Response to Referee 1's comments

Below we summarise the comments of Referee 1, along with our responses and actions:

#	Comment (verbatim)	Response	Action
R1.1	"In general, my concern is that this manuscript lacks of an in-depth analysis. The focus of this paper is set on the comparison and difference between the NRT and the final released product. But more elaboration of these differences is needed."	We agree that the paper would benefit from a more in-depth analysis of the differences between our NRT and archive data products. Please see our response to **R1.2** and **R1.4** for specific examples.	We have expanded our comparison of our NRT and archive data products. Please see action for **R1.2** and **R1.4** for specific examples.
R1.2	"The volume comparison in Figure 2 reveals higher values for the final release product. You state that this is mostly because of the use of different ice concentrations, but also due to the absence of orbits in the NRT level1b data. Nevertheless, Figure 1, 3, 4 and Table 1 only show statistics with respect to the NRT product. Can you include the same statistics for the final release product (as in Figure 3 and Table 1 for the NRT product) and also the different ice concentrations, you used? I think this is needed in order to proof your statement above and to turn out the differences."	We agree that readers may desire more information on differences between NRT and archive sea ice thickness products. After further inspection, we find that it is the absence of certain geophysical corrections (wet tropospheric, dry tropospheric and inverse barometer), rather than orbits, that drive the remaining differences in sea ice thickness and volume. This can be shown by plotting the spatial variability of these differences for two different months: one with corrections absent and one with corrections present.	We have included a new figure (Figure 3), which consists of 2 maps, detailing the spatial differences between NRT and archive sea ice thickness for data absent and present geophysical corrections. The explanatory text for this figure (Data and Methods final paragraph, final few sentences) reads: *"The remaining difference is likely due to the combined absence of the wet tropospheric, dry tropospheric and inverse barometer corrections in 93.8% of the Baseline-B fast delivery CryoSat-2 data. This is reduced to 0.3% for Baseline-C data. The mean sea ice thickness for both the NRT and archive datasets is ~1.8 m, and there is no bias between them, with or without geophysical corrections applied. When the corrections are missing the NRT and archive thickness values at any given location differ, on average, by 1.1 cm with a standard deviation of 23.0 cm (Figure 3a). This is reduced to 0.1 cm with a standard deviation of 7.4 cm when the corrections are present (Figure 3b). There is no spatial*

			pattern to these differences. Despite the improvement in performance of Baseline-C NRT data compared with Baseline-B we conclude that the satellite orbits and on-ground processing applied to fast delivery CryoSat-2 data are sufficient to determine accurate measurements of Arctic sea ice thickness and volume for both baselines. The thickness differences between the archive and NRT data products are not significant for either baseline given the estimated uncertainty on thickness and the typical thickness of sea ice floes." We have also added archive data to figures 3 and 4b (figures 4 and 5b in updated version), with discussion in the relevant places. Please see action to **R1.12** and **R1.13** for more details. We have also included a description of the spatial and temporal differences between NRT and archive sea ice thickness data in our Discussion and Conclusions section, second paragraph. This reads: *"The NRT and archive thickness differences, although small, vary temporally. The differences are reduced when all geophysical corrections are present in the fast delivery CryoSat-2 data, which is the case in 99.7% of the data since March 26th 2015, when the ESA on-ground processing chain switched from Baseline-B to Baseline-C. There is no spatial variability in the differences between our NRT and archive data products."*
R1.3	"Although many readers are interested only in the final thickness product, comparing only the thickness histograms of both products, is not enough from my point of view. I suggest to show freeboard (and thickness) maps of difference	Agreed. Please see response to **R1.2**	Please see action to **R1.2**

	between the NRT and the archive product in autumn and spring. This would give further information about the spatial distribution of differences between both products.”		
R1.4	“The CS-2 data processing starts with the NRT level1b data and the processing of each orbit segment. Therefore I would suggest also to consider differences on the orbit-scale, like the comparison of freeboard along track between both products or even just the comparison between the ellipsoidal elevations (after retracking). And what about the detected leads? Is it the same for both products?”	We agree that there is likely to be interest in the accuracy of our NRT data on an orbit-scale, and so we have included further illustrations and analysis of this in our revised paper. We feel that an along-track comparison of sea ice freeboard is sufficient, as the differences in sea surface heights at the leads will form part of the small differences seen in freeboard. If the referee is asking whether there is a difference in the number of leads detected in the NRT product compared to the archive then we can include this in our revision, but it is not clear from the question.	We have added an additional panel to Figure 2. Figure 2a now shows the point-by-point freeboard differences for our archive and NRT data products for an individual Arctic pass. This has been described in the final Data and Methods paragraph: *“Firstly we assessed our orbit-scale processing by calculating point-by-point differences of NRT and archive sea ice freeboard using one track of CryoSat-2 data from April 2015, for which all geophysical corrections were present in the NRT and archive data. These showed excellent agreement, with an average difference of 0.1 cm (Fig. 2a).”*
R1.5	**P2 L38:** “The oil and gas sector requires sea ice information for feasibility studies. Why is the reduction of plans for exploration and drilling a consequence? I think it needs one more sentence to explain this.“	We agree that this sentence would benefit from further justification, and so we have done this in our revised paper.	We have added an extra sentence that reads: *“Without these studies companies cannot be sure that their infrastructure is suitably robust for the Arctic environment, such as when the Shell oil rig Kulluk ran aground in January 2013.”*
R1.6	**P2 L28-30**: “So you use NRT SAR and SIN, right? Is there a difference between handling both modes in the NRT product. Or to be more specific, are the differences between NRT SAR and archive SAR the same as between NRT SIN and archive SIN? Would it make sense to separate	We agree that it is not clear in the paper which data modes we use, how we use them, and whether this differs for NRT and archive thickness processing. We have done this in our revised paper.	We have added an explanation of the way in which we process SAR and SARIn data for NRT situations. The first Data and Methods paragraph, first five sentences, now read: *“We use fast delivery radar altimeter measurements from the ESA CryoSat-2 satellite [Wingham et al., 2006] synthetic aperture radar (SAR) and SAR interferometric (SARIn) mode data products to produce NRT estimates of Northern*

	between the modes in this study?”		*Hemisphere (latitudes above 40° N) sea ice thickness and volume. The data are Level 1b, and consist of an echo for each point along the ground track of the satellite. For Arctic sea ice processing we assume that the ice surface is relatively flat and that slope variations are minimal [Rapley et al., 1983], so are concerned principally with power returns from nadir. Therefore SARIn mode waveforms are cropped to include only the central 128 range bins. This allows for identical processing of SAR and SARIn mode data as both now have 128 bins in their waveform data.”* We have also clarified that our processing of SAR and SARIn data is the same for NRT and archive cases. There is now a sentence in the final paragraph of Data and Methods that reads: *“Aside from this, the CryoSat-2 SAR and SARIn mode data are processed identically to the NRT case.”*
R1.7	**P4 L5:** “Can you be more specific: Which geophysical corrections are missing in the fast delivery data? What does ’often’ mean in this statement?”	We agree that it would be helpful to be specific about which geophysical corrections are missing, and so we have done this in our revised paper.	The sentence in question has been expanded to read: *“In the fast delivery data the wet tropospheric, dry tropospheric and inverse barometer corrections are missing in 93.8% of cases for Baseline-B data, but only 0.3% of cases for Baseline-C data. In these cases, all three of the corrections are missing. ”* We have also moved the sentence further up in the paragraph as we feel it makes more sense to include it immediately after the baseline processing is introduced.
R1.8	**P4 L15-19:** “How do you justify using the Warren climatology in regions where W99 is not based on measurements, for example in the Baffin Bay. W99 is a 2d fit and therefore it is not constraint in such areas and can produce substantial biases	We realise now that our treatment of the Warren climatology and our justification of its use are not clearly explained. We share the referee’s concerns regarding the Warren climatology, especially in regions where it is not constrained by *in situ* measurements. Hence we use the mean climatology values of snow depth and density from a	A sentence has been added to summarise our treatment of the Warren climatology. It reads: *“To obtain snow depth and density we average the values from a climatology (Warren et al. 1999) that fall within the ICESat domain, where the climatology is constrained by in situ*

	which are not considered in the uncertainty estimates. In some areas like Barents Sea in November, it can even cause negative snow depths.“	fixed central Arctic domain (where snow parameters are constrained) in all freeboard to thickness conversions, no matter where they are located. There are known differences between the climatology and the current snow depth on younger Arctic sea ice (Kurtz *et al*. 2011; Webster *et al*. 2014) so we halve the snow depth on FYI to account for reduced snow accumulation. Although this approach cannot capture all of the known variability, it removes the possibility of errors being introduced through extrapolation. This detail is now included in our revised paper.	*measurements."* The ICESat domain itself is defined earlier in the paper. Should the reader require further information, the second paragraph in the Data and Methods section, first sentence, now reads: *"The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling et al. (2015)."*
R1.9	**P4 L27-29:** "Why do you use the same weighting for all points? If you project on a 5 km grid, but using a 25 km radius for averaging, this means that the grid cell covers only 1% of the area which goes into the average (5x5 km = 25 km^2, pi x (25km)^2 = 1963 km^2)? Is that right? But then the grid cell is hardly representative for the thickness at this location. What is the circular operator doing? Would it make sense to apply a distance weighting?"	We agree that employing a distance weighting when computing our gridded thickness product may potentially be of benefit (it also may not). However, the aim of this study is not to alter our current processing method. Rather, our aim is to apply our existing method to fast delivery CryoSat-2 data and compare the results to calculations based on archive data, and to do this requires that our processing to remain the same. The effect of gridding methods on gridded sea ice thickness could form the basis of another study.	There is now a sentence in the final Discussion and Conclusions paragraph that reads: *"We will also investigate the impact of different gridding methods, including the application of a distance weighting, on our gridded NRT sea ice thickness product."*
R1.10	**P4 L33-34: "**How is the gap filled at the pole?"	We realise that our approach for filling the polar gap in volume calculation was not explained. Note that this procedure only applies to the volume calculation in the comparison with archive results, it is not required for the thickness products.	Our sea ice volume method description now includes a sentence that reads: *"Empty thickness grid cells within the sea ice extent mask, including those north of 88°N, are filled by nearest neighbour interpolation with a maximum search radius of 300 km."*
R1.11	**P6 L1:** "... absence 'o'f ..."	Agreed	Changed to "of"

R1.12	**Figure 3:** “Can you add the data for the final release product? I think it would be helpful to understand the differences in coverage between both products.”	We agree that this would be helpful, as would a description of the differences. Both are added to the revised paper.	The final data are now included in the figure (now Figure 4). The second Results paragraph, first sentence, now reads: *“To determine the utility of the 5 km grid measurements of NRT sea ice thickness for operational use, we performed a detailed assessment of the spatial and temporal distribution of the data and compared these to the equivalent for archive data.”* The paragraph then discusses these comparisons.
R1.13	**Figure 4b:** “Can you add the data coverage of the final release product (see previous comment)?”	We agree that this would also be helpful, as would a description of the differences. Again, both are added to the revised paper.	The final data are now included in the figure (now Figure 5b). The third Results paragraph, second sentence, now reads: *“We calculated the percentage of ice cover mapped by our NRT product for six key oceanographic basins (Fig. 5a), for the final 28 days of each month of the 2014-2015 sea ice growth season and compared this to the percentage of ice cover mapped by our archive data (Fig. 5b).”* The paragraph then discusses these comparisons. The third results paragraph summarises the new contents of figures 4 and 5b, saying: *“Although there is spatial variation in the coverage of our NRT sea ice thickness data, both with latitude (Fig. 4) and oceanographic basin (Fig. 5b), there is no significant spatial variability in the difference between the NRT and archive data coverage (Fig. 4 and Fig. 5c).”*

References

Rapley, C. G., et al. (1983), *A study of satellite radar atlimeter operation over ice-covered surfaces; EAS contract report no. 5182/82/f/CG(SC)*, ESA Scientific and Techincal Publication Branch ESTEC Noordwijk, Holland.

Tilling, R. L., A. Ridout, A. Shepherd, and D. J. Wingham (2015), Increased Arctic sea ice volume after anomalously low melting in 2013, *Nature Geoscience*, *8*, 643-646.

Wingham, D. J., et al. (2006), CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields, in *Natural Hazards and Oceanographic Processes from Satellite Data*, edited by R. P. Singh and M. A. Shea, pp. 841-871.

Response to Referee 2's comments

Below we summarise the comments of Referee 2, along with our responses and actions:

#	Comment (verbatim)	Response	Action
R2.1	"I believe a product such as this, and particularly the associated uncertainties, require a much more detailed treatment than what has presently been done." "I believe that the uncertainties in the data are larger than were presented in the paper due oversimplification of errors as well as the possible exclusion of key uncertainty factors."	There are insufficient observations to fully characterise (i.e. correct for) certain sources of variability in the retrieval of sea ice thickness and volume. Because of this, our estimates of sea ice thickness and volume are in error. Examples include temporal variations in the microwave scattering horizon, spatial variations in snow loading, and temporal variations in the concentration and extent of sea ice. None of these signals have been adequately sampled using independent measurements, and so we cannot be sure of their variance. To account for this, we introduce uncertainties in the key factors of our retrieval based on information present within the published literature. In the case of our archive product, this includes uncertainties in snow depth, snow density, ice density, sea ice concentration, sea ice extent, and sea ice freeboard (which decorrelates rapidly in space)(Tilling et al., 2015). We do not include an uncertainty associated with temporal variations in the microwave scattering horizon (i.e. the difference between the radar and ice freeboard), because these have been shown to rapidly decorrelate with time and to preferentially affect waveform retrackers designed to locate the ice surface (Ricker et al., 2015), which we do not employ. Our error model leads to uncertainties in Arctic-wide sea ice volume of around 15 %, and in sea ice thickness of around 25% at the 25 km scale of our grid. The latter are comparable to the spread of differences between our archive product and independent	We have expanded our error budget to include the contribution of sea ice freeboard uncertainty due to a.) sea surface height uncertainty and b.) floe height measurement uncertainty (due to radar speckle and random noise in the retracking step). Please see our response and action to **R2.3** and **R2.17**. We have added the treatment of a.) and b.) to the description of our error analysis, and introduce these by stating that *"The construction of our error budget is described in Tilling et al. [2015], but we now expand on this by considering the contribution of uncertainty in sea ice freeboard in more detail."* We have been explicit about which other factors we account for and have strengthened our description with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). We also highlight our desire to further tackle the largest sources of uncertainty, and their associated errors, in our concluding paragraph. The relevant sentence reads: *"The next steps in the advancement of the data are to develop improved estimates of snow loading on Arctic sea ice, and to*

		measurements of sea ice thickness determined from airborne and in situ platforms. Were this not to be the case, we would agree with the assertion that our errors are not well characterised. However, it is, and so we believe that our error budget is in fact a reasonable and credible assessment of the uncertainty in our retrieval. The reviewer does make some specific suggestions as to how our error budget might be modified to suit the case of the near real time data set, which is spatially and temporally under-sampled relative to the archive product. We agree that these suggestions make good sense, and so we have modified our error budget to take these additional uncertainties into account..	*further constrain the uncertainties in snow loading and sea ice density."*
R2.2	"In several areas of the text the mathematical operations performed on the data need to be explicitly written out as otherwise it is unclear exactly how some of the calculations were done. One example on this is that it is unclear whether a correction for the slower speed of light in snow has been applied to the calculation of freeboard. It is stated in Tilling et al., 2015 "A correction is applied to each freeboard measurement to account for the attenuation of the radar pulse as it passes through any snow cover on sea ice, where snow depth is based on a climatology." But this sentence is confusing as it could also apply to attenuation of energy through the snow, which in itself would not necessarily impact the freeboard determination. If this factor is applied, and whether it was	We agree that it is unclear in our original manuscript whether a correction for the slower speed of light in snow has been applied to the calculation of freeboard. We also accept that the use of the word "attenuation" could cause confusion. We agree also that it would be helpful to the reader if the factors included in our error budget were stated more clearly in the text. However, we do not agree that the mathematical operations performed on the data should be written out in full, because they do not differ from those presented in an earlier manuscript (Tilling et al., 2015); the aim of this study is to merely apply our method to fast delivery CryoSat-2 data and compare to archive results.	We have added a sentence to the methods paragraph stating that: *"A correction is applied to each freeboard measurement to account for the reduced speed of the radar pulse as it passes through any snow cover on sea ice."* Should the reader require any further information on our methods we now direct them explicitly to Tilling *et al.* (2015). The second Data and Methods paragraph, first sentence, now reads: *"The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling et al. (2015)."* We have also included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3).

	applied in the determination of sea ice thickness and volume uncertainty, is not clear in the text.”		
R2.3	“It is also unclear how freeboard retrieval errors would propagate into the uncertainty calculations. Tilling et al., 2015 state that an interpolation is done between ocean surface elevation measurements to determine freeboard. The interpolation procedure was not explicitly stated but needs to be done so here. Any such interpolation would change the correlation length of the errors in the assessment and needs to be considered.”	We agree that we should reconsider the contribution of freeboard uncertainty associated with the sparse sampling of the near real time products computed over short time intervals. We do this by comparing sea surface height profiles along individual Arctic passes for crossovers where the time between the ascending and descending arc is sufficiently small that the real sea surface height has not varied significantly (say three days or less). On average, sea surface heights have a standard deviation of ~6 cm. When combined with the difference between the sea surface height of the ascending and descending arc, the total uncertainty on an individual interpolated sea surface height is ~4 cm. We interpolate sea surface heights using along-track linear regression with a moving window of width 200km, so this uncertainty contribution due to sea surface height interpolation will be correlated between freeboard measurements along the same satellite pass separated by 200 km or less. We also agree with the reviewer that we should explicitly state the interpolation procedure.	We now consider the contribution of freeboard uncertainty, due to sea surface height interpolation, to our sea ice thickness error. This is considered separately to the contribution of freeboard uncertainty due to floe height measurement uncertainty, which is caused by radar speckle and random noise in the retracking step. Both of these are explained in detail in the text, with regards to their contribution to uncertainty in sea ice volume (third Data and Methods paragraph) and sea ice thickness (fourth Data and Methods paragraph). The interpolation procedure is now explicitly stated in the text. The relevant sentence reads: *“Sea surface height measurements are interpolated using along-track linear regression with a moving window of width 200km. ”*
R2.4	**P2L25:** “The need for model ingestion is mentioned. But it should be considered that many models which ingest data have trouble with gridded mean sea ice thickness data and prefer to work with swath level data because sea ice thickness in modern models is represented as a distribution rather than a mean value. It	Although we acknowledge that different data formats may be desired by different users, we provide the gridded product as it is compact and evenly distributed, to satisfy a wide range of users. Bespoke products, such as swath level data, are available on request. .	No changes made, because the remark relates to our data product rather than the manuscript.

	would be more useful to provide the point to point measurements of freeboard (the actual measurement made by CryoSat-2) which could be more easily ingested in a model.”		
R2.5	**P4:** “The mathematical expression for determination of sea ice thickness error needs to be written out.”	We agree that it would be helpful to the reader if we included the mathematical expression for the determination of sea ice thickness error.	We have included a mathematical expression for the conversion of sea ice freeboard to thickness (equation 1) to introduce the processing step at which the uncertainties are introduced. We have also expanded our description of our error analysis, and strengthened this with mathematical expressions for the determination of our errors (equations 2 and 3).
R2.6	**P4:** “Was the uncertainty due to the lower speed of light in snow considered in the error estimates?”	We appreciate that this was not clear from the paper	We have included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). From this we hope that it is clear that the uncertainty due to the lower speed of light in snow was not considered in our error estimate. However, we have also included explicit reference to this in our concluding paragraph by stating that: *“Our sea ice thickness and volume error budget could be further constrained by improved knowledge regarding the uncertainties in snow loading and sea ice density, as well as accounting for the uncertainty due to the reduced speed of light propagation through the snow pack.”*
R2.7	**P4L27:** “The mathematical expression for the circular operator needs to be written out as it is unclear how this was applied to the data.”	We agree that we do not make it clear how the circular operator was applied to the data. On consideration, the phrase ‘circular operator’ is misleading and needs to be removed.	The relevant sentence now reads: *“To obtain Arctic-wide and ROI grid values, we average all thickness measurements within a 25 and 5 km radius of the centre of the grid, respectively, with all points receiving equal weighting.”*

			We have also removed the reference to the 'circular operator' in the caption of Figure 1.
R2.8	**P3L19:** "The reference to Kwok et al., 2009 is confusing here as the paper does not describe the use of CryoSat-2 data."	We agree that the reference to Kwok *et al.*, 2009 is confusing, and that we need to clarify how it is relevant to CryoSat-2 data	The sentence now reads: *"NASA provide monthly-averaged thickness data for March 2014 and March 2015 within a fixed central Arctic region that covers an area of ~7.2×10^6 km^2. The region was first defined for use with the NASA ICESat satellite [Kwok et al., 2009], and will herein be referred to as the ICESat domain."*
R2.9	**P4L5:** "Which geophysical corrections are often missing in the data? They should be listed."	We agree that the geophysical corrections should be listed	The sentence has been expanded to read: *"In the fast delivery data the wet tropospheric, dry tropospheric and inverse barometer corrections are missing in 93.8% of cases for Baseline-B data, but only 0.3% of cases for Baseline-C data. In these cases, all three of the corrections are missing. "* We have moved the sentence further up in the paragraph as we feel it makes more sense to include it immediately after the baseline processing is introduced.
R2.10	**P4L16-17:** "How is snow from the Warren climatology applied beyond areas of the central Arctic? The reasons for this were mentioned clearly in the other review. I think this is a critical part of the manuscript as this could have a large impact on first year ice areas outside of the central Arctic basin."	We appreciate the referee's concern regarding the Warren climatology, especially in regions where it is not constrained by *in situ* measurements. To avoid using unconstrained value of snow depth and snow density we use the mean climatology values of snow loading from a fixed central Arctic domain (where snow parameters are constrained) in all freeboard to thickness conversions, no matter where they are located. There are known differences between the climatology and the current snow depth on younger Arctic sea ice (Kurtz *et al*. 2011; Webster *et al*. 2014) so we halve the snow depth on FYI to account for reduced snow accumulation. This should be explicitly stated in the paper.	A sentence has been added to summarise our treatment of the Warren climatology. It reads: "*To obtain snow depth and density we average the values from a climatology (Warren et al. 1999) that fall within the ICESat domain, where the climatology is constrained by in situ measurements*." The ICESat domain is defined earlier in the paper. Should the reader require further information, the second paragraph in the Data and Methods section, first sentence, now reads:

			"The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling et al. (2015)."
R2.11	**P4L17-18:** "The specific densities for sea ice and water need to be written out."	We agree that these densities should be written out	We have added the densities to the paper. The relevant sentence now reads: "We use a fixed estimate of first-year ice (FYI) density of 916.7 kg m^{-3}, multi-year ice (MYI) density of 882 kg m^{-3} [*Alexandrov et al.*, 2010], and a fixed seawater density of 1,023.8 kg m^{-3} [*Wadhams et al.*, 1992]."
R2.12	**P4L26:** "If a 1 km grid can be provided, why not also provide the swath level freeboard data which is of similar resolution?"	We appreciate that some users would prefer to have swath level data. However, this paper is intended as an introduction to the dataset that is currently publicly available. We provide the gridded product as it is compacts and evenly distributed, to satisfy a wide range of users. The 1km data is available over reduced regions of interest, so is still more compact than numerous satellite swaths. Bespoke products, such as swath level data, are available for collaborators on request.	No changes made, because the remark relates to our data product rather than the manuscript.
R2.13	**P4L37:** "Given the extrapolations of the Warren climatology outside of the central Arctic, as well as the modified version over first year ice, I would question these snow depth uncertainty estimates as they have been quite modified from their original source."	We agree with the referee that snow depth has been quite modified from its original source, and that this may cause issues with uncertainty estimates. However, there is a lack of real knowledge regarding the uncertainties in snow depth, as well as snow density, and sea ice density. We have attempted to account for this lack of knowledge in our error budget by including errors of snow depth, snow density and sea ice density that are likely an overestimate, owing to the sparse spatial and temporal sampling of the measurements [*Tilling et al.*, 2015]. We have developed the most comprehensive error budget we can, considering this lack of knowledge. We	We now highlight our desire to tackle this issue in our concluding paragraph. The relevant sentence reads: *"The next steps in the advancement of the data are to develop improved estimates of snow loading on Arctic sea ice, and to further constrain the uncertainties in snow loading and sea ice density."*

		believe that our error budget is a reasonable estimate of uncertainty, as the values are consistent with published comparisons of CryoSat-2 sea ice thickness estimates with independent measurements of thickness and draft from airborne and ocean-based platforms (Tilling *et al*., 2015).	
R2.14	**P4L42-44:** "The statement that the large number of freeboard measurements negates the uncertainty rests on the assumption that the errors are uncorrelated in space and time. This seems highly unlikely given that the retrieval method does not account for factors such as changing snow conditions as shown by Ricker et al., 2015."	We do not assume that uncertainties in freeboard are uncorrelated in space and time, as the referee suggests. Rather, we have attempted to characterise the degree to which they are correlated using an empirically determined length scale within our error budget. This approach leads to larger uncertainties when compared to error budgets that assume uncorrelated uncertainties (e.g. Ricker *et al*., 2014). Again, our error model leads to uncertainties in sea ice thickness that are comparable to the spread of differences from independent measurements determined from airborne and in situ platforms, and this leads us to believe that the model is in fact a reasonable and credible assessment of the uncertainty in our retrieval.	No changes made
R2.15	**P5L1-7:** "The method for determining volume uncertainties is unclear and should be written out mathematically to fully describe the procedure. Also, over what range is each parameter adjusted to calculate the rate of change?"	We agree that it would be helpful to include the mathematical expression for the determination of sea ice volume error	We have included a more in-depth description of our error analysis, and strengthened this with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3).

R2.16	**P5 second paragraph:** "I think this estimate of error is a gross simplification of the un- certainties and is not accurate. For the snow depth term, it was already acknowledged that there are large differences over first year and multi-year ice which are unrelated to synoptic scale meteorology but is rather related to the timing of snow fall events and ice freeze-up. Sea ice density would also similarly be unrelated to synoptic scale meteorology particularly as the values used in the study are based on first year and multi-year ice types. I would therefore not consider the 2000 km decorrelation length to be accurate. Have you looked at other data to determine the decorrelation length for these parameters?"	We appreciate the referee's concern that our estimate of error is a simplification. However, there is a lack of real knowledge regarding the uncertainties in snow depth, snow density, and sea ice density. We have attempted to account for this lack of knowledge in our error budget by including errors of snow depth, snow density and sea ice density that are likely an overestimate, owing to the sparse spatial and temporal sampling of the measurements [*Tilling et al.*, 2015]. We have developed the most comprehensive error budget we can considering this lack of knowledge. Our uncertainty estimates are consistent with published comparisons of CryoSat-2 sea ice thickness estimates with independent measurements of thickness and draft from airborne and ocean-based platforms (Tilling *et al.*, 2015). Again, we believe that attempting to characterise a de-correlation length scale is an improvement on alternative error budgets that assume uncorrelated uncertainties.	We have expanded our error budget to include the contribution of sea ice freeboard uncertainty due to a.) sea surface height uncertainty and b.) floe height measurement uncertainty (due to radar speckle and random noise in the retracking step). Please see the response and action to **R2.3** and **R2.17**. We have added the treatment of a.) and b.) to the description of our error analysis, and introduce these by stating that "*The construction of our error budget is described in Tilling et al. [2015], but we now expand on this by considering the contribution of uncertainty in sea ice freeboard in more detail.*" We have been explicit about which other factors we account for and have strengthened our description with mathematical expressions for the determination of our volume and thickness errors (equations 2 and 3). We now take care to be completely transparent about the difficulties associated with determining de-correlation lengths for contributing uncertainty factors. We open the fourth Data and Methods paragraph by saying: "*Estimating the error on individual or grid cell sea ice thickness measurements is complicated by lack of knowledge regarding the de-correlation length scales of the contributing uncertainty factors.*"
R2.17	**P5 second paragraph:** "The last sentence in this paragraph not accurate as there is likely residual error in the sea surface	We agree with the referee that it is important to consider how spatial variations in sea surface height references will impact on sea ice thickness uncertainty.	We now consider the impact of spatial variations in sea surface height references (when calculating sea ice freeboard) on sea ice thickness uncertainty. This is

	height estimate since there is a need to interpolate over data gaps due to the varying number of lead points available. The interpolation procedure needs to be written out so that the correlation length of errors in the sea ice thickness can be better understood and taken into account.”	Although uncertainty in sea surface height (~4 cm, see response to **R2.3**) will be a negligible component of our monthly volume uncertainty, as we typically include more than 1 million floe heights and 10,000 200 km arc segments when computing, it will impact on thickness uncertainty as the sea surface height uncertainty will remain correlated along each satellite pass crossing a 25 km radius averaging window. We estimate that the effect will be reduced in the averaging only by the square root of the number of individual passes crossing a significant part of the averaging window. Therefore the impact of sea surface height uncertainty on the overall thickness error budget will have a greater impact on thickness for shorter timescales and at lower latitudes, due to the increased sparsity in spatial sampling. We also agree that the interpolation procedure needs to be written out.	described in detail in the text (fourth Data and Methods paragraph). We explain that the magnitude of the contribution of sea surface height uncertainty to our thickness error budget depends on the spatial sampling of the data. We back this up by including typical values for the total thickness uncertainty for varying degrees of data coverage. The interpolation procedure is now written out in the text. The relevant sentence reads: “*Sea surface height measurements are interpolated using along-track linear regression with a moving window of width 200km.”* We now take great care to be completely transparent about the difficulties associated with determining de-correlation lengths for contributing uncertainty factors. We open the fourth Data and Methods paragraph by saying: “*Estimating the error on individual or grid cell sea ice thickness measurements is complicated by lack of knowledge regarding the de-correlation length scales of the contributing uncertainty factors.”*
R2.18	**Figure 2a:** “There appear to be negative ice thickness values in the distribution, I'm guessing this is due to uncertainties in the freeboard retrieval but some explanation on this is in order.”	The referee is correct that negative ice thickness values are due to uncertainties in the freeboard retrieval. We agree that some explanation is necessary.	We have added a sentence that reads: “*The negative thickness values apparent in Figures 2a and 2b are a consequence of negative freeboard measurements that occur due to random noise in the returns from thin ice floes, caused by radar speckle. These freeboards are included in our processing to ensure that the average freeboard, and therefore thickness, is not biased high.”*
R2.19	**“**A map of the differences with the final data compared to the NRT also needs to be shown. This will reveal whether	We understand that readers may desire more information with regards to the spatial differences between NRT and archive sea ice thickness products.	We have included a new figure (Figure 3), which consists of 2 maps, detailing the spatial differences between NRT and archive sea ice thickness data for absent and present

	regional differences are present."	Since our initial submission we have found that the absence of certain geophysical corrections (wet tropospheric, dry tropospheric and inverse barometer), caused the most noticeable differences in NRT and archive sea ice thickness. We feel that the best way to display this is by plotting the spatial variability of these differences for two different months: one with corrections absent and one with corrections present.	geophysical corrections. The explanatory text for this figure (Data and Methods final paragraph, final few sentences) reads: "*The remaining difference is likely due to the combined absence of the wet tropospheric, dry tropospheric and inverse barometer corrections in 93.8% of the Baseline-B fast delivery CryoSat-2 data. This is reduced to 0.3% for Baseline-C data. The mean sea ice thickness for both the NRT and archive datasets is ~1.8 m, and there is no bias between them, with or without geophysical corrections applied. When the corrections are missing the NRT and archive thickness values at any given location differ, on average, by 1.1 cm with a standard deviation of 23.0 cm (Figure 3a). This is reduced to 0.1 cm with a standard deviation of 7.4 cm when the corrections are present (Figure 3b). There is no spatial pattern to these differences. Despite the improvement in performance of Baseline-C NRT data compared with Baseline-B we conclude that the satellite orbits and on-ground processing applied to fast delivery CryoSat-2 data are sufficient to determine accurate measurements of Arctic sea ice thickness and volume for both baselines. The thickness differences between the archive and NRT data products are not significant for either baseline given the estimated uncertainty on thickness and the typical thickness of sea ice floes.*"

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Near Real Time Arctic sea ice thickness and volume from CryoSat-2

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Abstract. Timely observations of sea ice thickness help us to understand Arctic climate, and can support maritime activities in the Polar Regions. Although it is possible to calculate Arctic sea ice thickness using measurements acquired by CryoSat-2, the latency of the final release dataset is typically one month, due to the time required to determine precise satellite orbits. We use a new fast delivery CryoSat-2 dataset based on preliminary orbits to compute Arctic sea ice thickness in near real time (NRT), and analyse this data for one sea ice growth season from October 2014 to April 2015. We show that this NRT sea ice thickness product is of comparable accuracy to that produced using the final release CryoSat-2 data, with a mean thickness difference of 0.9 cm, demonstrating that the satellite orbit is not a critical factor in determining sea ice freeboard. In addition, the CryoSat-2 fast delivery product also provides measurements of Arctic sea ice thickness within three days of acquisition by the satellite, and a measurement is delivered, on average, within 14, 7 and 6 km of each location in the Arctic every 2, 14 and 28 days respectively. The CryoSat-2 NRT sea ice thickness dataset provides an additional constraint for seasonal predictions of Arctic climate change, and will allow industries such as tourism and transport to navigate the polar oceans with safety and care.

1 Introduction

Arctic sea ice is a key component of the global climate system, and changes in its thickness and volume impact on regional heat (Sedlar et al., 2011) and freshwater (Aagaard and Carmack, 1989) budgets, and on subsequent patterns of atmospheric (Singarayer et al., 2006, Schweiger et al., 2008, Francis and Vavrus, 2012) and oceanic (Vellinga and Wood, 2002) circulation across the Arctic and at lower latitudes. The availability of Arctic-wide sea ice thickness data, especially in near real time (NRT), will enable evaluation and improved skill in the prediction of sea ice thickness distributions by climate models (Day et al., 2014) which, in turn, will benefit models of the global climate. In addition, there is increasing interest in the behaviour of Arctic sea ice among operational services, with a growing need for accurate and timely information of sea ice thickness. For example, shipping through the Arctic Ocean via the Northern Sea Route (NSR) could save about 40% of the sailing distance from Asia (Yokohama) to Europe (Rotterdam) compared to the traditional route via the Suez Canal (Liu and Kronbak, 2010), which would quicken the regional export of natural resources, and delivery of cargo to the communities along the Siberian coast (Meier et al., 2014). Ease of passage is also a concern for those looking to ship along the Northwest Passage and future trans-Arctic shipping routes along the Russian coast, and when considering the potential for tourism in regions such as Canadian Arctic waters (Stewart et al., 2007). The oil and gas sector require hemispheric studies of sea ice concentration, extent, motion and thickness (Galley et al., 2013) to estimate productions costs and to assess the feasibility and safety of replacing ice-based construction with lower cost conventional construction equipment (Harsem et al., 2011). Without these studies, companies cannot be sure that their infrastructure is suitably robust for the Arctic environment, such as when the Shell oil rig Kulluk ran aground in January 2013. As a consequence many large oil companies are reducing their plans for Arctic exploration and drilling activities due to the high costs and risks and the possibility of safer investment in other regions. This will impact on northern areas and communities through local businesses who report losses in hotel revenues, restaurant businesses, and the local marine support (Meier et al., 2014). Up-to-date measurements of sea ice thickness are crucial when considering building costs for exploration platforms and icebreaker ships, transit speeds, and navigation difficulties and risks. Here we present a method for obtaining NRT sea ice thickness measurements across the northern hemisphere using fast delivery CryoSat-2 data.

A range of Arctic sea ice thickness measurements are currently available, with varying spatial and temporal coverage. The Beaufort Gyre Exploration Project (BGEP), based at the Woods Hole Oceanographic Institution in collaboration with researchers from Fisheries and Oceans Canada at the Institute of Ocean Sciences, have provided year-round sea ice draft data from upward

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looking sonar buoys since 2003, from three buoys in the Beaufort Sea. On a larger scale, NASA's Operation IceBridge utilises a suite of research aircraft each spring (March and April) to produce tracks of sea ice thickness estimates (Kurtz et al., 2013) concentrated around northern Greenland, the ocean region north of the Canadian Archipelago, and the Beaufort Sea. Currently the final and 'quick look' IceBridge data are available for spring 2009-2012 and spring 2013-2015, respectively. The quick look product is experimental and is designed only to be applicable for time-sensitive projects such as sea ice forecasting. On a larger spatial scale, there are currently three publically available datasets that provide sea ice thickness estimates across the whole Arctic Ocean. These datasets are produced by NASA (Kurtz et al., 2014), Germany's Alfred Wegener Institute (AWI) (Ricker et al., 2014), and the UK's Centre for Polar Observation and Modelling (CPOM) (Tilling et al., 2015) using final release data from the European Space Agency's (ESA) CryoSat-2 satellite (Wingham et al., 2006), which was launched in 2010. NASA provide monthly-averaged thickness data for March 2014 and March 2015 within a fixed central Arctic region that covers an area of ~7.2×10^6 km^2. The region was first defined for use with the NASA ICESat satellite (Kwok et al., 2009), and will hereafter be referred to as the ICESat domain. The NASA product is currently quick-look and experimental. AWI provide monthly averaged thickness data starting from January 2011 with a current lag of about 6 months, and these data again cover a central area of the Arctic Ocean. CPOM distribute sea ice thickness estimates for spring (March/April average) and autumn (October/November average) beginning in autumn 2010, also with a lag of about 6 months, depending on the availability of sea ice concentration data (Cavalieri et al., 1996, updated yearly). The CPOM estimates cover the entire northern hemisphere, defined as latitudes above and including 40° N.

2 Data and Methods

We use fast delivery radar altimeter measurements from the ESA CryoSat-2 satellite synthetic aperture radar (SAR) and SAR interferometric (SARIn) altimeter (Wingham et al., 2006) to produce NRT estimates of Northern Hemisphere (latitudes above 40° N) sea ice thickness and volume. The data are Level 1b, and consist of an echo for each point along the ground track of the satellite. For Arctic sea ice processing we assume that the ice surface is relatively flat and that slope variations are minimal. Under these circumstances, echoes are received primarily from the nadir point beneath the satellite ground track. We crop the SARIn mode waveforms to include only the central 128 range bins to allow for identical processing of SAR and SARIn mode data as both now have 128 bins in their waveform data. Prior to the release of Level 1b data, ESA perform some on-ground processing of the raw satellite data. Before March 26th 2015, ESA applied a processing chain known as 'Baseline-B' to the raw fast delivery data, and an updated processor, 'Baseline-C', has been applied since.

In the fast delivery data the wet tropospheric, dry tropospheric and inverse barometer corrections are missing in 94% of cases for Baseline-B data, but in less than 1% of cases for Baseline-C data. In these instances, all three of the corrections are missing. The fast delivery CryoSat-2 data are available from ESA on average 36 hours after acquisition by the satellite, although we run our sea ice processor with a latency of three days to ensure sufficient data are available. The main difference between the fast delivery and final release CryoSat-2 data is the orbits applied. For both datasets, an accurate determination of the satellite orbit is required to determine surface elevations above a reference ellipsoid. For the final release data product, ESA perform a ground-based Precise Orbit Determination (POD), which requires modelling of the forces acting on the satellite as well as a dense set of measurements regarding its position and velocity (Wingham et al., 2006). The primary means of making these measurements is with the on-board Doppler Orbit and Radio positioning Integration by Satellite (DORIS) receiver, which makes measurements of the relative velocity of the satellite to an extensive network of ground beacons. The messages uplinked from the beacons include time signals that allow the DORIS receiver time to be accurately determined. The DORIS receiver also includes software for the real-time, on-board computation of the orbit, known as the DORIS Navigator orbit. The DORIS

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Navigator orbit is estimated to be accurate to 30 cm in the radial direction, and is included in the fast delivery CryoSat-2 data to provide good quality orbit estimates before the POD can be produced. However, the fast delivery data are more susceptible to orbit dropout, meaning that certain orbits, for which the orientation of the satellite could not be sufficiently determined, are not included in the dataset. There is also a difference in the timeframe of on-ground processing of the raw fast delivery and final release data by ESA. Before February 22nd 2015, ESA applied the Baseline-B processing chain to the raw final release data, and an updated processor, Baseline-C, has been applied since April 1st 2015. Between these dates, a hybrid processor known as 'Baseline-BC' was applied. On average, it takes us six hours to process one day of data.

The processing steps for fast delivery CryoSat-2 data are identical to those used for the final delivery data, and are described in Tilling *et al.* (2015). The first step is the computation of sea ice freeboard, which is the difference in elevation between the snow-ice interface and that of the surrounding ocean. We do this by using the return echo shape to discriminate between measurements of the ocean surface and the ice surface (Peacock and Laxon, 2004). We define sea ice regions as those with a NRT sea ice concentration (Maslanik and Stroeve, 1999, updated daily) greater than 75%. NRT ice concentration data are taken from the National Snow and Ice Data Center (NSIDC) and are available to us by 01:00 UTC two days after measurement. A correction is applied to each freeboard measurement to account for the reduced speed of the radar pulse as it passes through any snow cover on sea ice. The next step is to convert sea ice freeboard to sea ice thickness. We assume that the ice floes are in hydrostatic equilibrium, under which circumstances sea ice thickness can be calculated using:

$$T_i = \frac{f_c \rho_w + h_s \rho_s}{\rho_w - \rho_i} \qquad (1)$$

where T_i is the sea ice thickness, f_c is the corrected sea ice freeboard, h_s is snow depth, ρ_w is seawater density, ρ_s is snow density, and ρ_i is sea ice density. We use a fixed estimate of first-year ice (FYI) density of 916.7 kg m^{-3} (Alexandrov et al., 2010), multi-year ice (MYI) density of 882 kg m^{-3} (Alexandrov et al., 2010), and a fixed seawater density of 1,023.9 kg m^{-3} (Wadhams et al., 1992). To obtain snow depth and density we average the values from a climatology (Warren et al., 1999) that fall within the ICESat domain, where the climatology is constrained by *in situ* measurements. Snow depth is halved over FYI to account for reduced snow accumulation (Kurtz and Farrell, 2011, Webster et al., 2014). NRT ice type data from the Norwegian Meteorological Service Ocean and Sea Ice Satellite Application Facility (http://osisaf.met.no/p/ice/#type) are used to classify FYI and MYI for each individual freeboard measurement, and this dataset is available to us by 01:00 UTC the day after measurement. During the sea ice melt season it becomes difficult to discriminate between measurements of the ocean and the ice due to melt ponds that form on the sea ice surface, and because of this we do not currently produce measurements of sea ice thickness between May and September. NRT sea ice thickness data are output Arctic-wide on a 5 km square grid (Fig. 1), or for user-configurable regions of interest (ROI) on a 1 km square grid. To obtain Arctic-wide and ROI grid values, we average all thickness measurements within a 25 and 5 km radius of the centre of the grid, respectively, with all points receiving equal weighting. We then compute sea ice volume Arctic-wide and within fixed oceanographic basins (Nurser and Bacon, 2014, Tilling et al., 2015) by averaging individual thickness and concentration values during each calendar month on a 0.1 by 0.5 degree grid, and defining the sea ice margin by applying a 15% sea ice concentration mask using data from the 15th day of each month. Empty thickness grid cells within the sea ice extent mask, including those north of 88°N, are filled by nearest neighbour interpolation with a maximum search radius of 300 km. Monthly estimates of sea ice volume are then calculated by summing the product of the ice thickness, the ice concentration, and the ice

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area, within the sea ice extent mask.

We estimate monthly errors in sea ice volume (Tilling et al., 2015) by considering the contributions due to uncertainties in sea ice freeboard (~9 cm), snow depth (4.0 to 6.2 cm in Warren et al., 1999), snow density (60.0 to 81.6 kg m^{-3} in (Warren et al., 1999), sea ice density (7.6 kg m^{-3} in(Romanov, 2004, Tilling et al., 2015), sea ice concentration (5% according to the NSIDC at http://nsidc.org/data/docs/daac/nsidc0051_gsfc_seaice.gd.html), sea ice extent (20,000 to 30,000 km^2 according to the NSIDC at http://nsidc.org/arcticseaicenews/faq/#error_bars), and sea ice freeboard. Uncertainties in seawater density are neglected because they have a negligible impact (Kurtz et al., 2013, Ricker et al., 2014).

Errors in our freeboard estimates arise through speckle in the radar echoes, which averages 8 cm across the Arctic but de-correlates from one measurement to the next, and from uncertainties in sea surface height, which may be correlated in space due to our interpolation scheme based on a linear regression of measurements along 200 km sections of the ground track. We examined the variability of sea surface heights over this scale, and their standard deviation at orbit crossing points is 4 cm. As a conservative estimate, we assume that this variability remains correlated within the 200 km window of our freeboard calculation, and include it as an additional source of uncertainty in our gridded product. The freeboard error is then a combination of that due to spatially uncorrelated speckle on floe heights and that due to spatially correlated errors in the interpolation of sea surface heights. This results in a 2 cm freeboard uncertainty, which scales to ~20 cm thickness, or 11% of a typical growth season thickness of 1.8 m (Tilling et al., 2015) for our gridded, 28-day product.

To calculate uncertainties in sea ice volume, we compute the monthly rate of change of volume with respect to each parameter that has an associated error. We do this by individually adjusting the value for each parameter six times, at even increments, and re-computing the volume each time. The computed rates of change are then multiplied by the error in each parameter in question to estimate their partial contributions to the total volume error. Finally, we combine the monthly contribution to the volume error for all significant error sources in a root-sum-square manner to arrive at an estimate of the total monthly sea ice volume error, using:

$$\sigma_V = \sqrt{\left(\frac{\partial V}{\partial h_s}\cdot\sigma_{h_s}\right)^2 + \left(\frac{\partial V}{\partial \rho_s}\cdot\sigma_{\rho_s}\right)^2 + \left(\frac{\partial V}{\partial \rho_i}\cdot\sigma_{\rho_i}\right)^2 + \left(\frac{\partial V}{\partial e_i}\cdot\sigma_{e_i}\right)^2 + {\sigma_{V_c}}^2} \qquad (2)$$

where σ_V is the uncertainty in sea ice volume in a given month, V is sea ice volume, h_s is Arctic-wide snow depth, σ_{h_s} is the uncertainty in snow depth, ρ_s is Arctic-wide snow density, σ_{ρ_s} is the uncertainty in snow density, ρ_i is Arctic-wide ice density, σ_{ρ_i} is the uncertainty in sea ice density, e_i is sea ice extent, σ_{e_i} is the uncertainty in sea ice extent, and σ_{V_c} is the uncertainty in sea ice volume due to uncertainty in sea ice concentration. We estimate that year-to-year uncertainties in Arctic-wide sea ice volume are typically about 13.5%, with small variations from month to month (Tilling et al., 2015).

Estimating local errors in sea ice thickness is complicated due to a lack of knowledge of the distances over which the contributing factors de-correlate. The main factors for which this information is important and lacking are snow depth, snow density, and sea ice density. In our sea ice volume error budget, we estimate their uncertainty over large scales as the standard deviation of monthly-averaged sparse field observations collected across the 9 million km^2 central Arctic region. However, these factors, and their variability, are influenced by synoptic-scale meteorology, and we suppose that the length scale over which they are correlated is

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comparable to that of a typical polar vortex – around 2000 km in diameter (http://www.cpc.ncep.noaa.gov/products/stratosphere/polar/ polar.shtml). Taking snow depth as an example, over areas that are large in comparison to this correlation scale, the variability of spatially averaged snowfall fluctuations will diminish in the ratio $1/\sqrt{n}$, where n is the effective number of independent values of accumulation sampled. We take $n \sim A/(\pi 2000^2)$, where A is the area in square kilometres. If $n < 1$, we set it equal to 1. For the 9 million km^2 central Arctic region, over which the large scale sea ice volume and thickness uncertainty is estimated to be 13.5%, $n \sim 3$, leading to an uncertainty of 23%. Using this approach, and accounting additionally for short-scale correlated errors in freeboard associated with interpolating sea surface heights, we estimate the uncertainty in sea ice thickness increases to 25% at the 5 km scale of our 28-day NRT grid.

We acknowledge that this is only a first attempt to characterise local uncertainty in sea ice thickness, and that more detailed observations of snow depth, snow density, and sea ice density are required to establish the extent to which their variability impacts on the retrieval accuracy. However, a 23% local error in our gridded, 28-day estimates of Arctic sea ice thickness derived from CryoSat-2 observations corresponds to an uncertainty of 41 cm for a typical thickness of 1.8 m. This uncertainty is consistent with the spread of differences relative to independent estimates acquired from airborne and ocean-based platforms (34 to 66 cm in Tilling et al., 2015). However, grid cell thickness uncertainty will increase with fewer days of data coverage. For example, for 2 days of data the averaged freeboard measurements often come from just one satellite pass. Therefore the full 4 cm uncertainty in sea surface height contributes to the freeboard error, which scales to ~40 cm for thickness, or 22% of a typical thickness of 1.8 m. Combined with the error of 23% from other sources this brings the total error on the 2 day 5 km grid sea ice thickness data to 32%.

To assess the reliability of our NRT sea ice data set we compared it to values derived from the final CryoSat-2 data release (the archive product), which have shown excellent agreement with an extensive set of independent observations (Tilling et al., 2015). It is currently not possible to evaluate our NRT sea ice product itself against *in situ* measurements, as the overlap between coverage periods is too short. During archive processing we use final sea ice concentration from NSIDC (Cavalieri et al., 1996, updated yearly), rather than the NRT concentration data used in our NRT sea ice calculations. Aside from this, the CryoSat-2 SAR and SARIn mode data are processed identically to the NRT case.

First, we assessed our processing at orbit-scale by calculating point-by-point differences of NRT and archive sea ice freeboards using a single track of CryoSat-2 data from April 2015, for which all geophysical corrections were present in both datasets. The track consisted of 3,968 lead and 5,246 freeboard measurements for the NRT data compared with 3,970 lead and 5,242 freeboard measurements for the archive data. Along this track, NRT and archive freeboards showed excellent agreement, with a mean difference of 0.02 cm (Fig. 2a). We then compared sea ice thickness and volume based on the NRT and archive products, using seven months of data acquired between October 2014 and April 2015, which corresponds to a season of ice growth. The thickness comparison was done over the 5 km square grid on which NRT data are output. In general, our NRT and archive estimates of sea ice thickness are in excellent agreement, with a mean difference of 0.9 cm (Fig. 2b). NRT and archive estimates of sea ice volume are also in excellent agreement, with an average difference of 175 km^3 (Fig. 2c) across the entire Arctic region. The negative freeboard and thickness values apparent in Fig. 2a and Fig. 2b respectively are a consequence of negative freeboard measurements that occur due to random noise in radar echoes from thin ice floes, caused by radar speckle. These freeboards are included in our processing to ensure that the average freeboard, and therefore thickness, is not biased high. Overall, differences between NRT and archive estimates of sea ice thickness and volume fall well within the corresponding estimates of their uncertainties (Tilling et al., 2015).

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Our archive estimates of sea ice volume are larger than the NRT product in part as a consequence of using the final sea ice concentration data set, which contains higher values than its NRT counterpart. For example, we recalculated sea ice volume using the NRT sea ice thickness and final sea ice concentration data sets, and the departure from the archive estimate reduced to 100 km^3. A contribution to the remaining difference is likely the combined absence of the wet tropospheric, dry tropospheric and inverse barometer corrections in 93.8% of the Baseline-B fast delivery CryoSat-2 data. This is reduced to 0.3% for Baseline-C data. The mean sea ice thickness for both the NRT and archive datasets is ~1.8 m, and there is no bias between them, with or without geophysical corrections applied. When the corrections are missing the NRT and archive thickness values at any given location differ, on average, by just 1.1 cm with a standard deviation of 23.0 cm (Fig. 3a-c). This is reduced to 0.1 cm with a standard deviation of 7.4 cm when the corrections are present (Fig. 3d-f). There is no spatial pattern to these differences. Despite the improvement in performance of Baseline-C NRT data compared with Baseline-B we conclude that the satellite orbits and on-ground processing applied to fast delivery CryoSat-2 data are sufficient to determine accurate measurements of Arctic sea ice thickness and volume for both baselines. The thickness differences between the archive and NRT data products are not significant for either baseline given the estimated uncertainty on thickness and the typical thickness of sea ice floes.

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3 Results

The spatial distribution of the NRT sea ice thickness data (Fig. 1) for any given time period depends on the nature of the CryoSat-2 orbit over that period. CryoSat-2 has an orbit repeat period of 369 days, which is built up by successive shifts of a 30-day repeat sub-cycle, meaning that uniform coverage of the Arctic Ocean is achieved every 30 days (Wingham et al., 2006). The density of orbit crossovers increases with latitude up to the CryoSat-2 limit of 88°N, and also with the number of days of coverage. We produce Arctic-wide maps of NRT sea ice thickness for the previous 2, 14, and 28 day periods. CryoSat-2 orbit patterns are visible in maps of thickness for the final 2 (e.g. Fig. 1a and Fig. 1d) and 14 (e.g. Fig. 1b and Fig. 1e) days of each month. The orbits are clearer at lower latitudes, below about 80°N. Over 28 days, almost complete coverage across the sea ice pack is achieved. However, there are still small areas of unmapped sea ice, and these typically occur at the ice edge (see Fig. 1). In these unmapped areas the sea ice concentration is above 15%, which we use as the sea ice margin threshold, but below 75%, which is the concentration required for a region to be classed as containing sea ice (see Data and Methods).

To determine the utility of the 5 km grid measurements of NRT sea ice thickness for operational use, we performed a detailed assessment of the spatial and temporal distribution of the data and compared these to the equivalent for archive data. Over the 2, 14 and 28 day time periods for which NRT data are available, we calculated the percentage of sea ice covered by NRT and archive data in 1 degree latitude bands from 60-90°N, for the final 2, 14 and 28 days of each month. This was done for data from October 2014 to April 2015, and averaged over all months (Fig. 4a). We produced the equivalent plot for the mean data separation in each latitude band, where separation is simply the square root of the number of measurements in each band, divided by the sea ice covered area (Fig. 4b). For 28 days data coverage, sea ice at latitudes between 85-88°N is mapped in its entirety by the NRT and archive products and the data separation drops to 5.0 km in each 1 degree latitude band, which is simply the grid separation. For 14 days coverage the CryoSat-2 orbit pattern achieves its maximum coverage for NRT data, of 98%, between 86 and 87°N but achieves 100% coverage for archive data between 86-88 °N. These correspond to a mean data separation of 5.1 km and 5.0 km (the grid separation), respectively. The maximum NRT coverage over 2 days is 91%, between 87 and 88°N, where the mean data separation is 5.2 km. This increases to 99%, between 87 and 88°N for archive data,

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with a mean data separation of 5.1 km. For both NRT and archive data the percentage of ice mapped decreases with decreasing latitudes, and the separation between data points increases, although there is some fluctuation in these trends that is likely due to the shift in the CryoSat-2 orbit pattern producing less favourable coverage for a given month. CryoSat-2 does not observe sea ice north of 88°N, so the percentage of ice mapped drops to 0% for 2, 14 and 28 days coverage in the region 88-90°N for both datasets. On average, the NRT sea ice thickness data maps 20, 51 and 66% of the Arctic sea ice north of 60°N every 2, 14 and 28 days respectively. This corresponds to a measurement within 14, 7 and 6 km of each location in the Arctic every 2, 14 and 28 days. For archive data the coverage increases to 23, 57 and 69% every 2, 14 and 28 days respectively, which corresponds to a measurement within 13, 7 and 6 km of each location in the Arctic.

The distribution of our NRT sea ice thickness measurements also varies with oceanographic basin and month, and the nature of the monthly variation depends on the region being observed. This is an important consideration for those wishing to use the data in a specific region of interest, or over the entirety of the sea ice growth season. We calculated the percentage of ice cover mapped by our NRT product for six key oceanographic basins (Fig. 5a), for the final 28 days of each month of the 2014-2015 sea ice growth season (Fig. 5b) and compared this to the percentage of ice cover mapped by our archive data (Fig. 5c). The percentage of the ice cover mapped in the Amerasian and Eurasian basins is high (≥ 76% for NRT data and ≥ 83% for archive data), with just a small increase over the growth season. Both regions are almost entirely covered in sea ice year-round, which means that the areal fraction of unmapped sea ice at the ice edge (see Fig. 1) is fairly consistent throughout the year. However, this is not the case for regions with more seasonal ice cover, such as the Canadian Archipelago and Northwest Passage, Hudson Bay, and the Beaufort Sea, where NRT and archive coverage improves throughout the growth season and peaks in February or March. In these regions, as the extent of the sea ice cover increases through winter, the unmapped area at the sea ice edge becomes a decreasing fraction of the ice-covered area, and a greater percentage of the ice cover is mapped. In addition, as the sea ice concentration increases through winter, echoes from sea ice floes becomes less noisy and are more likely to be included in our processing. Coverage in the Greenland Sea generally improves throughout the growth season, although there is some variation in this pattern due to fluctuations in the width of the unmapped area at the sea ice edge, which could be a consequence of the rapid sea ice transport in this sector. Overall, coverage is lowest for the Greenland Sea, Canadian Archipelago and Northwest Passage, and Hudson Bay. Due to the location of the Greenland Sea, there is also a persistent presence of unmapped sea ice along its eastern edge. The Canadian Archipelago and Northwest Passage, and Hudson Bay are in close proximity to substantial coastal areas, where it is difficult to construct sea surface height due to the absence of leads in the sea ice pack. Although there is spatial variation in the coverage of our NRT sea ice thickness data, both with latitude (Fig. 4) and oceanographic basin (Fig. 5b), there is no significant spatial variability in the difference between the NRT and archive data coverage (Fig. 4 and Fig. 5c).

We extended our analysis of NRT data sampling by calculating the percentage of sea ice mapped in all Arctic Ocean basins at the beginning and end of the sea ice growth season (Table 1). For this calculation, we considered the percentage of ice cover mapped in the final 2, 14 and 28 days of each month. In each month the coverage improves with the number of days sampling, in every basin. The coverage also improves from October to March, for each time period, for all but one basin; the Canadian Archipelago/Northwest Passage experiences a drop in coverage over the growth season, for the 2-day observation period. However, this change is very small, and over short observation periods we would expect some variability in the proportion of ice cover mapped as a consequence of the CryoSat-2 orbital repeat pattern. This becomes more important in regions such as the Canadian Archipelago, where there is a high fraction of land interspersed with ocean. The Bering Sea, the Sea of Okhotsk, the White Sea, the Baltic Sea and surrounding Gulfs and the Labrador Sea have the smallest proportional ice cover mapped in March 2015.

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These are regions of highly seasonal sea ice cover, and by the end of the growth season the unmapped area at the ice edge still constitutes a sizable fraction of the ice–covered area. In addition, they are all southerly basins (below 70°N), which are sampled with reduced spatial density by CryoSat-2. The most extensively sampled areas are in the central Arctic - the Amerasian and Eurasian basins - which experience substantial year-round sea ice cover and are at high latitudes. We conclude that the location, seasonality, and dynamic nature of any sea ice region are important considerations when assessing the reliability of the NRT Arctic sea ice thickness product.

4 Discussion and Conclusions

Our CryoSat-2 NRT sea ice thickness dataset will benefit Arctic sea ice projections, because it can be used to constrain physical models that investigate the sensitivity of the region to climate change (Day et al., 2014) in a timely manner. It will also assist Arctic operations that rely on accurate and timely information on sea ice thickness, such as natural resource exploration (Galley et al., 2013), and shipping for cargo (Liu and Kronbak, 2010) and tourism (Stewart et al., 2007). A previous study (Rinne and Similä, 2016) has highlighted the potential value of fast delivery CryoSat-2 data for the classification of sea ice into discrete stages of its development – thin (<70 cm) and thick (>70 cm) FYI and MYI – in the Kara Sea. Our product extends this analysis to provide continuous measurements of sea ice thickness across the entire northern hemisphere, complementing established records of sea ice concentration (Cavalieri et al., 1996, updated yearly, Maslanik and Stroeve, 1999, updated daily) upon which annual assessments (Stroeve et al., 2005) and forecasts (Posey et al., 2011) of Arctic conditions are based. Timely availability of sea ice concentration estimates (Maslanik and Stroeve, 1999, updated daily) and sea ice type classifications (http://osisaf.met.no/p/ice/#type) are crucial for the rapid computation of our NRT sea ice thickness measurements. The NSIDC sea ice concentration and OSISAF sea ice type data are available to us by 01:00 UTC two days after, and 01:00 UTC the day after measurement, respectively. The fast delivery CryoSat-2 data are typically available 36 hours after acquisition from the satellite, but can vary from 1-3 days, so we run our sea ice processor at a latency of three days to ensure sufficient data is available. Processing one day of data for the northern hemisphere takes six hours, on average. A more rapidly delivered product would require the CryoSat-2 data to be consistently available within 36 hours, and sea ice concentration data to become available sooner, or that older concentration measurements were used as an approximation.

By using a new fast delivery CryoSat-2 dataset we are able to produce estimates of sea ice thickness across the northern hemisphere three days after acquisition from the satellite. This marks the beginning of a new phase for the CryoSat-2 mission, in which its primary data can be used for operational purposes. The NRT estimates are of comparable accuracy to those produced using the final release CryoSat-2 data, with a mean difference of 0.9 cm between NRT and archive estimates of sea ice thickness. The NRT and archive thickness differences, although small, vary temporally. The differences are reduced when all geophysical corrections are present in the fast delivery CryoSat-2 data, which is the case in 99.7% of the data since March 26th 2015, when the ESA on-ground processing chain switched from Baseline-B to Baseline-C. There is no spatial variability in the differences between our NRT and archive data products. For the period from October 2014 to April 2015, the NRT dataset covers an average of 20, 51 and 66% of the Arctic sea ice north of 60°N every 2, 14 and 28 days respectively. This is equivalent to a measurement within 14, 7 and 6 km of each location in the Arctic every 2, 14 and 28 days. However, there are temporal and spatial variations in the data coverage. The time of year, location, and dynamic nature of any region of interest must be considered when assessing the reliability of the data. The next major step in the advancement of the data is to develop improved estimates of snow loading on Arctic sea ice. We also intend to investigate the impact of different gridding methods, including the application of a distance weighting, on our gridded NRT sea ice thickness product. Our sea ice thickness and volume error budget could be further

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constrained with improved knowledge on uncertainties in snow loading and sea ice density, and also by accounting uncertainties in the propagation speed of the radar signals through the snow pack. We encourage users to utilise the data for model assessments and to constraint the physics of sea ice within models that form the basis of future climate projections.

Author contribution

R. L. Tilling and A. Ridout developed and analysed the satellite observations. A. Shepherd supervised the work. R. L. Tilling, A. Ridout and A. Shepherd wrote the paper. All authors commented on the text.

Acknowledgements

Our NRT sea ice thickness data are publically available at http://www.cpom.ucl.ac.uk/csopr/seaice.html. We wish to thank those who provide the timely ancillary data that we require to deliver a NRT product: ESA, for the fast delivery CryoSat-2 Level 1B radar altimeter data (available via ftp at ftp://science-pds.cryosat.esa.int); OSI SAF, for their sea ice type maps (http://osisaf.met.no/p/ice/#type); and NSIDC, for NRT DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations (available via ftp at ftp://sidads.colorado.edu/pub/DATASETS/nsidc0081_nrt_nasateam_seaice). This work was funded by the UK Natural Environment Research Council, with support from the UK National Centre for Earth Observation.

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Table 1: Variations in the sampling of CryoSat-2 near real time (NRT) sea ice thickness products in 17 Arctic Ocean basins. Regions 1-10 encompass all October sea ice, and regions 1-16 encompass all March sea ice. Region 17 is a sub-region of region 1 (Figure 5a).

	Data Coverage (% of ice cover mapped)					
	2 days		**14 days**		**28 days**	
	Oct 2014	**Mar 2015**	**Oct 2014**	**Mar 2015**	**Oct 2014**	**Mar 2015**
Amerasian Basin (1)	33	38	78	82	92	98
Eurasian Basin (2)	24	44	58	73	76	88
Canadian Archipelago & Northwest Passage (3)	9	7	31	37	39	53
Hudson Bay (4)	0	6	0	48	0	71
Baffin Bay (5)	0	15	0	56	0	81
Greenland Sea (6)	8	13	31	50	49	63
Iceland Sea (7)	0	16	0	44	0	57
Barents Sea (8)	0	9	17	32	18	47
Kara Sea (9)	2	17	15	46	16	58
Siberian Shelf Seas (10)	11	20	38	60	49	85
Bering Sea (11)	n/a	3	n/a	35	n/a	40
Sea of Okhotsk (12)	n/a	0	n/a	21	n/a	33
White Sea (13)	n/a	0	n/a	6	n/a	6
Baltic Sea & surrounding Gulfs (14)	n/a	0	n/a	0	n/a	0
Labrador Sea (15)	n/a	1	n/a	13	n/a	19
Gulf of St Laurence & Nova Scotia Peninsula (16)	n/a	n/a	n/a	n/a	n/a	n/a
Beaufort Sea (17)	17	20	59	83	69	95

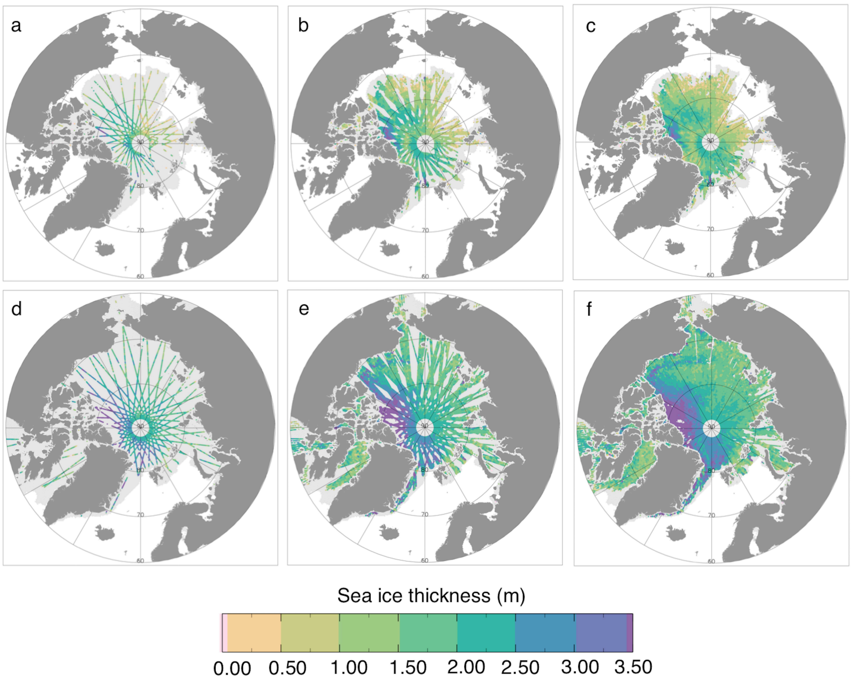

Figure 1: Near real time (NRT) Arctic sea ice thickness estimates from CryoSat-2. (a)-(c) Thickness estimates for the final 2, 14 and 28 days in October 2014, respectively. (d)-(f) Thickness estimates for the final 2, 14 and 28 days in March 2015, respectively. NRT sea ice thickness data are output Arctic-wide on a 5 km square grid. All thickness measurements within a 25 km radius of the centre of the grid are averaged, with all points receiving equal weight. The sea ice extent mask is shaded in light grey, and highlights unmapped areas of the sea ice.

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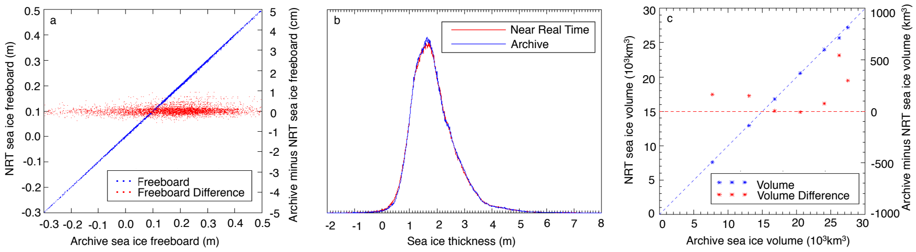

Figure 2: Comparison of near real time (NRT) and archive estimates of Arctic sea ice freeboard, thickness, and volume, from CryoSat-2. (a) Crossplot of point-by-point sea ice freeboard for an Arctic pass in April 2015. Also shown is the difference (archive minus NRT) in sea ice freeboard between the datasets. (b) Normalised distribution of NRT and archive thickness estimates over the period October 2014-April 2015, for all grid cells where measurements are available for both datasets. (c) Crossplot of sea ice volume for October 2014-April 2015. Also shown is the difference (archive minus NRT) in sea ice volume between the datasets.

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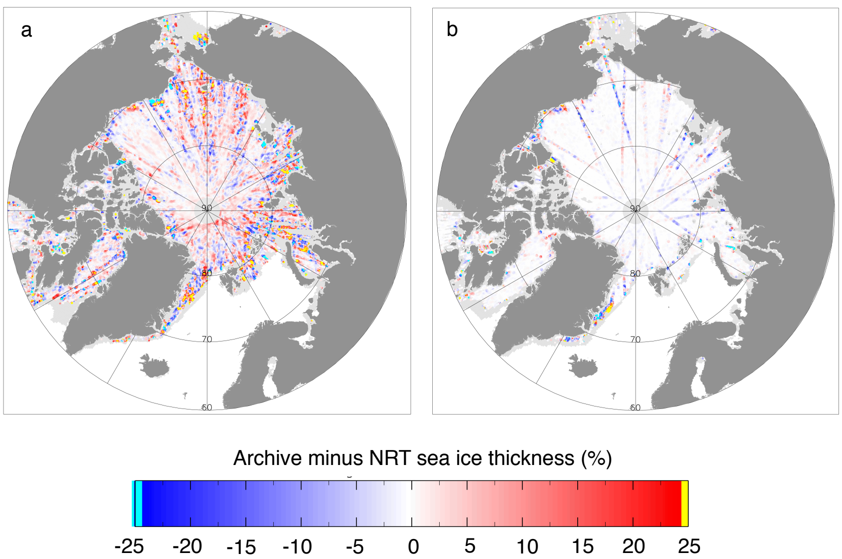

Figure 3: The impact of geophysical corrections on near real time (NRT) Arctic sea ice thickness estimates from CryoSat-2. (a) Percentage change in archive minus NRT thickness estimates for the final 28 days of March 2015. In March 2015 the wet tropospheric, dry tropospheric and inverse barometer corrections were missing in 80% of cases. (d) Percentage change in archive minus NRT thickness estimates for the final 28 days of April 2015. In April 2015 the wet tropospheric, dry tropospheric and inverse barometer corrections were missing in 0% of cases.

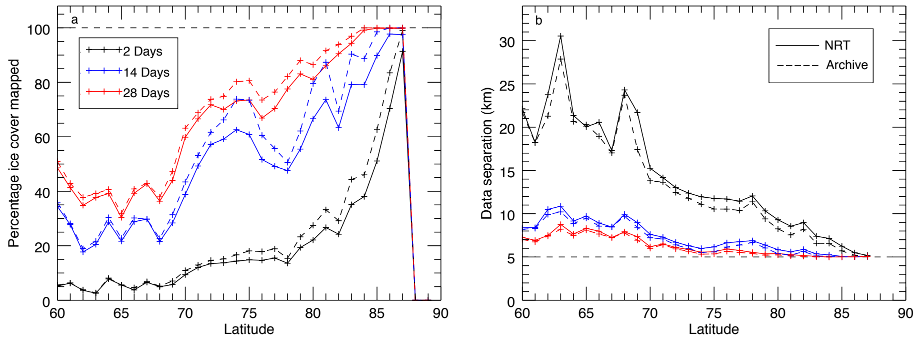

Figure 4: Spatial and temporal sampling of the Centre for Polar Observation and Modelling (CPOM) near real time (NRT) and archive Arctic sea ice thickness products, north of 60°N. (a) Plot showing the percentage of sea ice cover mapped in 1° latitude bands, averaged over each month from October 2014-April 2015. Data are plotted for the final 28, 14, and 2 days of all months. Solid lines = NRT data, dashed lines = archive data. (b) Plot showing the mean separation between NRT measurement points in 1° latitude bands, averaged over each month from October 2014-April 2015. Data are plotted for the final 28, 14, and 2 days of all months. Solid lines = NRT data, dashed lines = archive data.

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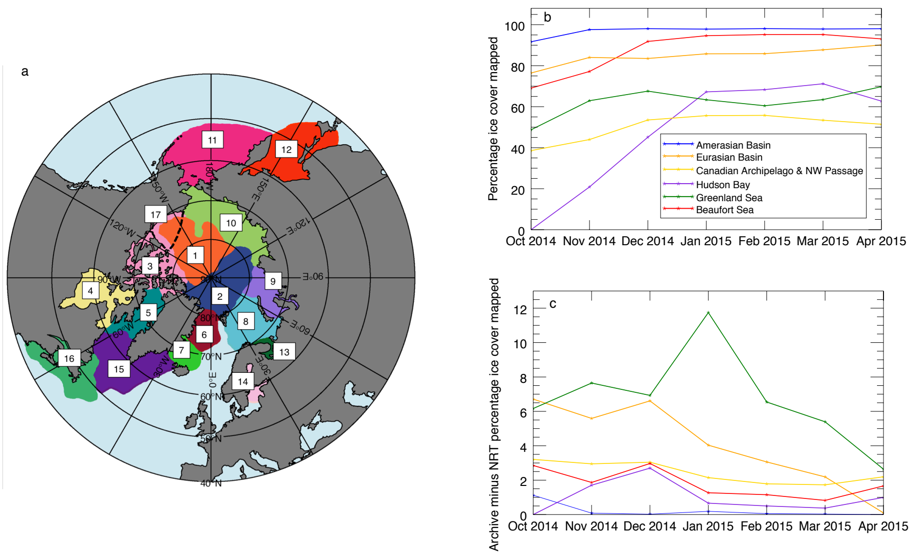

Figure 5: Regional and temporal sampling of the Centre for Polar Observation and Modelling (CPOM) near real time (NRT) and archive Arctic sea ice thickness products. (a) Arctic Ocean regions selected for analysis. The regions are the Amerasian Basin (1), Eurasian Basin (2), Canadian Archipelago and Northwest Passage (3), Hudson Bay & Foxe Bay (4), Baffin Bay (5), Greenland Sea (6), Iceland Sea (7), Barents Sea (8), Kara Sea (9), Siberian Shelf Seas (10), Bering Sea (11), Sea of Okhotsk (12), White Sea (13), Baltic Sea & surrounding Gulfs (14), Labrador Sea (15), the Gulf of St Lawrence & Nova Scotia Peninsula (16), and the Beaufort Sea (17). Regions 1-10 encompass all autumn sea ice, and regions 1-16 encompass all spring sea ice. Region 17 is a sub-region of region 1 and 3. (b) Plot showing the percentage of sea ice cover mapped by the NRT product in each month, for six key oceanographic basins. (c) Plot showing the difference (archive – NRT) in percentage ice cover mapped.

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