonna. Again, the surface reference data were collected in the spring before any significant melt. Airborne laser (ALS) data were collected over Austfonna in spring 2011 and 2012, and surface kinematic GPS in every spring since CS2 was launched. Some of the results are summarized in Fig. 4c and d. The SD of the CS2 minus surface elevation differences for the two years 2011 and 2012 were comparable to the results for Devon; 1.5 m (2011) and 1.8 m (2012), but the mean height differences were larger; -0.51 m (2011) and -0.65 m (2012).

Figure 5 illustrates the individual bias points (CS2 – surface height) plotted against the elevation at which they were obtained. The median elevation for each data set is marked and the mean bias for elevations above and below the median elevation are plotted with red markers. This shows that the bias between the surface and the CS2 elevation increases with elevation, particularly for Austfonna. In summary, under cold conditions any one CS2 elevation estimate will likely be lower than the surface elevation, but the bias between the surface and the CS2 elevation can be dependent on the conditions of the particular ice cap.

4.2 Error estimation

The average bias between the CS2 and surface elevations changed between 2011 and 2012 for both the Devon and Austfonna data sets. Are these changes from 2011 to 2012 (-0.13 to -0.22 m for Devon and -0.51 to -0.65 m for Austfonna) significant, or just a reflection of possible errors in the methodology? If each estimate is uncorrelated and part of a normal distribution, then the precision of the average can be estimated using the standard error of the mean; the SD of individual estimates divided by the square root of the number of estimates in the average. This leads to an estimate of $\sim$ 0.06–1.7 m for the standard error of the means, implying that the year-to-year differences may be significant, and that there may have been some difference in the conditions year-to-year that led to the changing bias. However, the histograms in Fig. 4 appear asymmetric so that the standard error may give an optimistic error estimate because the factors contributing to the spread in the results are not necessarily uncorrelated.

When we consider the errors in average height and height change we need to consider the following aspects:

1. Changes in near-surface physical characteristics: the CS2 signal will reflect from the surface if it is wet (e.g. summer), but can penetrate the surface if it is cold and dry (e.g. winter). Changing meteorological conditions; accumulation, storms, heavy snow falls, etc., could change the bias between the CS2 detected surface and the true surface, even during the winter. ~~Changing historical meteorological conditions, even in winter, could change the bias between the CS2 detected surface and the true surface.~~ We expect that the magnitude of this variable bias may be dependent on the winter accumulation and conditions.

2. Temporal sampling: the CS2 data acquisition occurs only on some of the 30 days in each period so that if monthly elevations are studied, some rapid changes, e.g. due to summer melt, may be underestimated. This error can be estimated for each location based on the slope of the summer height change and normally should be less than $\sim$ 20 cm.

3. Spatial sampling – hypsometry: CS2~~CryoSat-2~~ preferentially samples ridges and high areas since these are frequently the POCA position. Consequently, depressions and low elevation regions will be undersampled. This can be corrected when a DEM is available because we know both the ice cap hypsometry and the distribution of elevations used for the CS2 average height change.

4. Spatial sampling – glacier facies: the height estimates may not uniformly sample the various glacier facies. As we cannot assume a constant bias between CS2

and the surface elevations for the different ice facies, the non-uniform sampling may lead to an additional error. These errors are difficult to quantify, but can be addressed on an ice-cap to ice-cap basis.

5. Altimetric corrections: there may be small systematic bias errors related to factors such as signal strength and surface slope, together with inaccuracies in atmospheric corrections.

In general, these errors have to be addressed on an ice-cap to ice-cap basis. The sampling errors, 2 to 4, will be greatest for the 30 day height changes due to the smaller sample sizes used, and should be small for year-to-year elevation change estimates when many thousands of points are averaged. Likewise, the noise and uncertainty in the CS2 results increases when analyzing separate regions due to the use of fewer points than from the ice cap as a whole. When estimating year-to-year elevation change the error associated with a possible year-to-year bias change is likely less than the combined contributions of the temporal and spatial sampling for the 30 day data set that would occur by, for example, considering end of summer height from year-to-year.

In summary, although the SD of CS2 estimates in relation to the surface elevation was $\sim$ 1.7 m for the Devon Ice Cap and Austfonna in the springs of 2011 and 2012, care should be taken in generalizing this result. The histograms (Fig. 4) appear asymmetric and the standard error of the mean may give an optimistic error estimate for an average of CS2 elevations over a specific area and time period. Of course, when considering an elevation change, the bias between the surface and the CS2 elevation is unimportant as long as it has not changed in the time period between the two averages. The 0.09 and 0.14 m differences between the CS2 data and the reference data in 2011 and 2012 for Devon and Austfonna implies that this may happen, and that the possibility cannot be ignored.

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5 Ice Cap results and discussion

In this section we present CS2 elevation results, first for Devon Ice Cap, using them to illustrate the elevation changes over time, and the correlation with independent surface elevation measurements and temperature data from sensors on an automatic weather station (AWS). Comparisons are also made with airborne Ku band altimeter results. The same approach is used when interpreting the height change data from the other ice caps.

5.1 Devon Ice Cap

We use ∼ 60 000 CS2 elevation estimates over Devon acquired from June 2010 to the end of December 2104 (Fig. 6). The separation into the NW (blue) and SE (maroon) sectors allows a comparison of regions with different accumulation. Although there are clear dips in the CS2 elevations during the two warm summers in 2011 and 2012, it is apparent that some of the CS2 elevation changes don't follow the AWS relative surface height change measurements during the cold winter-spring period (Fig. 7a and b). Indeed for the 2012–2013 winter the CS2 heights decrease from October to April when, as shown by the height sensor, the surface height change should be relatively stable. While there is a slow downslope component of the AWS sensor movement, this explains just part of the discrepancy. Also, in February–March 2014 there is a dip in the CS2 derived height which is unlikely to be real.

The apparent differences between the CS2 and surface elevations suggest that under freezing temperatures the bias between the physical surface and the derived CS2 height does change with meteorological conditions. The variation in backscattered power with position and depth of penetration recorded by the CReSIS Ku band altimeter flown in both 2011 and 2012 shows that the waveforms vary significantly year-to-year at the same position, and in any one year with changing position (Fig. 8). In particular, the maximum return need not be from the snow surface but could be from the ice layer associated with the previous summer melt. It is important to recognize

that while the airborne altimeters can see subsurface layers it is very unlikely that the CS2 altimeter could resolve these features. The reason is not just the higher resolution of the airborne systems but rather the large difference in the footprint size. In general, the shape of the leading edge of the CS2 return waveform is related to the time rate of change of illuminated area (controlled essentially by the topography), and the relative surface and volume backscatter. The link between the CS2 waveform shape and the ice cap topography was demonstrated by the success in simulating CS2 waveforms using only CS2 timing and position data, and the DEM produced by swath processing the CS2 data (Gray et al., 2013).

It is difficult to deconvolve the effect of surface topography and volume backscatter in traditional satellite altimetry data (Arthern et al., 2001), and the same is true for the delay-Doppler processed CS2 data. Consequently, the CS2 waveforms will be affected by the multiple layer and volume backscatter, but it is very unlikely that the CS2 could resolve the kind of layering that is visible in Fig. 8. ~~It is possible that the changing nature of the winter accumulation reduces the surface reflectivity in relation to the vol- ume component, such that the bias between the surface and the CS2 detected height increases during the winter.~~ It is possible that the changing nature of the winter accumulation reduces the surface reflectivity in relation to the volume component, such that the bias between the surface and the CS2 detected height increases during the winter. If the previous summer melt layer remains as the dominant backscatter layer then the apparent height could decrease because of firn compaction and the additional two-way path length due to the permittivity of the winter snow layer. This could then contribute to the apparent decrease in surface height seen in the 2012/13 winter.

The only time period when we can be confident that the peak return is simply related to the surface height is during the summer period when the solar illumination and above zero surface temperatures lead to snow metamorphosis, a wet surface snow layer, densification and melt. With a wet surface layer the dominant returns will be from the surface as losses increase for the component transmitted into the firn volume due to the presence of moisture.

Bearing this in mind, we can now begin to interpret the progression of CS2 derived elevation changes. In both 2011 and 2012 there was extensive summer melt across all elevations, accompanied by a clear CS2 height increase at the onset of melt (Fig. 7a). This apparent surface height increase likely reflects the transition from volume returns to a surface dominated return, rather than a real surface height increase. After the

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initial CS2 height increase, there was a clear decrease in CS2 height throughout the rest of the summer, coincident in time with melting temperatures and thus interpreted as representing a real surface height decrease. This surface elevation decrease can therefore provide an estimate of summer ablation and snow/firn compaction. Following

5 from this, accumulation can then be estimated by differencing the minimum height of one summer with the early summer peak the following year, although this requires extensive m[...]t across the ice cap for both summers, so would apply only for the winter 2011–2012 accumulation on Devon Ice Cap. T[...]e influence of changing conditions on the apparent CS2 detected elevation was also observed with the low resolutio[...] mode (LRM) data in Greenland after the extensive 2012 melt (Nilsson et al., 2015).

There is a marked contrast between the large CS2 derived height losses during the warm summers (June–August) of 2011 and 2012, compared to 2013, when there were low temperatures and little surface melt (Fig. 7c). How well the CS2 height changes represent summer melt can be assessed by comparison with the AWS and mass balance pole data. From this it is clear that the maximum in accumulation and melt occur in the SE (Fig. 7a; maroon line vs. blue line). Comparing the NW CS2 height changes with those measured at the lowest AWS, which at 1317 m is the closest to the average height of the NW sector CS2 measurements, a good correspondence is found; -0.72 ± 0.~~3~~5 m (CS2) vs. -0.64 m (AWS) for 2011, and -0.44 ± 0.~~3~~5 m (CS2) vs. -0.67 m (AWS) for 2012.

As described in the methods section, we can minimize the uncertainties introduced by temporal and spatial sampling by considering the ice cap wide average CS2 winter elevation change (red markers in Fig. 7a). Again, we find a correspondence between the average CS2 winter elevation change with the surface elevation change recorded at the AWS at 1317 m, averaged over the same period (Fig. 7b). However, because the AWS is fixed to the upper firn layers of the ice cap, it only provides a relative measure of surface height change. The red markers (Fig. 7b) indicate the AWS height change corrected for the -0.16 ± 0.05 m a^{-1} vertical displacement measured by GPS between spring 2013 and 2014, and with the same correction assumed for the other years. These elevation changes now show a better correspondence with the red markers in Fig. 7a.

The 3 year elevation change as a function of elevation (Fig. 9a) for Devon was obtained by differencing closely spaced elevation measurements from two time periods; the winter of 2013/2014 minus elevations from the first winter of CS2 operation (2010/2011). This indicates that surface elevation decrease has been greatest at lower

6 altitudes.

7 Table 1 includes the estimated accuracy of surface height change for the Devo[...]e Cap based on CS2 measurements. The high temporal resolution row reflects the potential accura[...] of year-to-year height change based on the monthly height estimates, and on the relative acc[...]cy of monthly height change in the summer or winter. For Devon the errors include a possible bias c[...]nge (item 1 in section 4.2; ~0.2 m), temporal and spatial sampling issues (items 2-4 in section 4.2; ~0[...]m) and the 'altimetric' errors (item 5 in section 4.2; ~0.2 m). Assuming these contributions are indepe[...]ent, the root square sum will give the overall error but it should be emphasized that these results a[...] rounded, and are estimates. The year-to-year height change (final row) is based on the much lar[...] winter time periods and the sampling errors are much reduced.

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5.2 Austfonna

The CS2 data coverage of Austfonna is relatively good, due to the ice cap's high latitude and moderately sloped surface topography: over 100 000 CS2 height estimates have been used in our analysis over the CS2 time period to the end of 2014. This allows the data set to be split into 3 sub-regions with distinct mass balance characteristics, without introducing unacceptable sampling errors (Fig. 10). We define a southern (fawn) and northern (pink) region extending from the margin to 600 m elevation and a summit region (green) above 600 m. Here, we exclude the area which has been strongly affected by the ongoing surge in Basin-3 (McMillan et al., 2014b; Dunse et al., 2015).

The CS2 elevation change for all three regions shows a clear drop during the summer melt period (Fig. 11a), and, as expected, is smaller for the high elevation region. The largest summer height decreases were detected in 2013. This is in agreement with

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As discussed for Devon, and expected from the ASIRAS results, the fluctuations in the high temporal resolution CS2 height change data suggests that under cold conditions there can be a variable bias between the surface and CS2 derived heights. With the larger accumulation and milder, more variable winter temperatures on Austfonna one would expect the variable bias problem to be more severe than on Devon. For example, there is a large spike in elevation of 1 to 1.5 m between April and May 2013 for the southern low elevation region (fawn in Figs. 10 and 11a). Data from the AWS in Basin-3 can be used to help explain this sudden jump; this indicates air temperatures in April of around $-15\,^{\circ}$C, before warm air moves in at the beginning of May accompanied by a significant snow fall. The apparent CS2 height increase of $\sim$ 1–1.5 m over the southern coastal areas is therefore likely explained by a shift from volume to surface scatter and a real height change associated with fresh, probably wet, snow. The estimate of the error in the year-to-year CS2 based surface height change is estimated as 0.35 m in Table 1, larger than that for Devon because of the larger accumulation. With the high latitude the sampling issues are however less severe and the potential error in the monthly CS2 height in Table 1 has been estimated as 0.5 m, the same as for Devon.

In the northern and summit region there is an overall increase in average elevation over the CS2 time frame (Figs. 11a and 12). The total winter-to-winter elevation increase for the summit region is $\sim$ 1 m over the three years from 2010/2011 to 2013/2014. This took place primarily in the first two years and there was little change in average high altitude elevation between the winters of 2012/2013 and 2013/2014, spanning the large melt in the summer of 2013 (Fig. 11a). The northern side shows a winter-to-winter increase in elevation for the first two years, which then dips to an overall increase in 3 years of $\sim$ 0.5 m. This dip may also be related to the large 2013 melt. In contrast, the southern region has lost elevation. This may be explained partly by the hypsometry of Bråsvellbreen (Basin 1 in Fig. 12), a surge type glacier in its quiescent phase since the last surge in 1936/1937. A large fraction of the glacier lies at low elevations, and is characterized by strong ablation.

We derived the height change over 3 years by taking all the height data from the last year of data acquisition, November 2013 to December 2014, and subtracting the heights from July 2010 to December 2011 (Fig. 12). Individual pairs of height estimates within 400 m were differenced, slope corrected and binned into footprints of $\sim$ 1 km^2. The most striking feature is the large height decrease of > 30 m associated with the surge of Basin-3. Otherwise, the pattern of interior thickening, especially along the east side of the main ice divide, and the marginal thinning resembles the elevation-change pattern reported for earlier time periods (Bamber et al., 2004; Moholdt et al., 2010). Also, the CS2 height change results are consistent with the results obtained from re- peated GPS tracks (spring 2011 to spring 2014, see Fig. 12). ~~The average difference between the CS2 elevation change and that from reference GPS points within 100 m of the CS2 footprint centre was 0.18 m.~~ The three-year surface height gain at elevations above 600 m was measured by finding pairs of surface GPS points within 1 m of one another, where one point was from the spring of 2011 and the other from the spring of 2014 (blue points in Fig. 12). The mean height increase was 1.19 m with a standard deviation of 0.32 m. The CS2 height change was also estimated by using pairs of height estimates adjacent to the GPS transect with time windows Nov. to April in the winters of 2010/11 and 2013/14. In this case the CS2 height increase was 0.96 m with a standard deviation of 1.15 m. Although the approaches are very different this does provide added credibility that the 3-year CS2 height change illustrated in Fig 12 does bare a strong resemblance to the surface height change.

The 3 year height loss as a function of elevation for all the Austfonna data, but with the Basin 3 data removed, mirrors the situation in Canadian Arctic ice caps (Fig. 9e). The height loss decreases with increasing elevation although the linear approximation used for the others isn't appropriate in this case.

5.3 Barnes Ice Cap

On Barnes Ice Cap the relative maximum power of each return waveform shows increased power and dynamic range in the summers (Fig. 13a), which we interpret to be a consequence of the presence of moisture in the snow, melt and the possibility of a specular return from a wet surface. Initially moisture in the snow can reduce the backscatter but with continued melt and the creation of a wet surface there is the possibility of relatively strong coherent reflection. The 30 day CS2 height changes (Fig. 13b) clearly show significant ice loss due to the warm summers in 2011 and 2012, with much lower losses in 2013 and 2014 due to the colder summers in those years.

Each year there is a small height increase in June, immediately prior to the height loss due to summer melt (Fig. 13b). This is consistent with the observations for Devon and Austfonna, and is interpreted as the transition from a composite surface and volume signal to one dominated by the snow surface as melt begins. The height loss due to summer melt each year ranged from 1.38 to 2.55 m, whereas winter accumulation, estimated from the summer minimum in one year to the maximum at the onset of melt in the following year, remained relatively constant at ~ 1 m each winter. It is therefore clear from the high temporal resolution data that summer melt is dominant in defining the annual mass balance. Estimating errors is more straightforward for Barnes because of the simpler configuration of surface facies: the ice cap consists essentially of snow over ice in winter, with the loss of all the winter snow the following summer. In this case we base the error estimate on the statistics of the 50+ estimates of each height change: the error bars on the elevation change estimates (Fig. 13b) indicate ± 2 times the standard error of the mean. This approach has not been used for the other ice caps where it might lead to an optimistic error estimate (see Table 1). As the summer melt period has increased in recent years to ~ 87 days (Dupont et al., 2012) the potential error in summer height loss due to melt associated with the temporal sampling is also smaller than for Devon.

When analyzing the winter-to-winter height change results derived from the average of the December to May data each year (red dots in Fig. 13b), it is evident that between winter 2010/2011 and winter 2013/2014 Barnes Ice Cap lost 2.73 ± 0.2~~30~~ m in average elevation, with most of that loss occurring in the summers of 2011 and 2012. These numbers agree well with the high temporal resolution height change estimates. An increase in melt at lower elevations on the ice cap is also observed (Fig. 9c), an effect originally shown by the work of Abdalati et al. (2004) and confirmed in the work of Gardner et al. (2012).

5.4 Agassiz and Penny Ice Caps

At 81° N the Agassiz Ice Cap receives less accumulation and has much less summer melt than the Penny Ice Cap on southern Baffin Island (67° N). The magnitudes of the peak CS2 returns reflect these different surface temperature regimes: Agassiz experienced relatively less melt than Penny at high elevations even in the warm 2011 and 2012 summers, consequently the seasonal variation in the peak returns is much less (Fig. 14a and b). The effect of summer melt on the CS2 returns is obvious in the Penny results (Fig. 14c and d). The strong peak returns even at high elevations at the end of July imply a strong specular reflection from a wet ice surface.

The increased time gap between the groups of passes evident for Penny in comparison to those from Agassiz is due to the fact that the ascending and descending passes over Penny occurred in the same time period, as well as the influence of the spreading of the passes due to the lower latitude.

There is little point in attempting to assess ~~at~~ the monthly height change for either ice cap as there is simply not enough data (Table 1). However, winter-to-winter height change estimates can be made on the assumption that the conditions have not changed between each winter so that the bias between the physical surface and the CS2 detected POCA does not change. The average height change for the winters

2011/2012, 2012/2013 and 2013/2014 with respect to the winter of 2010/2011 show a larger ice loss for Penny in relation to Agassiz (Fig. 14e). Again the effect of the warm 2011 and 2012 summers, and the contrast with the summer of 2013, is evident. On both ice caps, height loss decreases with increasing elevation (Fig. 9b and d).

The different climate regime between Agassiz and Penny is obvious in the contrast between the plots of the peak returns in Fig. 14 (a, b vs. c, d). This implies that the bias between surface and CS2 detected surface will be less variable for Agassiz than Penny, and that the errors in surface height change will be smaller. This is reflected in the estimates of potential errors in the year-to-year height change (Table 1).

6 Conclusions

The airborne Ku band altimeter results over Devon and Austfonna imply that there will be a variable bias between the physical surface and the heights derived from CryoSat-2. This has been confirmed with our analysis of CS2 data; with ice cap wide melt the bias between the CS2 ~~height and the physical surface~~ derived elevation and the physical surface will be a minimum in the summer, but will increase with winter accumulation and the change in the nature of the surface. The transition from freezing temperatures to melt in the early summer is accompanied by an increase in the CS2 elevation, but without an equivalent increase in the surface height. This corresponds to the transition from a composite surface-volume backscatter to one dominated by the surface. Under freezing conditions the bias between the CS2 derived elevation and the physical surface appears to vary with the current and historical conditions on the ice cap in a way that is hard to quantify although for Austfonna the difference appears to increase with increasing elevation.

Although some of the details of the seasonal change in elevation, e.g. summer-winter, may change slightly with the form of the retracker, e.g. Ricker et al., 2014 showed some influence of the form of the retracker on sea ice freeboard results, we suspect that any CS2 detected elevation will be more dependent on the changing conditions than on the detailed form of the retracker.

Notwithstanding the uncertainty in the bias between the surface and CS2 elevation, the winter-to-winter CS2 height change results can give a credible estimate of ice cap surface height change, particularly as more years are added to the time series. The largest uncertainty in these estimates, and the most difficult to quantify, comes from the fact that the conditions winter-to-winter may change in a manner that affects the bias between the surface and the CS2 elevation. Surface field measurements under cold spring conditions may help identify conditions which could lead to a changing bias between the CS2 and surface elevations.

~~A change~~

~~in near surface density would also affect the density one should use in estimating the mass change based on the volume change.~~

~~However, the r~~Results for the Canadian ice caps show clearly the large year-to-year height decrease associated with the strong summer melt in 2011 and 2012. All show a net height loss over the CS2 time period, although Devon and Agassiz show a modest height increase after the low summer 2013 melt. This is in contrast to Austfonna where the summer of 2013 showed the largest melt induced height loss although the upper elevations of the ice cap appears to be still gaining elevation since mid-2010 when CryoSat-2 was commissioned. However, all the ice caps show a height loss at their lower elevations.

For the first time, CryoSat-2 has provided credible monthly height change results for some relatively small ice caps, and the summer surface height decrease has been identified and measured. For some of the ice caps this allows the estimation of both accumulation and summer melt. For Barnes, thanks to the absence of firn, the CS2 results provide an excellent record of change since the fall of 2010. The continued loss of elevation even after the relatively cold snowy summer of 2013 attests to the eventual demise of this ice cap. ~~The key CS2 attribute which has made these advances possible is the ability to geocode the footprint position.~~ In summary, we believe that the improved resolution and interferometric capability of the SARIn mode of Cryosat allows the user to identify the POCA position more accurately than with previous altimeters, and that the temporal height changes we have shown in this work depend to a large extent on the ability to better geocode the POCA footprint.

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References

Abdalati, W., Krabill, F., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Yungel, J., and Koerner, R.: Elevation changes of ice caps in the Canadian Arctic Archipelago, J. Geophys. Res.-Earth, 109, F04007, doi:10.1029/2003JF000045, 2004.

Abdalati, W., Zwally, H. J., Bindschadler, R., Csatho, B., Farrell, S. L., Fricker, H. A., Harding, D., Kwok, R., Lefsky, M., Markus, T., Marshak, A., Neumann, T., Palm, S., Schutz, B., Smith, B., Spinhirne, J., and Webb, C.: The ICESat-2 laser altimetry mission, Proc. IEEE, 98, 735–751, 2010.

Andrews, J. T. and Barnett, D. M.: Holocene (Neoglacial) moraine and proglacial lake chronology, Barnes Ice Cap, Canada, Boreas, 6, 341–358, 1979.

Arthern, R. J., Wingham, D. J., and Ridout, A. L.: Controls on ERS altimeter measurements over ice sheets: footprint-scale topography, backscatter fluctuations, and the dependence of microwave penetration on satellite orientation, J. Geophys. Res.-Atmos., 106, 33471–33484, doi:10.1029/2001JD000498, 2001.

Baird, P. D.: Method of nourishment of the Barnes ice cap, J. Glaciol., 2, 2–9, 1952.

Bamber, J., Krabill, W., Raper, V., and Dowdeswell, J.: Anomalous recent growth of part of a large Arctic ice cap: Austfonna, Svalbard, Geophys. Res. Lett., 31, L12402, doi:10.1029/2004GL019667, 2004.

Bell, C., Mair, D., Burgess, D., Sharp, M., Demuth, M., Cawkwell, F., Bingham, R., and Wadham, J.: Spatial and temporal variability in the snowpack of a high Arctic ice cap: implications for mass-change measurements, Ann. Glaciol., 48, 159–170, 2008.

Bouzinac, C.: CryoSat-2 Product Handbook, Tech. Report, European Space Agency, available at: https://earth.esa.int/documents/10174/125272/CryoSat_Product_Handbook, last access: 26 February 2014.

Brandt, O., Hawley, R. L., Kohler, J., Hagen, J. O., Morris, E. M., Dunse, T., Scott, J. B. T., and Eiken, T.: Comparison of airborne radar altimeter and ground-based Ku-band radar

measurements on the ice cap Austfonna, Svalbard, The Cryosphere Discuss., 2, 777–810, doi:10.5194/tcd-2-777-2008, 2008.
Burgess, D. O.: Mass balance of the Devon (NW), Meighen, and South Melville ice caps, Queen Elizabeth Islands for the 2012–2013 balance year, Open File 7692, Geological Survey of Canada, Ottawa, Canada, p. 26, doi:10.4095/295443, 2014.
Burgess, D. O., Sharp, M. J., Mair, D. W. F., Dowdeswell, J. A., and Benham, T. J.: Flow dynamics and iceberg calving rates of the Devon Island ice cap, Nunavut, Canada, J. Glaciol., 51, 219–238, doi:10.3189/172756505781829430, 2005.
Davis, C. H.: A robust threshold re-tracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters, IEEE T. Geosci. Remote, 35, 974–979, doi:10.1109/36.602540, 1997.
Davis, C. H. and Segura, D. M.: An algorithm for time-series analysis of ice sheet surface elevations from satellite altimetry, IEEE T. Geosci. Remote, 39, 202–206, 2001.
de la Peña, S., Nienow, P., Shepherd, A., Helm, V., Mair, D., Hanna, E., Huybrechts, P., Guo, Q., Cullen, R., and Wingham, D.: Spatially extensive estimates of annual accumulation in the dry snow zone of the Greenland Ice Sheet determined from radar altimetry, The Cryosphere, 4, 467–474, doi:10.5194/tc-4-467-2010, 2010.
Dowdeswell, J. A.: Drainage-basin characteristics of Nordaustlandet ice caps, Svalbard, J. Glaciol., 32, 31–38, 1986.
Dowdeswell, J. A., Drewry, D., Cooper, A., Gorman, M., Liestøl, O., and Orheim, O.: Digital mapping of the Nordaustlandet ice caps from airborne geophysical investigations, Ann. Glaciol., 8, 51–58, 1986.
Dowdeswell, J. A., Benham, T. J., Strozzi, T., and Hagen, J. O.: Iceberg calving flux and mass balance of the Austfonna ice cap on Nordaustlandet, Svalbard, J. Geophys. Res., 113, F03022, doi:10.1029/2007JF000905, 2008.
Dunse, T., Schuler, T. V., Hagen, J. O., Eiken, T., Brandt, O., and Høgda, K. A.: Recent fluctuations in the extent of the firn area of Austfonna, Svalbard, inferred from GPR, Ann. Glaciol., 50, 155–162, 2009.
Dunse, T., Schellenberger, T., Hagen, J. O., Kääb, A., Schuler, T. V., and Reijmer, C. H.: Glacier-surge mechanisms promoted by a hydro-thermodynamic feedback to summer melt, The Cryosphere, 9, 197–215, doi:10.5194/tc-9-197-2015, 2015.

Dupont, F., Dupont, F., Royer, A., Langlois, A., Gressent, A., and Picard, G.: Monitoring the melt season length of the Barnes Ice Cap over the 1979–2010 period using active and passive microwave remote sensing data, Hydrol. Process., 26, 2643, doi:10.1002/hyp.9382, 2012.
Ferguson, A. C., Davis, C. H., and Cavanagh, J. E.: An autoregressive model for analysis of ice sheet elevation change time series, IEEE T. Geosci. Remote, 42, 2426–2436, 2004.
Fisher, D. A., Koerner, R. M., Bourgeois, J. C., Zielinski, G.,Wake, C., Hammer, C. U., Clausen, H. B., Gundestrup, N., Johnsen, S., Goto-Azuma, K., Hondoh, T., Blake, E., and Gerasimoff, M.: Penny Ice Cap, Baffin Island, Canada and the Wisconsinan Foxe Dome connection: two states of Hudson Bay ice cover, Science, 279, 692–695, 1998.
Fisher, D., Zheng, J., Burgess, D. O., Zdanowicz, C., Kinnard, C., Sharp, M. J., and Bourgeois, J.: Recent melt rates of Canadian Arctic ice caps are the highest in many millennia, Global Planet. Change, 84/85, 3–7, doi:10.1016/j.gloplacha.2011.06.005, 2012.
Galin, N., Wingham, D. J., Cullen, R., Fornari, M., Smith, W. H. F., and Abdall, S.: Calibration of the CryoSat-2 interferometer and measurement of across-track ocean slope, IEEE T. Geosci. Remote, 51, 57–72, 2012.
Gardner, A. S., Moholdt, G., Wouters, B., Wolken, G. J., Burgess, D. O., Sharp, M. J., Cogley, J. G., Braun, C., and Labine, C.: Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago, Nature, 473, 357–360, doi:10.1038/nature10089, 2011.
Gardner, A. S., Moholdt, G., Arendt, A., and Wouters, B.: Accelerated contributions of Canada's Baffin and Bylot Island glaciers to sea level rise over the past half century, The Cryosphere, 6, 1103–1125, doi:10.5194/tc-6-1103-2012, 2012.
Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., and Paul, F.: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009, Science, 340, 852–857, doi:10.1126/science.1234532, 2013.
Gray, L., Burgess, D., Copland, L., Cullen, R., Galin, N., Hawley, R., and Helm, V.: Interferometric swath processing of Cryosat data for glacial ice topography, The Cryosphere, 7, 1857–1867, doi:10.5194/tc-7-1857-2013, 2013.
Hawley, R. L., Morris, E. M., Cullen, R., Nixdorf, U., Shepherd, A., and Wingham, D. J.: ASIRAS airborne radar resolves internal annual layers in the dry-snow of Greenland, Geophys. Res. Lett., 33, L04502, doi:10.1029/2005GL025147, 2006.
Hawley, R. L., Brandt, O., Dunse, T., Hagen, J. O., Helm, V., Kohler, J., Lang- ley, K., Malnes, E., and Gda, K. H.: Using airborne Ku-band altimeter waveforms to investi-

gate winter accumulation and glacier facies on Austfonna, Svalbard, J. Glaciol., 59, 893–899, 2013.

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

Helm, V., Humbert, A., and Miller, H.: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2, The Cryosphere, 8, 1539–1559, doi:10.5194/tc-8-1539-2014, 2014.

Jensen, J. R.: Angle measurement with a phase monopulse radar altimeter, IEEE T. Antenn. Propag., 47, 715–724, 1999.

Koerner, R. M.: Accumulation on the Devon Island Ice Cap, Northwest Territories, Canada, J. Glaciol., 6, 383–392, 1966.

Koerner, R. M.: Some observations on superimposition of ice on the Devon Island Ice Cap, N. W. T., Canada, Geogr. Ann. A, 52, 57–67, 1970.

Koerner, R. M.: Mass balance of glaciers in the Queen Elizabeth Islands, Nunavut, Canada, Ann. Glaciol., 42, 417–423, doi:10.3189/172756405781813122, 2005.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., and Wingham, D.: Increased ice losses from Antarctica detected by CryoSat-2-2, Geophys. Res. Lett., 41, 3899–3905, doi:10.1002/2014GL060111, 2014a.

McMillan, M., Shepherd, A., Gourmelen, N., Dehecq, A., Leeson, A., Ridout, A., Flament, T., Hogg, A., Gilbert, L., Benham, T., van den Broeke, M., Dowdeswell, J., Fettweis, X., Noël, B., and Strozzi, T.: Rapid dynamic activation of a marine-based Arctic ice cap, Geophys. Res. Lett., doi:10.1002/2014GL062255, in press, 2014b.

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., Glazovsky. A. F.: Glaciers dominate eustatic sea-level rise in the 21st century, Science, 317, 1064–1067, doi:10.1126/science.1143906, 2007.

Moholdt, G. and Kääb, A.: A new DEM of the Austfonna ice cap by combining dif- ferential interferometry with ICESat laser altimetry, Polar Res., 31, 18460–18470, doi:10.3402/polar.v31i0.18460, 2012.

Moholdt, G., Hagen, J. O., Eiken, T., and Schuler, T. V.: Geometric changes and mass balance of the Austfonna ice cap, Svalbard, The Cryosphere, 4, 21–34, doi:10.5194/tc-4-21-2010, 2010.

Nilsson, J., P. Vallelonga, S. B. Simonsen, L. S. Sørensen, R. Forsberg, D. Dahl-Jensen, M. Hirabayashi, K. Goto-Azuma, C. S. Hvidberg, H. A. Kjær, and K. Satow (2015), Greenland 2012 melt event effects on CryoSat-2 radar altimetry. Geophys. Res. Lett., 42, 3919–3926. doi: 10.1002/2015GL063296.

Pinglot, J. F., Hagen, J. O., Melvold, K., Eiken, T., and Vincent, C.: A mean net accumulation pattern derived from radioactive layers and radar soundings on Austfonna, Nordaustlandet, Svalbard, J. Glaciol., 47, 555–566, 2001.

Raney, R. K.: The Delay/Doppler Radar Altimeter, IEEE T. Geosci. Remote, 36, 1578–1588,
9 , 1998.

10 Ricker, R., Hendricks, S., Perovich, D. K., Helm, V., and Gerdes, R.: Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: An observational approach with buoy data. Geophys. Res. Lett., 42, 4447–4455. doi: 10.1002/2015GL064081. 2015.

11

Schuler, T. V., Dunse, T., Østby, T. I., and Hagen, J. O.: Meteorological conditions on an Arctic ice cap – 8 years of automatic weather station data from Austfonna, Svalbard, Int. J. Climatol., 34, 2047–2058, doi:10.1002/joc.3821, 2014.

Sharp, M., Burgess, D. O., Cogley, J. G., Ecclestone, M., Labine, C., and Wolken, G. J.: Extreme melt on Canada's Arctic ice caps in the 21st century, Geophys. Res. Lett., 38, L11501, doi:10.1029/2011GL047381, 2011.

Sneed, W. A., Le, R., Hooke, B., and Hamilton, G. S.: Thinning of the south dome of Barnes Ice Cap, Arctic Canada, over the past two decades, Geology, 36, 71–74, doi:10.1130/G24013A.1, 2008.

Taurisano, A., Schuler, T. V., Hagen, J.-O., Eiken, T., Loe, E., Melvold, K., and Kohler, J.: The distribution of snow accumulation across Austfonna ice cap Svalbard: direct measurements and modeling, Polar. Res., 26, 7–13, 2007.

VanWychen, W., Copland, L., Gray, L., Burgess, D., Danielson, B., and Sharp, M.: Spatial and temporal variation of ice motion and ice flux from Devon Ice Cap, Nunavut, Canada, J. Glaciol., 58, 657–664, doi:10.3189/2012JoG11J164, 2012.

Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere, in: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2013.

Wingham, D., Francis, C. R., Baker, S., Bouzinac, C., Cullen, R., de Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F.,

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Viau, P., and Wallis, D.: CryoSat-2: a mission to determine the fluctuations in earth's land and marine ice fields, Adv. Space Res., 37, 841–871, 2006.
Zdanowicz, C., Smetny-Sowa, A., Fisher, D., Schaffer, N., Copland, L., Eley, J., and Dupont, F.: Summer melt rates on Penny Ice Cap, Baffin Island: past and recent trends and implication for regional climate, J. Geophys. Res., 117, F02006, doi:10.1029/2011JF002248, 2012.

Table 1. Ice Cap information.

	~~Devon~~	~~Austfonna~~	~~Barnes~~	~~Agassiz~~	~~Penny~~
~~Location~~	~~75° N 82° W~~	~~79° N 23° E~~	~~70° N 73° W~~	~~80° N 75° W~~	~~67° N 66° W~~
~~Size (km^2)~~	~~12 000~~	~~8100~~	~~5900~~	~~21000~~	~~6400~~
~~Elevation range~~	~~0–1920~~	~~0–830~~	~~400–1102~~	~~0–1980~~	~~0–1980~~
~~Current glacier facies~~	~~Ablation Superimposed ice (SI) Wet Snow Percolation~~	~~Ablation SI Wet snow~~	~~Ablation (SI)~~	~~Ablation SI Wet snow Percolation~~	~~Ablation SI Wet snow~~
~~DEM~~	~~Modified CDED~~	~~U. Oslo~~	~~CDED~~	~~CDED~~	~~CDED~~
~~Validation data~~	~~SMB stakes Surface GPS profiles NASA ATM* ESA ALS* AWS~~	~~SMB stakes Surface GPS and GPR profiles ESA ALS[a] AWS~~		~~SMB stakes Surface GPS profiles~~	~~SMB stakes Surface GPS profiles~~
~~Approx. 2 day westward orbit drift (km)~~	~~25~~	~~15~~	~~34~~	~~15~~	~~38~~
~~Average no. of CS2 height estimates per 30 day/per year~~	~~1350/16 000~~	~~2500/30 000~~	~~1000/12 300~~	~~670/8100~~	~~530/6300~~
~~Mean elevation of CS2 height estimates~~	~~1260 m~~	~~530 m~~	~~900 m~~	~~1588 m~~	~~1530 m~~
~~Estimated elevation change accuracy; high temporal resolution~~	~~0.5 m~~	~~0.5 m~~	~~0.35 m~~	~~N/A~~	~~N/A~~
~~Estimated elevation change accuracy; year-to-year~~	~~0.25 m~~	~~0.35 m~~	~~0.2 m~~	~~0.25 m~~	~~0.35 m~~

~~* Scanning laser altimeters.~~
~~CDED; Canadian Digital Elevatio Data: http://www.pancroma.com/downloads/NRCAN_CDED_specs.pdf.~~

	Devon	Austfonna	Barnes	Agassiz	Penny
Location	75°N 82°W	79°N 23°E	70°N 73°W	80°N 75	67°N 66°W
Size (km2)	12,000	8,100	5,900	2,1000	6,400
Elevation range	0 - 1920	0 - 830	400 - 1102	0 - 1980	0 - 1980
Current glacier facies	Ablation, Superimposed ice (SI), Wet snow, Percolation.	Ablation, SI, Wet snow.	Ablation, (SI)	Ablation, SI, Wet snow, Percolation.	Ablation, SI, Wet snow.
DEM	CDED[1]	U. Oslo[2]	CDED[1]	CDED[1]	CDED[1]
Validation data	SMB stakes, Surface GPS profiles, NASA ATM*, ESA ALS*, AWS.	SMB stakes, Surface GPS and GPR profiles, ESA ALS*, AWS.		SMB stakes, Surface GPS profiles.	SMB stakes, Surface GPS profiles.
Approx. 2 day westward orbit drift (km)	25	15	34	15	38
Average no. of CS2 height estimates per 30 day / per year	1,350/16,000	2,500 / 30,000	1000/12,300	670 / 8,100	530 / 6,300
Mean elevation of CS2 height estimates	1260 m	530 m	900 m	1588 m	1530 m
Estimated elevation change accuracy; high temporal (~ 30 day) resolution	0.5 m	0.5 m	0.35 m	N/A	N/A
Estimated elevation change accuracy; year-to-year	0.25 m	0.35 m	0.2 m	0.25 m	0.35 m

* Scanning laser altimeters.

1. CDED; Canadian Digital Elevation Data: http://www.pancroma.com/downloads/NRCAN_CDED_specs.pdf. DEMs derived from 1:50,000 and 1:250,000 maps based on historical imagery.

2. DEM derived from ERS 1-day repeat-pass interferometry and refined with ICESat laser altimeter data (Moholdt et al., 2012).

Figure 1. Location of the five ice caps measured in this study.

Figure 2. Flow chart showing the methodology developed to derive terrain elevation from the L1b SARIn files.

Figure 3. Digital elevation model of Devon Ice cap showing the positions of the spring 2011 reference surface elevations (in black) and the CS2 elevations (in blue) acquired between January 1 and the end of May 2011. The rectangular grid over the ice cap summit was collected from ground-based kinematic GPS surveys while the remaining transects were collected by ESA and NASA airborne missions.

Figure 4. Histograms of the height differences, CS2 minus the reference elevations, acquired for Devon (**a**; 2011, and **b**; 2012) and Austfonna (**c**; 2011 and **d**: 2012).

Figure 5. Biases between CS2 elevations and adjacent reference heights plotted against elevation for Devon (**a**; 2011 and **b**; 2012) and Austfonna (**c**; 2011 and **d**; 2012). The red markers indicate the average biases above and below the median elevation.

Figure 6. The colored dots indicate the over 60 000 positions for which height data have been calculated superimposed on a grey scale representation of the Devon topography. Points for the NW and SE sectors are coloured dark blue and maroon respectively. The positions of the 4 automatic weather stations is indicated by the green dots and the mass balance pole positions are marked as yellow dots. NASA acquired airborne Ku altimeter data (Fig. 8) over the flight lines marked in red in both 2011 and again in 2012.

Figure 7. **(a)** Average CS2 height change over Devon Ice Cap as a function of time from July 2010 until December 2014 for all elevations (black), and for the NW (blue) and SE (maroon) sectors shown in Fig. 6. The short dashed black lines at the top indicate the time periods of CS2 data collection for the high temporal resolution plot. The four red dots indicate the winter-to-winter height change for all the elevation data for the time periods shown by the horizontal red lines. **(b)** Surface height change recorded by an ultrasonic surface height sensor on the AWS labelled A in Fig. 6. Black dots indicate the height change averaged over the same time frames as the CS2 winter-to-winter height change. The red dots show the same data corrected for the AWS vertical displacement. **(c)** Average AWS temperature data at the CS2 pass times (blue dots) and the cumulative positive degree day data (green).

Figure 8. Variability in surface and near surface backscatter collected over Devon Ice Cap by the CReSIS Ku band altimeter in early May in both 2011 (**a** and **b**) and 2012 (**c** and **d**). The two left panels show the 2011 and 2012 reflected power as a function of penetration into the upper snow-firn layers and position along the north–south shown in Fig. 6. The two right panels show the change in waveform between the spring of 2011 and 2012 for the east–west line. A sub-surface propagation speed of 0.225 $\mathrm{m\,ns^{-1}}$ was assumed in preparing this figure.

Figure 9. Height loss between the winter of 2010/2011 and the winter of 2013/2014 as a function of elevation for the 5 ice caps. Red lines are a linear fit to the data except for Austfonna **(e)** where the points are averages over 100 m elevation bands.

Figure 10. The different basins on Austfonna are illustrated by the white lines. Data from Basin 3, which has surged during the CryoSat-2 time period, has been removed and studied separately. The remaining CS2 data set has been split into the areas shown in different colors above, and the temporal height change plotted for both a monthly and a winter-to-winter height change in Fig. 11 below. The positions of the three automatic weather stations are marked E, D and B.

Figure 11. (a) CS2 height change plots for the 3 different areas illustrated in different colors in Fig. 10. The square markers indicate the height change for the larger temporal winter-to-winter time periods (October to May). Sonic ranger heights and cumulative positive degree day (CPDD) data from the 3 AWS sensors are shown in **(b)**.

Figure 12. Three year height change estimates illustrated for different footprints across Austfonna. Each coloured pixel represents an average of the height change estimates in that footprint ($\sim 1\,km^2$). Note the colour scale is very nonlinear to better represent the height increase of a few meters at higher elevations, and in the north east, and still illustrate the large height loss of $\sim 30\,m$ in the lower area in basin 3 due to the surge which began in 2012. The blue dots indicate the positions where surface elevation was measured with GPS in the spring of 2011 and again in 2014.

Figure 13. Maximum of each of the $>44\,000$ waveforms from >300 CS2 passes over Barnes Ice Cap between 2010 and 2014. With surface melt, both the dynamic range and average POCA power (dashed black line) increase due to the occasional strong specular reflection; **(b)** height change over time based on the CS2 data grouped into 55 periods, which are shown as the short dashed lines in the upper part of the panel. Red dots indicate the winter-to-winter height change calculated from the periods represented by the 4 red lines at the bottom of the panel.

Figure 14. Waveform maxima **(a–d)** for two elevation ranges of the Agassiz and Penny Ice Caps. The winter-to-winter height change for the four data groups are shown with the same colours in **(e)**.