CryoSat-2 estimates of Arctic sea ice thickness and volume

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Received 14 December 2012; accepted 16 January 2013; published 28 February 2013.

[1] Satellite records show a decline in ice extent over more than three decades, with a record minimum in September 2012. Results from the Pan-Arctic Ice-Ocean Modelling and Assimilation system (PIOMAS) suggest that the decline in extent has been accompanied by a decline in volume, but this has not been confirmed by data. Using new data from the European Space Agency CryoSat-2 (CS-2) mission, validated with in situ data, we generate estimates of ice volume for the winters of 2010/11 and 2011/12. We compare these data with current estimates from PIOMAS and earlier (2003–8) estimates from the National Aeronautics and Space Administration ICESat mission. Between the ICESat and CryoSat-2 periods, the autumn volume declined by 4291 km^3 and the winter volume by 1479 km^3. This exceeds the decline in ice volume in the central Arctic from the PIOMAS model of 2644 km^3 in the autumn, but is less than the 2091 km^3 in winter, between the two time periods. **Citation:** Laxon S. W., K. A. Giles, A. L. Ridout, D. J. Wingham, R. Willatt, R. Cullen, R. Kwok, A. Schweiger, J. Zhang, C. Haas, S. Hendricks, R. Krishfield, N. Kurtz, S. Farrell and M. Davidson (2013), CryoSat-2 estimates of Arctic sea ice thickness and volume, *Geophys. Res. Lett.*, *40*, 732–737, doi:10.1002/grl.50193.

1. Introduction

[2] Changes in Arctic sea ice cover represent one of the most visible components of climate change. While changes in sea ice extent affect the albedo, changes in sea ice volume reflect changes in the heat budget of the Arctic and the exchanges of fresh water between sea ice and the ocean. Global climate simulations predict that the decline in Arctic sea ice volume (3.4% per decade), due to anthropogenic greenhouse gas forcing, will be greater than the decline in sea ice extent (2.4% per decade) [*Gregory et al.*, 2002].

[3] Satellite records show a continued downward trend in Arctic sea ice extent during all seasons, but particularly in summer [*Stroeve et al.*, 2012]. Sea ice extent anomalies were less extreme following 2007, but estimates of Arctic sea ice volume from the Panarctic Ice Ocean Modeling and Assimilation System [PIOMAS, *Zhang and Rothrock*, 2003] sea ice reanalysis exhibited a continued downward trend [*Schweiger et al.*, 2011, hereinafter S11]. PIOMAS is based on a numerical model with ocean and ice components which is forced with National Centers for Environmental Prediction Atmospheric Reanalysis data. Satellite observed sea ice concentration and sea surface temperature are assimilated to improve the ice thickness analysis and resulting volume estimates produced by PIOMAS. The only recent observational record of ice volume with near-Arctic wide coverage up to 86°N comes from National Aeronautics and Space Administration (NASA)'s ICESat satellite [*Kwok et al.*, 2009, hereinafter K09], but the period covered (2003–8) is considered too short to validate PIOMAS trends (S11). In addition ICESat volume estimates are not currently available after March 2008 and therefore cannot be used to confirm the continuing decline in Arctic sea ice volume simulated by PIOMAS since 2008.

[4] In this paper, we use estimates of ice volume from CryoSat-2 (CS-2) [*Wingham et al.*, 2006] satellite radar altimeter measurements of sea ice thickness to extend the ICESat record of Arctic ice volume to March 2012. We describe the methodology used to process and validate CS-2 thickness estimates using three independent in situ data sets. We then use CS-2 to compute ice volumes for the winters of 2010/11 and 2011/12 and compare the data with earlier ICESat volume estimates and with more recent PIOMAS simulations.

2. Data and Methodology

[5] Although the measurement principle of CS-2 is similar to previous satellite radar altimeters carried on the European Space Agency (ESA) European Remote Sensing (ERS) [*Laxon et al.*, 2003] and Envisat [*Giles et al.*, 2008] satellites, the mission concept of CS-2 and the synthetic aperture radar (SAR)/Interferometric Radar Altimeter (SIRAL) altimeter carried onboard differ in three important respects. First,

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0094-8276/13/10.1002/grl.50193

This article was corrected on 29 OCT 2014. See the end of the full text for details.

the orbital inclination of CS-2 of 92° provides coverage to a latitude of 88°N for the first time (the coverage of ERS and Envisat was limited to 81.5°N). Second, SIRAL uses "Synthetic aperture radar altimetry" to reduce the size of the instrument footprint to approximately 0.3 km by 1.5 km along track and across track, respectively, compared to ~10 km on the earlier ESA missions. Finally, as CS-2 moves along its orbit, SIRAL uses multiple-looks of each point on the surface to reduce noise caused by radar speckle. For a full description of the CryoSat mission, processing, and data products, see *Wingham et al*. [2006].

[6] We compute sea ice thickness, from measurements of ice freeboard obtained by processing CS-2 Level 1B data using the same method as used to process data from the Envisat RA-2 instrument [*Giles et al*., 2008], but with minor modifications to account for differences between the instruments and a modified algorithm to convert thickness to freeboard. We now detail the differences between the processing of CS-2 and that used for RA-2.

[7] The first step in processing is the discrimination between measurements of the surface elevation of the ocean and the surface elevation of the ice (above a reference ellipsoid). The discrimination relies on the fact that the variation in the surface reflectivity with incidence angle differs depending on whether the echo is dominated by specular reflections from leads, or by diffuse reflections from ice floes [*Drinkwater*, 1991; *Laxon*, 1994]. Surface type detection is implemented by examining the "pulse peakiness" (PP) parameter used previously [*Giles et al*., 2008; *Peacock and Laxon*, 2004] and a new parameter, known as the "stack standard deviation" (SSD) that uses SIRALs multilooking to provide a measure of the variation in surface backscatter with incidence angle [*Wingham et al*., 2006]. Returns from leads are identified by PP > 18 and a SSD < 4, while echoes from floes are identified by their low PP (< 9) and high SSD (> 4). A correction is also required to account for the difference in range between the center of the range window and the point on the leading edge of the echo corresponding to the mean scattering level on the surface [*Laxon*, 1994]. For echoes from leads, we replace the simple leading edge threshold algorithm used previously [*Giles et al*., 2008], with a more sophisticated Gaussian plus exponential model fit to the echo [*Giles et al*., 2007]. For echoes from ice floes, the tracking point is positioned at the point where the rise reaches 50% of the amplitude of the first peak in the echo. Following *Giles et al*. [2012], we remove a bias in elevation due to differences in the model fits between diffuse and specular echoes, determined by comparing ocean elevations, with and without ice cover, in areas of seasonal ice. To remove the geoid and mean ocean topography from the derived elevations, we constructed a new mean sea surface model from the first year of CryoSat lead and open ocean elevations.

[8] To convert freeboard to thickness, we employ a more sophisticated approach than that used previously [*Giles et al*., 2008; *Laxon et al*., 2003] by modifying the snow loading from *Warren et al*. [1999, hereinafter W99] and the ice density, depending on whether first or multiyear ice is present (identified using gridded data on ice type from the Norwegian Met. Service OSI SAF system). Recent analyses of snow radar data show that, while the W99 is representative of snow on multiyear ice, snow depth on first year ice is approximately 50% of that given by W99 [*Kurtz and Farrell*, 2011]. For first year ice, we therefore multiply the W99 snow depths (h_s) by 0.5 before converting CS-2 freeboard measurements to thickness (we use the snow densities given by W99). We use a density of 916.7 kg m^{-3} for first year ice and 882.0 kg m^{-3} for multiyear ice [*Alexandrov et al*., 2010].

[9] The absolute thickness estimates from CS-2 may be subject to biases from a number of different sources. Our assumption that the radar penetrates to the snow-ice interface is still the subject of investigation and may also introduce errors into bias our thickness estimates [*Willatt et al*., 2011]. Additional uncertainties may be introduced due to uncertainties in our assumed snow loading and ice/water densities, employed when converting freeboard to thickness. For this reason, it is important to compare our CS-2 retrievals with other sources of co-incident ice thickness data. We use three independent data sets that allow us to verify the CS-2 retrievals over a wide area, including both first- and multiyear ice, and over an entire ice growth season.

[10] Before comparing with in situ data, it is necessary [*Giles et al*., 2007] to average the individual freeboard measurements to reduce errors arising from the random fluctuations in the incoherent radar echoes known as "speckle" [*Elachi*, 1988; *Peacock and Laxon*, 2004]. The number of freeboard measurements averaged must be sufficient to ensure that the contribution to the error in ice thickness due to this noise is no more than the error due to other uncertainties (e.g., snow loading). In addition, to produce a map with regular spatial coverage over the Arctic requires the averaging of data over one month due to the 30-day subcycle of the satellites orbit pattern [*Wingham et al*., 2006]. For CS-2, the estimated speckle noise for individual average echoes is 0.10 m to 0.14 m, depending on the operating mode employed [*Wingham et al*., 2006], and will affect both the lead and floe elevation retrievals. To reduce the error in freeboard, due to speckle noise, to a level of 2 to 3 cm, we grid the CS-2 thickness estimates and require a minimum of 100 measurements in each cell to reduce the error due to speckle by at least a factor of 10 ($=\sqrt{100}$).

[11] The airborne ice thickness data that we use to compare with CS-2 were obtained using an EM sensor towed by a DC-3 aircraft known as "Polar-5" [*Haas et al*., 2010]. Ten surveys, with lengths ranging between 65 and 350 km, flown in April 2011 and 2012 (black lines in Figures 1d and 1f), provided measurements of combined snow + ice thickness over both first- and multiyear ice in the Western Arctic. While the accuracy of EM data over level ice is 0.1 m, the uncertainty may be larger when ridged ice is present [*Haas et al*., 2010].

[12] To compare the CS-2 and EM data, both data sets were gridded onto the same 0.4° latitude by 4° latitude grid. The comparison of ice plus snow thickness (Figure 2a) yields a correlation coefficient $R = 0.701$ and a mean difference of 0.066 ± 0.624 m. The root-mean-square difference includes both the errors in CS-2 ice thickness and in the EM data and differences due to the temporal and spatial sampling of the two data sets. The SD of 0.624 m between in situ and CS-2 data may be compared with the estimated error on gridded ice thickness estimates of 0.46 m [*Giles et al*., 2007] (0.49 m when adding the additional uncertainty in snow depth), excluding sampling errors and errors in *in*-situ data.

[13] To further assess our CS-2 thickness estimates, we compared ice draft, calculated from CS-2, with measurements of sea ice draft from three Beaufort Gyre Experiment

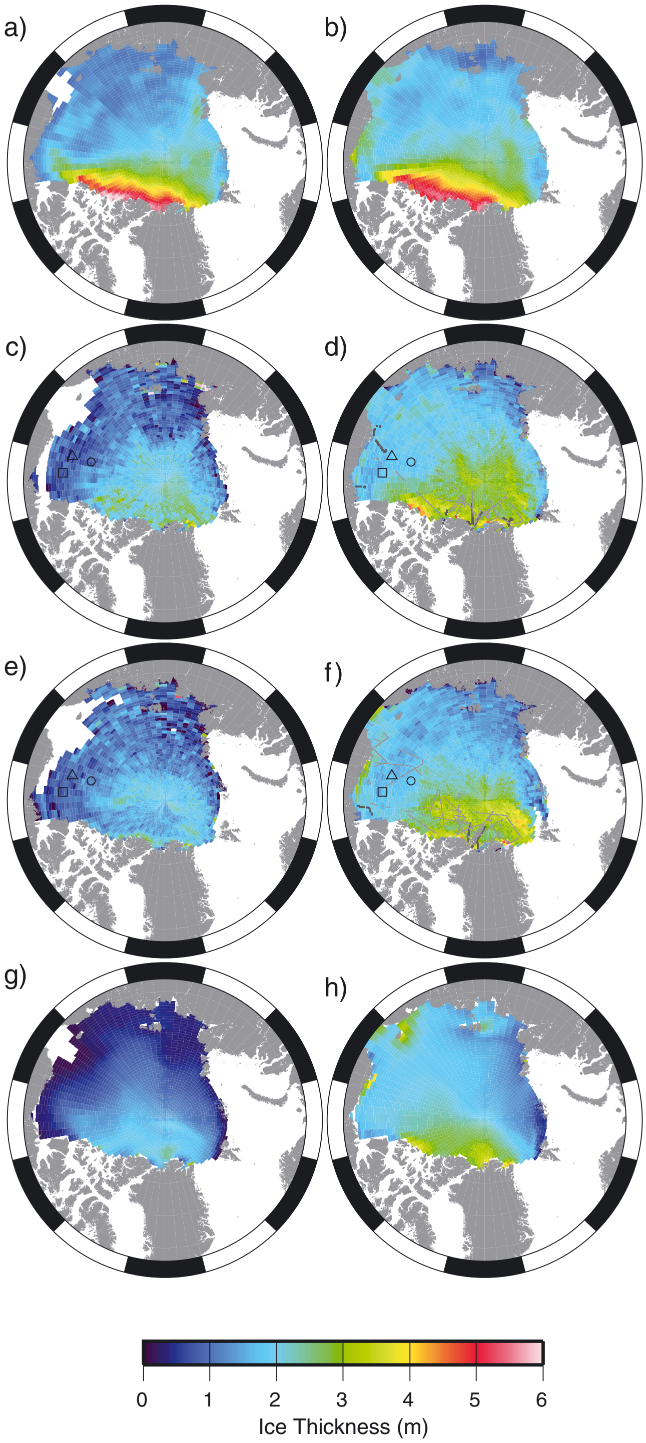

Figure 1. CryoSat sea ice thickness compared with PIOMAS and ICESat ice thickness measurements. The data are restricted to the "ICESat" domain covering the central Arctic Ocean. (a) 2003–7 average ICESat ice thickness for October/November and (b) 2004–8 average for February/March. (c and d) CryoSat thickness for October/November 2010 and February/March 2011 and locations of the airborne EM data (black lines) and OIB data (grey lines) used for validation, ULS moorings (triangle, circle, square). (e and f) CryoSat thickness for October/November 2011 and February/March 2012 and locations of the airborne EM data (black lines) and OIB data (grey lines) used for validation. (g) PIOMAS for October/November 2011 and (h) February/March 2012.

Program (BGEP) Upward Looking Sonar (ULS) moorings located in the Beaufort Sea (Figure 1a; http://www.whoi.edu/page.do?pid=66559) over the period October 2010 to April 2011 and October 2011 to April 2012. The error in ULS measurements of ice draft are estimated as 0.1 m [*Melling et al.*, 1995]. Monthly averages of all CS-2 draft estimates within 200 km of each mooring were compared with monthly averages of ice draft obtained by each ULS. The comparison (Figure 2b) shows a higher correlation ($R = 0.886$) than for the EM measurements and a mean

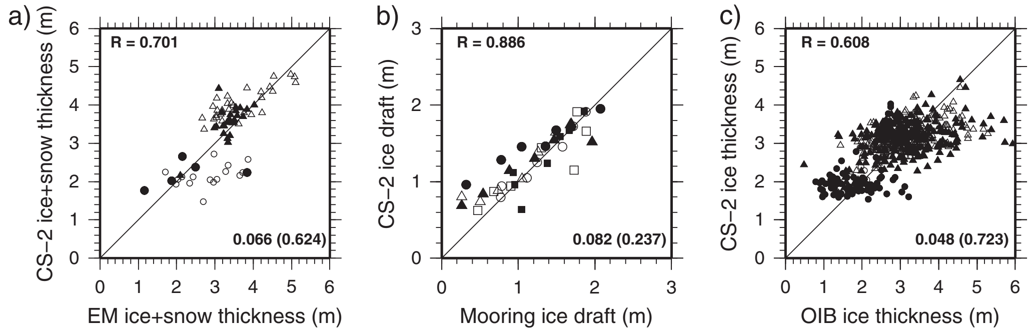

Figure 2. Validation of CryoSat sea ice thickness. (a) Comparison of Polar-5 aircraft EM and Cryosat-2 snow plus ice thickness over first year (**circle**) and multiyear (triangle) ice during April 2011 (open symbols) and 2012 (solid symbols). (b) Comparison of monthly average ice draft from CryoSat-2 within 200 km of the Beaufort Gyre Experiment Program Upward Looking Sonar Moorings (Mooring A: triangle, Mooring B: circle, Mooring D: square) for the period October 2010 to April 2011 and October 2011 to April 2012 (solid symbols). (c) Comparison of Operation IceBridge (OIB) aircraft laser and Cryosat-2 ice thicknesses over first year (**circle**) and multiyear (triangle) ice between 10 March 2011/12 and 9 April 2011/12 (solid symbols are data from 2012). Both aircraft comparisons were conducted by gridding CryoSat and the aircraft data onto a common (0.4 latitude by 4 longitude) grid and comparing those grid cells in which both data sets contained data. The locations of the in situ data sets are shown in Figure 1.

difference in draft of -0.082 ± 0.237 m. This figure compares with differences between ice draft from ICESat and ice drafts from the same BGEP moorings, but for the period 2003–7, of -0.14 ± 0.51 m in K09. K09 obtained similar differences of -0.1 ± 0.42 m when comparing ICESat with submarine ULS draft measurements.

[14] Finally, we compare CS-2, gathered between 10 March and 09 April 2011, with ice thickness estimates computed using laser altimeter freeboard measurements from the NASA Operation IceBridge (OIB) mission gathered between 16 and 28 March 2011. CryoSat data acquired over the same dates in 2012 are also compared with IceBridge data gathered between 12 March and 2 April 2012. We compare these data by gridding both CS-2 and the airborne data onto the same 0.4 latitude × 4 longitude grid as used for the EM comparison. The correlation (Figure 3c) is lower ($R = 0.608$) than either the EM or ULS, and the mean difference is -0.048 ± 0.723 m. The reasons for the increased scatter relative to the EM and ULS comparisons are unclear and are the subject of further investigation.

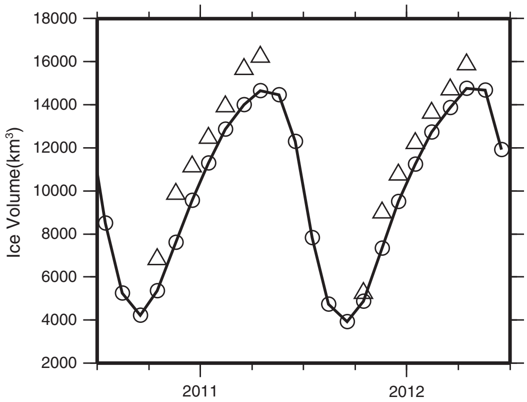

Figure 3. Timeseries of monthly Arctic sea ice volume from CS-2 (triangle) and from PIOMAS (solid line and circle) for two winter growth periods (October–April).

[15] Overall comparisons of CS-2 thickness estimates with in situ data (Figure 2) show an agreement in thickness to within 0.1 m. It is notable that the best agreement is found when using ULS that is arguably the most established method for ice thickness estimation. At present, there is no evidence from the continuous ULS draft time series, or the spatially more representative OIB thickness data for a large-scale systematic bias in our CS-2 thickness retrievals. Future validation missions should attempt to further constrain the remaining scatter between in CS-2 and in situ data.

[16] Ice volume is computed using CS-2 over the "ICESat domain" (Figure 1; K09; S11). The domain covers the central Arctic Ocean and has an area of 7.2 million km^2 (K09). Values for grid cells north of the CS-2 latitudinal limit (88°N for CS-2 and 86° for ICESat) are obtained by substituting values from the nearest grid cells that include thickness data. Substituted values were also used in areas of fast ice, in particular, south of the New Siberian Islands in late spring, where an absence of leads prevents freeboard measurement.

[17] In common with earlier satellite radar altimeters CS-2 sea ice thickness estimates exclude open water [*Laxon et al.*, 2003]. To compute sea ice volume, we therefore take the product of the area, the thickness excluding open water obtained from CS-2 and the ice concentration obtained from SSM/I [*Meier et al.*, 2006] (the more accurate Advanced Microwave Scanning Radiometer–EOS ice concentration is not available for the more recent part of the CS-2 mission. http://nsidc.org/data/docs/daac/nsidc0051_gsfc_seaice.gd.html give the accuracy of total sea ice concentration as ± 5% during winter). Using the same method, we also calculate ice volume using ICESat thickness estimates available from Jet Propulsion Laboratory (http://rkwok.jpl.nasa.gov/icesat/index.html). We refer to these estimates as "adjusted" (for ice concentration) but also compute ice volume estimates "unadjusted" for ice concentration for comparison with K09.

[18] PIOMAS is a numerical model with components for sea ice and ocean and the capacity for assimilating some kinds of

observations. For comparison with PIOMAS, we use monthly averages of CS-2 ice thickness adjusted using average ice concentration. For comparison with the ICESat volume estimates in K09, we take the average center date for the autumn and winter ICESat campaigns, between 2003 and 2008, of 28 October and 11 March. Ice volumes are computed from CS-2 using data for a 30-day period centered on these campaign center dates.

3. Results and Discussion

[19] Figure 1 shows CS-2 sea ice thickness from CS-2 for autumn/winter 2010/11 and 2011/12 (adjusted for ice concentration) and the autumn/winter ice thickness from ICESat averaged over the period 2003–8 and the autumn/winter 2011/12 thickness from PIOMAS. When comparing CS-2 with the earlier ICESat data, the most striking difference is the apparent disappearance of thick ice to the north of Greenland and the Canadian Archipelago and to a lesser extent to the northeast of Svalbard. First year ice also appears thinner in the autumn than during the earlier ICESat period although it is similar in the winter. Comparing the CS-2 thickness between the two winters, the ice in autumn is noticeably thinner in 2011 than 2010, though again the difference is less pronounced during the later winter period.

[20] Table 1 shows the average ice volumes computed for the ICESat period and for the two CS-2 winters. Also shown is the change in ice volume between the two time periods for both the satellite and model estimates. We include the "unadjusted" ice volumes for comparison with K09 (who do not adjust ICESat thickness data for ice concentration) but consider the adjusted volumes as more representative since they account for changing ice concentration between the two periods. From the "adjusted" data, the loss of sea ice volume for the autumn period is 4291 km^3 more than twice the 1479 km^3 loss in winter; it also exceeds the decline in autumn ice volume predicted by the PIOMAS (2644 km^3) in the autumn. However, PIOMAS's prediction of the change in the winter ice volume (2091 km^3) is greater than that indicated by the satellite record. Adjusted volumes are within 10% of the unadjusted values, and the decline in the unadjusted volumes is within 5% of the "adjusted." The difference in spring volume between the two time periods corresponds to a net increase in net winter ice growth, between the autumn and winter periods, from ~5000 km^3 between 2003 and 2008 to 7500 km^3 in 2010 and 2012. Averaged over the basin, this represents an extra 36 cm of ice growth, equivalent to an increase in sea ice latent heat output, between the autumn and winter periods, of ~9 W m^{-2}. However, because this net growth is compensated by increased summer melt, changes in sea ice volume between the two time periods correspond to only a net annual change in sea ice latent heat of 1.3 Wm^{-2}. In addition, while trends from only two years of data are not indicative of long-term change, we note that between 2010 and 2011 the CS-2 autumn volume fell from 8283 km^3 to 6838 km^3 (a decline of 1445 km^3) and the winter volume fell from 15,424 km^3 to 14,125 km^3 (a decline of 1209 km^3).

Table 1. Arctic Sea Ice Volume (km^3) for the ICESat Domain Averaged over the ICESat Campaigns and for the Corresponding CryoSat Periods during 2010–2012. Volumes are Shown for Data that Have Been "Adjusted" for Ice Concentration (following S11) and "Unadjusted" for Ice Concentration (Following K09).

	Volume (adjusted)		Volume (unadjusted)		PIOMAS	
Dates	Oct/Nov	Feb/Mar	Oct/Nov	Feb/Mar	Oct/Nov	Feb/Mar
2003–2008	11,852	16,299	13,128	16,725	9119	15,451
2010–2011	8283	15,424	9060	15,348	6846	13,429
2011–2012	6838	14,215	7907	14,406	6104	13,290
Change[a]	−4291	−1479	−4488	−1444	−2644	−2091

[a]Change in volume between the CryoSat-2 (2010–12) and ICESat (2003–2008) time periods for the satellite and PIOMAS estimates.

[21] As noted earlier, ICEsat shows a negative difference of order 0.1 m when compared with in situ data while CS-2 data appear to be biased high by approximately 0.06 m. As a further test, we compared both ICESat and CS-2 ice thickness data with thickness estimates from the Envisat RA-2 [*Giles et al*., 2008] but using the same freeboard to thickness conversions as applied to CS-2 in this paper. The Envisat data span the period October 2003 to March 2012 and provide overlapping data below 81.5°N. The comparison of ICESat and RA-2, from 2005 to 2008 (ice type data are not available before 2005) yields ICESat thicknesses 0.04 m higher than RA-2 (SD 0.28 m) while the comparison of CS-2 and RA-2 yields, between October 2010 and April 2012, yields CS-2 thicknesses −0.06 m (SD 0.04 m) below RA-2. Thus, the in situ data might suggest that CS2 could be biased high by order 0.1 m with respect to ICESat while the RA-2 cross calibration suggests CS2 could be biased 0.1 m lower than ICESat. There is no contradiction in the apparent discrepancy in these biases; they reflect that different data are used in the two comparisons. Our present understanding of both the satellite and in situ data is insufficient to resolve any inter-satellite bias to a higher degree of certainty, but we note that an inter-satellite bias of 10 cm would result in an error in volume of ~700 km^3, much less than the change in volume between the two time periods.

[22] Figure 3 compares CS-2 and PIOMAS ice volume over two seasons of ice growth. Both growth curves are similar in shape although CS-2 exhibits a more rapid initial increase in ice volume during the winter growth season. CS-2 ice volume in 2010/11 is higher than PIOMAS throughout the growth season while CS-2 volume estimates agree with PIOMAS more closely in 2011/2.

4. Conclusions

[23] Data from CS-2 show a pattern of ice thickness similar to that observed in previous satellite data and submarine climatologies [*Bourke and Mclaren*, 1992; *Kwok et al*., 2009; *Laxon et al*., 2003]. The pattern of ice thickness from CS-2 is also similar to data from PIOMAS during winter 2011/12 with a similar winter growth curve for total ice volume.

[24] A comparison of CS-2 with in situ data shows a varying amount of scatter, depending primarily on the source of the in situ data and, to a lesser extent, on ice type. Whether this scatter is caused by errors in the in situ data, sampling differences, or errors at small scales in our assumptions regarding penetration of the radar into the snow, ice surface geometry, ice/water densities, or snow loading is unknown. Further questions surround any dependence of potential biases or uncertainties with ice type, although the fact that the mean difference between CS and the ULS data (that are almost exclusively in the presence of first year ice) and the EM and OIB data (that also cover multiyear ice) does not suggest a substantial dependence when averaged over large scales.

[25] These issues will be addressed through a more detailed analysis of the airborne and in situ data gathered during 2011

and 2012, in particular from CS-2 under-flights by the ESA Airborne Synthetic Aperture and Interferometric Radar Altimeter System instrument and NASA's IceBridge campaigns that are now becoming available. Nevertheless, comparison of CS-2 measurements with three independent in situ data sets reveals differences of less than 0.1 m in thickness when averaged on a large scale, or over a full winter growth season. These comparisons and previous comparisons of ICESat with in situ data reveal no evidence for an inter-satellite bias that would invalidate the changes in ice volume calculated from the two satellite data sets.

[26] Our data provide further evidence for the long-term decrease in Arctic sea ice volume simulated by PIOMAS. The average volume loss over both the autumn and winter periods is ~500 $km^3\ a^{-1}$, equivalent to a 0.075 $m\ a^{-1}$ decrease in thickness, which is close to the peak thinning rates observed in the submarine record [*Kwok and Rothrock*, 2009]. The rate of decline in autumn ice volume that our data show (~800 $km^3\ a^{-1}$) is 60% higher than the decline in the PIOMAS integration analyzed in S11. This is further evidence that the PIOMAS estimates of autumn volume loss are conservative (S11). The decline in winter ice volume that we observe is however less than for PIOMAS (by around 25%). These results suggest a greater loss of Arctic sea ice volume in summer and a greater gain of volume in winter than PIOMAS.

[27] Finally, we can speculate that the lower ice thickness and volume in February/March 2012, as compared with February/March 2011, may have been one factor behind the record minimum ice extent reached in September 2012.

[28] **Acknowledgments.** This work was funded by the UK's Natural Environment Research Council, the European Space Agency, the German Aerospace Center (DLR), Alberta Ingenuity, National Science Foundation (NSF). Thanks to Kenn Borek and the NASA IceBridge team.

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Erratum

In the originally published version of this article, an instance of text was incorrectly typeset. The following has since been corrected, and this version may be considered the authoritative version of record.

In section 2, paragraph [7], “50% of the amplitude” has been changed to “70% of the amplitude”.