**Article:**

Tilling, RL, Ridout, A, Shepherd, A orcid.org/0000-0002-4914-1299 et al. (1 more author) (2015) Increased Arctic sea ice volume after anomalously low melting in 2013. Nature Geoscience, 8 (8). pp. 643-646. ISSN 1752-0894

https://doi.org/10.1038/NGEO2489

**Increased Arctic sea ice volume after anomalously low melting in 2013**

Rachel L. Tilling[1]*, Andy Ridout[1], Andrew Shepherd[1,2], Duncan J. Wingham[1]

[1]*Centre for Polar Observation and Modelling, Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK*

[2]*Centre for Polar Observation and Modelling, School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK*

**Changes in Arctic sea ice volume impact on regional heat and freshwater budgets, on patterns of atmospheric circulation at lower latitudes and, potentially, on global climate. Despite a well-documented ~40% decline in summer Arctic sea ice extent since the late 1970's, it has been difficult to quantify trends in sea ice volume because detailed thickness observations have been lacking. Here, we assess changes in northern hemisphere sea ice thickness and volume using five years of CryoSat-2 measurements. Between autumn 2010 and 2012, there was a 14% reduction in Arctic sea ice volume, in keeping with the long-term decline in extent. However, we observe 33% and 25% more ice in autumn 2013 and 2014, respectively, relative to the 2010-2012 seasonal mean, offsetting earlier losses. The increase was driven by the retention of thick sea ice northwest of Greenland during 2013 which, in turn, was associated with a 5% drop in the number of days on which melting occurred – conditions more typical of the late 1990's. In contrast, springtime Arctic sea ice volume has remained stable. The sharp increase in sea ice volume after just one cool summer indicates that Arctic sea ice may be more resilient than has been previously considered.**

Arctic-wide observations of sea ice thickness are essential for estimating trends in sea ice volume, and for assessing the fidelity of the numerical models that form the basis of future climate projections[1-3]. Unfortunately, past observations of arctic sea ice thickness have been spatially incomplete and temporally sporadic[4-7]. Despite the ability of global climate models to relate dynamic and thermodynamic processes of the Arctic region[8], many still underestimate the rate at which sea ice extent has declined[9, 10], which reduces confidence in their capacity to simulate past and future trends in sea ice volume. The Pan-Arctic Ice-Ocean Modelling and Assimilation System (PIOMAS) - a coupled ocean and sea ice model that, unlike other numerical models, assimilates sea ice data by including measurements of near-real-time sea ice concentration and drift[11] – provides an alternative approach to estimating regional trends in volume. However, although PIOMAS has shown good agreement with contemporaneous observations of sea ice volume in the high-Arctic region derived from satellite observations[12], the system has not yet been evaluated across its whole domain. Here, we quantify five years of inter-annual variations in the volume of sea ice across the entire northern hemisphere using observations acquired by the European Space Agency's (ESA) CryoSat-2 mission[13].

### *1. Measuring sea ice volume using CryoSat-2*

We use 88 million individual CryoSat-2 altimeter measurements to estimate changes in northern hemisphere (latitudes above 40°N) sea ice freeboard, thickness, and volume over the period October 1st 2010 to November 30th 2014 (see Methods). Over sea ice, we assume that the CryoSat-2 echoes scatter from the interface between the ice surface and the layer of overlying snow[12], and we compute freeboard as the difference in elevation between this location and that of the surrounding ocean. Ice thickness is then calculated from these freeboard measurements, assuming that the sea ice floats in hydrostatic equilibrium and using estimates of snow depth and density derived from a climatology[14], fixed estimates of first-year (FYI) and multi-year (MYI) densities[15], a fixed seawater density[16], and a reduced fraction of snow on FYI[17]. Norwegian Meteorological Service Ocean and Sea Ice Satellite Application Facility data are used to classify FYI and MYI for each individual freeboard. We then integrate the product of sea ice thickness, fractional ice concentration and area[18] over monthly intervals and within fixed oceanographic basins[19] (Supplementary Figure 2) to compute regional (Supplementary Table 2) and hemisphere-wide (Table 1, Figure 2) changes in sea ice volume during the sea ice growth period (October to April) of each year. To estimate uncertainties in sea ice thickness and volume, we account for uncertainties in the sea ice density, snow loading, sea ice area, sea ice concentration, and for spatial variations in the measurement of sea ice freeboard - by far the smallest error source we consider (see Methods and Supplementary Table 1).

To assess the accuracy of the CryoSat-2 observations, we compared them to 772,090, 430, and 80 million independent estimates of thickness and draft derived from springtime airborne laser and electromagnetic sensor campaigns[20, 21] and year-round upward looking sonar observations, respectively (see Supplementary Information). CryoSat-2 estimates of ice thickness agree with these independent measurements to within 2 mm, on average – a difference that is much smaller than the certainty of either dataset (10 to 40 cm).

### *2. Recent trends in Arctic sea ice volume*

Between 2010 and 2014, there have been marked variations in the quantity of sea ice in key sectors of the Arctic (Figure 1). During this period, the average northern hemisphere springtime (March/April) sea ice thickness was

2.09 ± 0.28 m. In autumn (October/November), after the summer melting season, the average thickness reduced to 1.41 ± 0.19 m. While the thickest sea ice is in most years concentrated around the coast north of Greenland and Ellesmere Island, it often extends into the central Arctic - a region that has been, until now, beyond the limit of satellite altimetry. As a result, earlier satellite-derived estimates of Arctic-wide sea ice thickness and volume[6, 22] will have been biased low. Our CryoSat-2 observations show that below 81.5°N (the latitudinal limit of the ERS and Envisat satellites) sea ice is, on average, 13% thinner than Arctic-wide estimates. Around the coast of Greenland, the amount of thick ice in autumn (the period following the sea ice minimum extent) has fluctuated from year to year. It is notable, for example, that the record minimum Arctic sea ice extent of September 2012[10] was accompanied by thicker autumn ice in this region compared to previous years, demonstrating that decreasing ice extent does not necessarily result in a proportionate decrease in ice volume. Elsewhere, the amount of sea ice in Fram Strait is quite variable, with the thickest ice appearing in spring 2012. There are also marked inter-annual variations in the spread of thick ice across the central Arctic region and the Beaufort Sea.

Our estimates of seasonal sea ice volume changes (Figure 2) allow us to quantify the rate of sea ice growth from autumn to winter (Supplementary Table 3), which influences peak annual ice thickness and volume[23] and, in turn, affects the Arctic heat budget by moderating heat exchange between the ocean and the atmosphere[24]. At 4.20 $km^3$/month, the average October-January sea ice growth rate during the period of our survey is 15% higher than estimates derived from PIOMAS[11], leading to springtime sea ice volumes that are 12% higher. Difference between the PIOMAS and CryoSat-2 domains, which are truncated at 45°N and 40°N, respectively, cannot explain the shortfall, because the volume of sea ice in the omitted region (parts of the Sea of Okhotsk and the Gulf of St Lawrence) is far too small (< 0.15%). Although PIOMAS does reproduce, qualitatively, many aspects of the observed variability, including the seasonal progression and the step increases in sea ice volume recorded in the autumns of 2013 and 2014, the discrepancy in growth rates, springtime volume, and inter-annual springtime volume variability all point to a need for further investigation.

Since 2010, there have been large (408 to 468 $km^3\ yr^{-1}$) inter-annual fluctuations in the amount of northern hemisphere sea ice (Figure 2 and Table 1), two to four times greater than the variability that occurred in the central Arctic between 2003 and 2008 (115 to 275 $km^3 yr^{-1}$) - the only other period for which Arctic sea ice volume observations exist[22]. MYI is the most variable ice type and, between 2010 and 2012, we record a 31% (1,640 $km^3$) decline in its autumn volume, followed by an 88% (3,251 $km^3$) increase in 2013 and an 11% (771 $km^3$) decrease in 2014. These changes impact on the total autumn sea ice volume, which declined by 14% (1,279 $km^3$) between

2010 and 2012, increased by 41% (3,184 $km^3$) in 2013, and decreased by just 6% (673 $km^3$) in 2014. The peak autumn volume in 2013 manifests as a thick ice cover in the MYI region north of Greenland and Ellesmere Island (Figure 1d), with ice being 21% thicker, on average, than the five year mean. The volume of autumn FYI is much less variable. Inter-annual variations in hemisphere-wide volume in spring are less significant than in autumn for all ice types, as FYI is replaced by MYI over the growth season – the 9% volume increase in spring 2014, following the autumn 2013 increase, was not significant. At the scale of oceanographic basins (Supplementary Figure 2), only the Amerasian basin, which encompasses the Beaufort Sea, exhibits a significant trend in sea ice volume over the period of our survey (Supplementary Table 2). The 40% growth of ice in this sector in autumn 2013 contributed significantly to the overall increase in Arctic sea ice volume.

### *3. Understanding the drivers of Arctic sea ice variability*

We use ERA-Interim reanalysis data[25] to investigate factors that commonly influence Arctic sea ice volume, including fluctuations in snow loading, wind-driven ice drift, and ice melting, to identify the origin of the observed inter-annual variability. Together, the Amerasian and Eurasian basins (Supplementary Figure 4) contain the majority of all northern hemisphere sea ice – 65% and 42% in autumn and spring, respectively – and comprise the main region of near-persistent sea ice cover, and so we considered influences on sea ice in this region (sea ice persistence simplifies our analysis of climate records). Inter-annual changes in sea ice volume could arise, for example, through our use of a temporally invariant snow depth in the ice thickness calculation, or they could be related to dynamic or thermodynamic forcing, as has been shown in the past[5, 22]. First, we computed an alternative estimate of sea ice volume in the Amerasian and Eurasian basins using a time-varying snow load derived from the climate reanalyses (Supplementary Figures 3 and 5). In this region, there is very little difference (< 5% per month, on average) in sea ice volume compared to our climatology-based retrieval. We found a weak ($r^2 = 0.05$; Supplementary Figure 6) correlation between temporal variations in snow load and sea ice volume in autumn (the main growth period), suggesting that inter-annual variations in autumn ice volume are driven by other factors. We then compared year to year changes in autumn sea ice volume to the annual (November-November) wind convergence (a proxy for wind-driven ice convergence), and the annual number of melting degree days[26] (a proxy for ice melting) within the Amerasian and Eurasian basins (see Supplementary Information). This analysis shows that inter-annual changes in autumn sea ice volume in the Amerasian and Eurasian basins are weakly correlated with wind forcing ($r^2 = 0.38$; Supplementary Figures 7 and 8), and are strongly correlated with the degree of melting ($r^2 = 0.73$; Supplementary Figure 9). Although other environmental factors may have influenced Arctic sea ice volume, such as ocean-driven changes in dynamics, our analysis suggests that thermodynamics play an important role.

Because the quantity of autumn sea ice in the Amerasian and Eurasian basins is strongly affected by inter-annual variations in melting, we compared hemisphere-wide and regional trends in both parameters (Figures 3a and 3b) to establish whether a similar relationship holds elsewhere. At the hemisphere scale, the correlation between autumn total and MYI sea ice volume and the number of melting degree days (Figure 3c) is even stronger ($r^2 \geq 0.78$) than in the Amerasian and Eurasian basins; on average, 142 $km^3$ of ice is lost per additional degree day of melting ($M_{DD}$). However, there are regional variations in the strength of this relationship (Supplementary Table 4), with a relatively poor correlation in the Greenland Sea ($r^2 = 0.10$), likely a consequence of the rapid sea ice transport in this sector. In contrast, there is a strong correlation in the Canadian Archipelago ($r^2 = 0.98$) where sea ice motion is inhibited by islands. Regionally, the amount of autumn ice lost per $M_{DD}$ is dependent on the size of the region (Supplementary Table 4 and Supplementary Figure 10). These findings illustrate the need to survey large fractions of the Arctic sea ice pack, or else the effects of ice drift may be missed.

Although Arctic-wide melting has increased steadily over recent decades (by 0.25 $M_{DD}$ $year^{-1}$, on average, since 1980, Figure 3b), there was a marked (5% $M_{DD}$) reduction in 2013 prior to the sharp increase in autumn sea ice volume recorded by CryoSat-2. In fact, 2013 was an anomalously cool year, with temperatures more typical of conditions during the late 1990's, and by autumn 2014 Arctic sea ice volume had still not returned to pre-2013 levels. If Arctic temperatures continue to rise, as is widely predicted[27], the volume of sea ice will diminish further[28], and we believe that the ice pack may become increasingly dependent on regional responses to thermodynamic, wind and ocean forcing. The CryoSat-2 record is presently too short to establish the trend in Arctic sea ice volume. However, it does demonstrate that the long-term decline is punctuated by inter-annual variability (e.g. a sharp increase in volume in 2013), which allows for positive, negative and stable variations in the range ±600 $km^3$ $yr^{-1}$. Improved certainty in the long-term trend will require a longer record of satellite observations.

The fine spatial sampling and high latitude orbit of ESA's CryoSat-2 mission have allowed us to produce the first comprehensive assessment of inter-annual variations in northern hemisphere sea ice volume and insight into the drivers of the variability. Using the first five years of mission data, we observe a modest reduction in total and MYI volume between autumn 2010 and spring 2013. These reductions were followed by a marked increase in volume in the autumn of 2013, with total volume increasing by 41% compared to the previous year and remaining higher than the 5-year average through to autumn 2014. The increase was due to the retention of thick, predominantly MYI, north of Greenland and Ellesmere Island over the summer of 2013. This was a relatively cool year, with temperatures comparable to those of the late 1990's rather than the past few years and the net result is an Arctic sea ice cover that is on average 21% thicker, and presumably stronger, than during the previous three autumns. However, 2013 was anomalous in relation to the long-term trend of increasing temperature in the Arctic, and if the regional temperatures continue to rise it is inevitable that further reductions in northern hemisphere sea ice thickness and volume will occur. Although a longer observational record is needed before trends in Arctic sea ice volume can be established with confidence, the recent increases do not reverse the long-term decline apparent in model-based reanalyses[11]. Our measurements also highlight the importance of obtaining Arctic-wide observations when attempting to quantify trends or to establish their origins. The next steps in Arctic sea ice research are to develop improved estimates of snow loading, and to use satellite observations of sea ice thickness as an additional factor in model assessments of the historical climate state and as a new constraint on the physics within models that form the basis of future climate projections.

**Methods**

Methods and any associated references are available in the online version of the paper.

**References**


1. Sewall, J.O. & Sloan, L.C. Disappearing Arctic sea ice reduces available water in the American west. *Geophysical Research Letters* **31**, L06209 (2004).
2. McGuire, A.D., Chapin, F.S., III, Walsh, J.E. & Wirth, C. Integrated regional changes in arctic climate feedbacks: Implications for the global climate system. *Annual Review of Environment and Resources* **31**, 61-91 (2006).
3. Singarayer, J.S., Bamber, J.L. & Valdes, P.J. Twenty-first-century climate impacts from a declining Arctic sea ice cover. *Journal of Climate* **19**, 1109-1125 (2006).
4. Wadhams, P. Evidence for thinning of the Arctic ice cover north of Greenland. *Nature* **345**, 795-797 (1990).
5. Laxon, S., Peacock, N. & Smith, D. High interannual variability of sea ice thickness in the Arctic region. *Nature* **425**, 947-950 (2003).

6. Giles, K.A., Laxon, S.W. & Ridout, A.L. Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum. *Geophysical Research Letters* **35**, L22502 (2008).

7. Kwok, R. & Rothrock, D.A. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958-2008. *Geophysical Research Letters* **36,** L15501 (2009).

8. Holland, M.M., Serreze, M.C. & Stroeve, J. The sea ice mass budget of the Arctic and its future change as simulated by coupled climate models. *Climate Dynamics* **34**, 185-200 (2010).

9. Stroeve, J.C. *et al.* Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters* **39**, L16502 (2012).

10. Fetterer, F., Knowles, K., Meier, W. & Savoie, M. in Sea Ice Index (National Snow and Ice Data Center. Digital Media. Boulder, Colorado USA; 2002, updated daily).

11. Zhang, J.L. & Rothrock, D.A. Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates. *Monthly Weather Review* **131**, 845-861 (2003).

12. Laxon, S.W. *et al.* CryoSat-2 estimates of Arctic sea ice thickness and volume. *Geophysical Research Letters* **40**, 732-737 (2013).

13. Wingham, D.J. *et al.* CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields, in *Natural Hazards and Oceanographic Processes from Satellite Data*, Vol. 37. (eds. R.P. Singh & M.A. Shea) 841-871 (2006).

14. Warren, S.G. *et al.* Snow depth on Arctic sea ice. *Journal of Climate* **12**, 1814-1829 (1999).

15. Alexandrov, V., Sandven, S., Wahlin, J. & Johannessen, O.M. The relation between sea ice thickness and freeboard in the Arctic. *The Cryosphere* **4**, 373-380 (2010).

16. Wadhams, P. *et al.* Relationship between sea ice freeboard and draft in the Arctic Basin, and implications for ice thickness monitoring. *Journal of Geophysical Research-Oceans* **97**, 20325–20334 (1992).

17. Kurtz, N.T. & Farrell, S.L. Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge. *Geophysical Research Letters* **38**, L20505 (2011).

18. Maslanik, J. & Stroeve, J.C. in Near-Real-Time DMSP SSM/I-SSMIS Daily Polar Gridded Sea Ice Concentrations. [concentration] (NASA DAAC at the National Snow and Ice Data Center. Digital Media. Boulder, Colorado USA; 1999, updated daily).

19. Nurser, A.J.G. & Bacon, S. Eddy length scales and the Rossby radius in the Arctic Ocean. *Ocean Science Discussions* **10**, 1807–1831 (2013).

20. Kurtz, N.T. *et al.* Sea ice thickness, freeboard, and snow depth products from Operation IceBridge airborne data. *Cryosphere* **7**, 1035-1056 (2013).

21. Haas, C., Lobach, J., Hendricks, S., Rabenstein, L. & Pfaffling, A. Helicopter-borne measurements of sea ice thickness, using a small and lightweight, digital EM system. *Journal of Applied Geophysics* **67**, 234-241 (2009).

22. Kwok, R. *et al.* Thinning and volume loss of the Arctic Ocean sea ice cover: 2003-2008. *Journal of Geophysical Research-Oceans* **114**, C07005 (2009).

23. Holland, M.M., Bitz, C.M. & Weaver, A.J. The influence of sea ice physics on simulations of climate change *Journal of Geophysical Research* **106**, 19639-19655 (2001).

24. Maykut, G.A. Energy exchange over young sea ice in the central Arctic. *Journal of Geophysical Research-Oceans and Atmospheres* **83**, 3646-3658 (1978).

25. Dee, D.P. *et al.* The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**, 553-597 (2011).

26. Kwok, R. Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005 summer. *Geophysical Research Letters* **34**, L05501 (2007).

27. Overland, J.E. & Wang, M. When will the summer Arctic be nearly sea ice free? *Geophysical Research Letters* **40**, 2097-2101 (2013).

28. Gregory, J.M. *et al.* Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. *Geophysical Research Letters* **29**, 2175 (2002).

**Corresponding Author**

Please address all correspondence and requests for materials to Rachel Tilling (rachel.tilling.12@ucl.ac.uk)

**Acknowledgements**

This study is based on the work of our late colleagues Seymour Laxon and Katharine Giles, and we are indebted to them for the excellent foundations they have left. We thank Christian Haas and the CryoVEx EM-Bird team for providing us with their data, as well as all those whose publically available data we have used. This work was funded by the UK's Natural Environment Research Council, with support from the UK's National Centre for Earth Observation.

**Author contributions**

Rachel Tilling and Andy Ridout developed and analysed the satellite and ancillary observations. Andrew Shepherd and Duncan Wingham supervised the work. Rachel Tilling, Andy Ridout and Andrew Shepherd wrote the paper. All authors commented on the text.

**Competing Financial Interests statement**

The authors of this paper do not have any competing financial interests, in relation to the work described.

## Figure Legends

Figure 1: Northern hemisphere sea ice thicknesses as measured by CryoSat-2, from 2010-2014. Thicknesses are shown at 50°N and above, where the majority of ice is located. (a-e) Average autumn (October/November) thicknesses for 2010-2014. (f-i) Average spring (March/April) thicknesses for 2011-2014.

Figure 2: Observed and modelled northern hemisphere sea ice volume, from 2010-2014. Cryosat-2 estimates of total (red stars), first-year (green diamonds) and multi-year (blue triangles) sea ice volume are shown, as well as model estimates of volume from PIOMAS. To estimate uncertainties in CryoSat-2 monthly sea ice volume, we account for uncertainties in the sea ice density, snow density, snow depth, and the measurement of sea ice freeboard.

Figure 3: The relationship between Arctic sea ice volume and summer melting. (a) Time series of PIOMAS model arctic sea ice volume for autumn 1980-2014 (solid line) and spring 1981-2014 (dashed line). CryoSat-2 volume estimates (red stars) are plotted for 2010-2014. (b) Time series of average melting degree days ($M_{DD}$) across the Arctic Ocean for 1980-2014 (solid purple line), and CryoSat-2 autumn ice volume for 2010-2014 (red stars). The $M_{DD}$ time series mean (solid black line) and standard deviation (dashed black lines) are shown. (c) The relationship between anomalies of CryoSat-2 autumn ice volume and the number of $M_{DD}$ during the preceding year, for first-year ice (green diamonds; $r^2 = 0.12$), multi-year ice (blue triangles; $r^2 = 0.78$) and total ice (red stars; $r^2 = 0.75$).

## Tables

Table 1: Average CryoSat-2 Arctic sea ice volume ($10^3$ $km^3$) for autumn (October/November) 2010-2014 and spring (March/April) 2011-2014. To estimate uncertainties in monthly sea ice volume, we account for uncertainties in the sea ice density, snow density, snow depth, and the measurement of sea ice freeboard. The autumn and spring uncertainties are the averaged uncertainties of their corresponding months.

| Year | Volume (MYI) | | Volume (FYI) | | Volume (total) | |
|---|---|---|---|---|---|---|
| | Autumn (Oct/Nov) | Spring (Mar/Apr) | Autumn (Oct/Nov) | Spring (Mar/Apr) | Autumn (Oct/Nov) | Spring (Mar/Apr) |
| 2010-2011 | 5.34 ± 0.69 | 7.64 ± 0.94 | 3.69 ± 0.59 | 17.99 ± 2.44 | 9.03 ± 1.28 | 25.63 ± 3.37 |
| 2011-2012 | 3.75 ± 0.56 | 5.72 ± 0.71 | 4.11 ± 0.63 | 19.57 ± 2.66 | 7.86 ± 1.19 | 25.29 ± 3.36 |
| 2012-2013 | 3.70 ± 0.48 | 6.23 ± 0.80 | 4.05 ± 0.62 | 18.20 ± 2.53 | 7.75 ± 1.10 | 24.43 ± 3.32 |
| 2013-2014 | 6.95 ± 0.82 | 9.63 ± 1.12 | 3.99 ± 0.61 | 16.96 ± 2.29 | 10.94 ± 1.43 | 26.59 ± 3.41 |
| 2014-2015 | 6.18 ± 0.73 | - | 4.08 ± 0.62 | - | 10.26 ± 1.34 | - |

## Methods

### *Sea ice thickness and volume methods*

We compute changes in northern hemisphere sea ice freeboard, thickness and volume using CryoSat-2 Level-1B synthetic aperture radar (SAR) and SAR interferometer (SARIn) altimeter mode observations (available at https://earth.esa.int/web/guest/data-access, or via an ftp client at ftp://science-pds.cryosat.esa.int). In this study, altimeter measurements are not restricted to the central Arctic region, as has been done in the past[12, 22]. Instead, the region of interest extends as far south as 40°N to ensure that the formation and drift of sea ice into lower latitudes is not excluded from our analysis.

First we estimate sea ice freeboard above the ocean surface. We assume that the radar pulses penetrate through any snow cover on ice floes and scatter from the snow-ice interface. This assumption is consistent with laboratory experiments[29] where the snow cover on sea ice is cold and dry, as is the case during Arctic winter. Despite some evidence that the scattering horizon migrates as temperature rises[30], we do not observe any bias in our thickness retrieval when compared to year-round ice draft data, and so we conclude that the impact of this effect is not significant. We discriminate between elevation measurements of the ice and ocean surfaces by analysing the shape of the returned echoes; diffuse echoes originate from rough surfaces such as ice floes, whereas specular echoes originate from the smooth, mirror-like leads between the floes[31]. This discrimination is achieved by examining the echo “pulse peakiness” and “stack standard deviation” parameters[12], and elevations to the ice and ocean surfaces are then calculated. We compute freeboard for each waveform classed as containing ice floes by subtracting the interpolated ocean surface elevation at the floe location from the elevation of the ice surface. 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[14].

To convert ice freeboard to thickness, we assume that the sea ice floats in hydrostatic equilibrium. This calculation requires assumptions about the densities of sea ice, seawater and snow, and on the snow depth. We use values of 916.7 kg m$^{-3}$ and 882.0 kg m$^{-3}$ for the densities[15] of first-year ice (FYI) and multi-year ice (MYI), respectively, and we use Norwegian Meteorological Service Ocean and Sea Ice Satellite Application Facility (OSI SAF) data (available at http://www.osi-saf.org/) to classify ice (for each individual freeboard) into these two categories. Seawater density[16] is set at 1023.8 kg m$^{-3}$. Snow density and depth values are obtained from a monthly climatology[14] compiled from *in situ* measurements collected over MYI in the central Arctic from 1954-1991, with a twodimensional quadratic function fitted to all measurements to represent the spatial variability of snow characteristics. However, these quadratic functions are not constrained at latitudes below 70°N, so we use the mean climatology values of snow depth and density at latitudes above 70°N 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[17, 32]. Therefore we halve the snow depth on FYI[17] to account for reduced snow accumulation. Areas of open water within the sea ice pack are removed from our thickness calculations using daily values of passive microwave sea ice concentration data[18]. We then average thickness and concentration values during each calendar month on a 0.1 by 0.5 degree grid. The sea ice margin is defined by applying a 15% sea ice concentration mask using data from the 15$^{th}$ day of each month, and monthly changes in sea ice volume are calculated by taking the product of the ice thickness excluding open water, the ice concentration, and the ice area.

***Sea ice volume error***

We estimate monthly errors[33] in sea ice volume by considering the contributions due to uncertainties in snow depth (4.0 to 6.2 cm), snow density (60.0 to 81.6 km m$^{-3}$), sea ice density (7.6 km m$^{-3}$), sea ice concentration (5%) and sea ice extent (20,000 to 30,000 km$^{2}$). Uncertainties in seawater density and in Arctic-wide measurements of sea ice freeboard have a negligible impact on the sea ice volume error budget. Year-to-year errors in sea ice volume are typically about 13.5%, with a slight variation from month to month (Supplementary Table 1).

First, we compute, numerically, the monthly rate of change of volume with respect to each source of error. We then multiply these computed rates by an estimate of the error in each parameter in question to estimate the partial contributions to the total volume error. Taking snow depth as an example, we compute the volume time series seven times, changing the snow depth on each freeboard measurement by -6cm, -4cm, -2cm, 0cm +2cm, +4cm and +6cm. This allows us to compute the monthly rate of change of volume per centimetre change in snow depth. We then multiply this rate by a monthly estimate of the error in snow depth to estimate the contribution to error in sea ice volume. Supplementary Table 1 illustrates the contribution of each significant error source to the total estimated sea ice volume error in two months (October and April). 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 (Supplementary Table 1).

Uncertainties in snow depth and in snow density are taken from a climatology[14] derived from fieldwork measurements acquired between 1954 and 1991. This climatology provides, as an error estimate, the standard deviation of snow depth and density in each calendar month. These errors are likely to be an overestimate, due to the sparse spatial and temporal sampling of the measurements.

Uncertainties in sea ice density (FYI and MYI) are based on measurements acquired during the Sever expeditions[34]. These data consist of mean values of sea ice freeboard, sea ice thickness and snow depth on sea ice runways used for 689 aircraft landings between 1982 and 1988. We calculate the ice density associated with each of these measurements by setting the densities of seawater and snow to be 1025 kg $m^{-3}$ and 324 kg $m^{-3}$, respectively, following the method of Alexandrov and colleagues[15]. Densities falling outside the range 860 to 970 kg $m^{-3}$ are considered unrealistic and are discarded, and we also discard monthly averages where fewer than four measurements were available. Unlike the snow climatology, average sea ice densities are not available for all months as the Sever expedition only ran in the spring. We therefore set the ice density uncertainty as the standard deviation of all available monthly averages, of which there are 18. This results in an uncertainty of 7.6 kg $m^{-3}$. This value is likely to be an overestimate of the true uncertainty due to under-sampling, as was the case with the snow depth and density uncertainties.

NSIDC quote a figure of 5% for the uncertainty in their sea ice concentration values http://nsidc.org/data/docs/daac/nsidc0051_gsfc_seaice.gd.html). As they do not estimate the distance over which the concentration uncertainty is correlated, we assume, conservatively, that it is correlated over the entire northern hemisphere for each month. The contribution of sea ice concentration uncertainty to the total sea ice volume uncertainty is complicated, because we use the concentration data at two stages of our processing – to discriminate between radar echoes returning from ice floes and open water, and to weight our volume calculation according to the density of leads within the sea ice pack. Therefore, sea ice concentration is the one source of uncertainty for which we do not calculate a monthly rate of change of sea ice volume with respect to. Instead, we estimate the uncertainty in volume due to a 5% error in concentration. To do this we recomputed the volume time series twice for each month. In the first case we lowered the sea ice concentration at every location by 5% and removed from the processing any ice floes where the concentration fell below the threshold of 75%. In the second case we raised the sea ice concentration by 5% at every location, but capped it at 100%. We then estimated the monthly volume error as half the difference between these two recomputed volume time series.

Uncertainties in sea ice extent are taken from the data authors (http://nsidc.org/arcticseaicenews/faq/#error_bars). NSIDC estimate sea ice extent as the region where its' concentration exceeds 15%, and they estimate the relative (year-to-year) error as approximately 20,000 to 30 000 km$^2$ - a small fraction (0.1 to 0.5%) of the total extent. To estimate the rate of change of sea ice volume with respect to sea ice extent, we recomputed sea ice volume in winter using ice extent masks for each month that were a few days too early and then a few days too late, respectively. From these additional estimates, we were able to compute the monthly rate of change of sea ice volume with respect to ice extent and hence to assess the impact of this on its error (Supplementary Table 1). At 0.25% or less, the error in sea ice volume associated with year-to-year uncertainties in sea ice extent is insignificant. At sub-annual timescales, it is important to consider seasonal biases in sea ice extent when charting variability. During the period of sea ice freeze up, sea ice extent could be consistently underestimated by as much as 1 million km$^2$ (http://nsidc.org/arcticseaicenews/faq/#error_bars). Although the effect of this uncertainty on the volume error is not insignificant (Supplementary Table 1), it is does not affect year-to-year comparisons, and so we have not included this in our error budget, which is designed to illuminate uncertainties in inter-annual trends.

Uncertainties in seawater density have a negligible impact on the uncertainty in sea ice volume[20, 35]. Although individual freeboard measurements have a standard deviation of about 1 metre, we typically include more than 1 million observations in each estimate of monthly volume, and the impact of this variability is also negligible.

**Data Sources**

CryoSat Level 1B radar altimeter data (ftp://science-pds.cryosat.esa.int)

Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations (http://nsidc.org/data/NSIDC-0081)

OSI SAF sea ice type maps (http://osisaf.met.no/p/ice/#type)

NASA IceBridge Sea Ice Freeboard, Snow Depth, and Thickness Quick Look [*Thickness*] (http://nsidc.org/data/docs/daac/icebridge/evaluation_products/sea-ice-freeboard-snowdepth-thickness-quicklook-index.html)

NASA IceBridge Sea Ice Freeboard, Snow Depth, and Thickness [*Thickness*] (http://nsidc.org/data/IDCSI2)

WHOI Beaufort Gyre Exploration Project mooring data [*Sea ice Draft*] (http://www.whoi.edu/page.do?pid=66559)

ECMWF ERA Interim data [*Evaporation and Total Precipitation, Daily*] (http://apps.ecmwf.int/datasets/data/interim-full-daily/?levtype=sfc)

IABP Drifting Buoy Pressure, Temperature, Position, and Interpolated Ice Velocity [*Interpolated Ice Velocity*] (ftp://iabp.apl.washington.edu/pub/IABP/)

PIOMAS model Daily Ice Volume Data, (http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/data)

NSIDC Sea Ice Index (http://nsidc.org/data/G02135)

SEVER Aircraft Landing Observations from the Former Soviet Union [*Sea ice Density*] (http://nsidc.org/data/g02140)

CPOM CryoSat-2 operational polar monitoring [*Sea Ice thickness and volume*] (http://www.cpom.ucl.ac.uk/csopr/seaice.html)

**References**


29. Beaven, S.G. *et al.* Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets. *International Journal of Remote Sensing* **16**, 851-876 (1995).
30. Willatt, R.C., Giles, K.A., Laxon, S.W., Stone-Drake, L. & Worby, A.P. Field investigations of Ku-band radar penetration into snow cover on Antarctic sea ice. *Ieee Transactions on Geoscience and Remote Sensing* **48**, 365-372 (2010).
31. Peacock, N.R. & Laxon, S.W. Sea surface height determination in the Arctic Ocean from ERS altimetry. *Journal of Geophysical Research-Oceans* **109**, C07001 (2004).
32. Webster, M.A. *et al.* Interdecadal changes in snow depth on Arctic sea ice. *Journal of Geophysical Research-Oceans* **119**, 5395-5406 (2014).
33. Giles, K.A. *et al.* Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002. *Remote Sensing of Environment* **111**, 182-194 (2007).

34. Romanov, I.P. in Morphometric Characteristics of Ice and Snow in the Arctic Basin: Aircraft Landing Observations from the Former Soviet Union, 1928-1989 (National Snow and Ice Data Center. Boulder, Colorado USA; 2004).

35. Ricker, R., Hendricks, S., Helm, V., Skourup, H. & Davidson, M. Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation. *Cryosphere* **8**, 1607-1622 (2014).