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About uncertainties in sea ice thickness retrieval from satellite radar altimetry: results from the ESA-CCI Sea Ice ECV Project Round Robin Exercise

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Abstract

One goal of the European Space Agency Climate Change Initiative sea ice Essential Climate Variable project is to provide a quality controlled 20 year long data set of Arctic Ocean winter-time sea ice thickness distribution. An important step to achieve this goal is to assess the accuracy of sea ice thickness retrieval based on satellite radar altimetry. For this purpose a data base is created comprising sea ice freeboard derived from satellite radar altimetry between 1993 and 2012 and collocated observations of snow and sea ice freeboard from Operation Ice Bridge (OIB) and CryoSat Validation Experiment (CryoVEx) air-borne campaigns, of sea ice draft from moored and submarine Upward Looking Sonar (ULS), and of snow depth from OIB campaigns, Advanced Microwave Scanning Radiometer aboard EOS (AMSR-E) and the Warren Climatology (Warren et al., 1999). An inter-comparison of the snow depth data sets stresses the limited usefulness of Warren climatology snow depth for freeboard-to-thickness conversion under current Arctic Ocean conditions reported in other studies. This is confirmed by a comparison of snow freeboard measured during OIB and CryoVEx and snow freeboard computed from radar altimetry. For first-year ice the agreement between OIB and AMSR-E snow depth within 0.02 m suggests AMSR-E snow depth as an appropriate alternative. Different freeboard-to-thickness and freeboard-to-draft conversion approaches are realized. The mean observed ULS sea ice draft agrees with the mean sea ice draft computed from radar altimetry within the uncertainty bounds of the data sets involved. However, none of the realized approaches is able to reproduce the seasonal cycle in sea ice draft observed by moored ULS satisfactorily. A sensitivity analysis of the freeboard-to-thickness conversion suggests: in order to obtain sea ice thickness as accurate as 0.5 m from radar altimetry, besides a freeboard estimate with centimetre accuracy, an ice-type dependent sea ice density is as mandatory as a snow depth with centimetre accuracy.

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1 Introduction

As part of the European Space Agency (ESA) Climate Change Initiative (CCI) sea ice Essential Climate Variable (ECV) project quality-controlled long-term data sets of sea ice thickness and concentration will be derived from Earth observation data. The product of sea ice thickness and sea ice area is the sea ice volume which is considered to be among the most sensitive indicators of the amplification of Climate change in the Arctic (Schweiger et al., 2011; Zhang et al., 2012; Krinner et al., 2010; Stranne and Björk, 2012; Wadhams et al., 2012).

The main data source for the calculation of the sea ice thickness is satellite radar altimetry. It has been shown by Laxon et al. (2003) that European Remote Sensing Satellite (ERS) 1/2 radar altimeter (RA) data can be used to obtain a first estimate of the Arctic Ocean sea ice thickness. More recently Envisat and CryoSat-2 radar altimetry has been used to compute sea ice thickness (Giles et al., 2008; Laxon et al., 2013). A number of studies has been dedicated to the evaluation of the retrieved sea ice freeboard and its derived thickness product, e.g. (Laxon et al., 2003; Giles and Hvidegaard, 2006; Giles et al., 2007; Connor et al., 2009). Yet to be calculated and evaluated is the sea ice thickness retrieved from the combined time series of ERS-1/2 RA data and Environmental Satellite (Envisat) radar altimeter-2 (RA-2) data covering the period 1993 to 2012.

Sea ice thickness can be obtained with other methods than radar altimetry. The Ice Cloud and Elevation Satellite (ICESat) with its Geophysical Laser Altimeter System (GLAS) allowed computing sea ice thickness from laser altimetry for up to three periods each of about one month duration every year for years 2003 to 2009 (Kwok et al., 2009). Methods using active or passive microwave satellite sensor data (e.g. Kwok et al., 1995; Martin et al., 2004; Kaleschke et al., 2012) or using infrared satellite sensor data (e.g. Yu and Rothrock, 1996) do not allow computation of Arctic wide sea ice thickness distribution. These methods are limited in the maximum thickness to be retrieved, which

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is less than a meter, and can additionally be hampered by clouds. Note that also laser altimetry is influenced by clouds.

Ground-based, submarine-based, moored, and airborne sensors provide precise information about sea ice thickness, either directly or via measurement of sea ice freeboard or snow (sea ice plus snow) freeboard or sea ice draft. Such data form the basis of our current understanding of Arctic Ocean sea ice volume loss (Rothrock et al., 2008; Lindsay, 2010; Haas et al., 2008, 2011; Schweiger et al., 2011, Wadhams et al., 2011). On the one hand this data has a limited spatial-temporal coverage on contrast to satellite remote sensing data. On the other hand this data is extremely valuable for the validation of the satellite sea ice thickness products.

Within the ESA CCI sea ice ECV project a selection of the most suitable retrieval methods and the most appropriate input data sets is carried out using the so-called Round Robin Exercise (RRE). This exercise is based on the analysis of data compiled in the so-called Round Robin Data Package (RRDP). The RRDP comprises ERS-1/2 and Envisat radar altimeter data, input data required to convert sea ice freeboard into sea ice thickness and validation data of sea ice thickness, freeboard and draft as well as snow depth and snow freeboard. One important part of this exercise is the investigation of the quality of the data used and an estimation of the sensitivity of the methods used to the input parameters.

The paper is organized as follows: Sect. 2 describes the RRDP. Section 3 describes the methods used. In Sect. 4 we present the results of our analyses. These are discussed in Sect. 5 and concluded in Sect. 6.

2 Data

This paper is based on data of the RRDP. These can be divided into two groups. The first group is used for the sea ice thickness retrieval and comprises ERS-1/2 RA and Envisat RA-2 sea ice freeboard data, snow depth data from the Warren climatology, henceforth abbreviated with W99, which also provides estimates of the snow density

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(Warren et al., 1999), and snow depth data from Advanced Microwave Scanning Radiometer aboard Earth Observation Satellite (AMSR-E) and Operation Ice Bridge (OIB) campaign flights. The second group of data comprises the test and validation data for the RRE. These are basically data from moored, submarine, and airborne sensors
5 a listed in Table 1.

2.1 Data for sea ice thickness retrieval

Sea ice freeboard data are derived from ERS-1/2 RA and Envisat RA-2 data using the methodology introduced in (Laxon et al., 2003; Giles et al., 2008) and described in detail in (SICCI ATBD). To shortly recap, elevation measurements from leads and
10 ice floes are distinguished based on the pulse peakiness of the waveform. After re-tracking the range and applying necessary corrections (namely the Doppler range and delta Doppler, the ionospheric, the dry tropospheric and the modelled wet tropospheric, ocean tide, long-period tide, loading tide, earth tide, pole tide and inverse barometer corrections), and filters (removal of complex waveforms, failed re-tracking and echoes
15 that yielded elevations more than 2 m from the mean dynamic sea surface height) the local sea level at ice floe locations is interpolated from nearby lead elevations. Freeboard is then calculated as the difference of radar altimetry measured ice floe elevation and the local sea level. Individual radar altimeter freeboard measurements are present in the RRDP data base. However, because the freeboard measurement is known to be
20 noisy, averaging several measurements is required. For the RRDP freeboard estimates are averaged into a $2^\circ \times 0.5^\circ$ grid over one calendar month. Depending on the latitude, this results into about 20–150 measurements per grid cell.

W99 snow depth and density data is available as climatological monthly values for a given location. These are calculated individually for each radar altimeter freeboard
25 estimate and averaged over the same area and time as the freeboard data. Due to distribution of freeboard measurements not being even over the averaging area, the W99 snow estimates used here are different from W99 estimates in the centre of the

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averaging area. However, given the climatological nature of W99, this difference is negligible.

Figure 1 provides an overview of collocated RA-2 and W99 data for the Arctic Ocean for March and April 2010. The majority of the RA-2 sea ice freeboard values are in a reasonable range and only a few grid cells have negative sea ice freeboard (flagged black in Fig. 1a and b). The W99 snow depth (Fig. 1c and d) shows reasonable values for the Arctic Ocean. For the Bering Sea, the Hudson Bay, the Baffin Bay and parts of the Canadian Archipelago a decrease in W99 snow depth from March to April can be observed together with a strong north-south gradient in the Baffin Bay. Figure 1e and f illustrates that W99 provides reasonable snow densities for the Arctic Ocean but reveals an unrealistic north-south gradient and snow densities less than 150 kg m^{-3} for large regions outside the Arctic Ocean, e.g. the Baffin Bay.

AMSR-E snow depth on sea ice data for the Arctic are taken from the AMSR-E/Aqua Daily L3 12.5 km Brightness Temperature, Sea Ice Concentration, & Snow Depth Polar Grids product available from NSIDC (Cavalieri et al., 2004; http://nsidc.org/data/docs/daac/ae_si12_12km_tb_sea_ice_and_snow.gd.html). This data is provided at 12.5 km grid resolution as running 5 day mean and is limited to snow depth below 0.45 m on seasonal ice (Markus and Cavalieri, 1998; Comiso et al., 2003). The algorithm is sensitive to sea ice roughness (Worby et al., 2008, Ozsoy-Cicek et al., 2011; Kern et al., 2011) as well as snow wetness and grain size (Maksym and Markus, 2008; Markus and Cavalieri, 1998). Recently, AMSR-E snow depth data set quality has been assessed for the Arctic (Cavalieri et al., 2012; Brucker and Markus, 2013). A comparison between OIB snow depth and AMSR-E snow depth for about 600 12.5 km grid cells between 2009 and 2011 (Brucker and Markus, 2013) indicated a basin average bias of up to 0.07 m and RMSE values between 0.03 m and 0.15 m. Under ideal conditions, i.e., for high concentration ($> 90 \%$) level first-year ice (FYI) thicker than 0.5 m the RMSE was below 0.06 m for an on average 0.2 m thick snow cover (Brucker and Markus, 2013). For our study, AMSR-E snow depth is collocated with RA sea ice freeboard by averaging data over a calendar month over a circular area with a 100 km radius centred at

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each RA sea ice freeboard grid cell; for OIB data a 100 km radius is used and for BGEF a 12° by 30° latitude-longitude box.

2.2 Data for sea ice thickness validation and algorithm selection

The combination of a laser scanner and snow radar or a radar altimeter provides simultaneous collocated snow depth, snow freeboard and sea ice freeboard data. The laser scanner senses the snow surface and is used to derive the snow (sea ice plus snow) freeboard – similar to the ICESat GLAS instrument – if the instantaneous sea surface height (SSH) is known. The snow radar directly measures snow depth on top of sea ice using the range difference between the reflections at the two interfaces ice–snow and snow–air. For a radar altimeter it is assumed that it provides the height of the ice–snow interface above the SSH: the sea ice freeboard, under dry snow and/or freezing conditions.

The RRDP includes a combination of CryoVEx laser scanner (ALS) and radar altimeter data (ASIRAS) measured snow freeboard and sea ice freeboard. ALS and ASIRAS data are taken from DTU Space, National Space Institute: <ftp://ftp2.spacecenter.dk/pub/ESACCI-SI/> and are averaged over 50 km transects of flight line. The collocated RA-2 data are averages of a circular area of 100 km radius centred at each ALS 50 km transect centre for end of April 2008 and beginning of May 2011. ALS data are used to derive snow freeboard (Hvidegaard and Forsberg, 2002) with an accuracy and a precision of independent measurements of about 0.1 m to 0.15 m. ASIRAS sea ice freeboard data are derived using a method similar to Ricker et al. (2012) and have an accuracy of 0.15 to 0.2 m for independent measurements.

The RRDP includes OIB laser scanner (Airborne Thematic Mapper, ATM) and snow radar measured snow freeboard and snow depth (Panzer et al., 2013; Kurtz et al., 2013). OIB data are taken from the NSIDC: <http://nsidc.org/data/icebridge/index.html> and are averaged over 100 km transect of flight line. The collocated RA-2 data are averages of a circular area of 100 km radius centred at each OIB 50 km transect centre for March 2009 and March and April 2010. Kurtz et al. (2013) summarize the uncer-

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tainty sources of OIB snow depth retrieval. They point out that the results of Farrell et al. (2012) are a bit too optimistic: 0.01 m uncertainty in snow depth, and instead suggest a snow depth uncertainty of 0.06 m in agreement with the uncertainty estimation of Kwok et al. (2011): 0.03 m to 0.05 m for snow depths between 0.1 and 0.7 m.

5 Minimum retrievable snow depth is 0.05 m.

Connor et al. (2009) report an agreement of within 0.01 m between ATM measured snow freeboard and sea ice freeboard for bare thin sea ice. Problems identified with the automatic SSH retrieval from ATM data alone for 2009 (Nathan Kurtz, personal communication, 2013) were mitigated starting with the 2010 OIB data by including contemporary digital imagery (Onana et al., 2013). In conclusion, for the bulk of the OIB ATM freeboard the bias can be expected to be close to zero with an accuracy of between 0.05 m and 0.1 m (Farrell et al., 2012; Kurtz et al., 2013). This is confirmed by a study of Kwok et al. (2012) who found agreement between ICESat and OIB-ATM freeboards of within 0.01 m and a measurement repeatability of about 0.04 m.

15 Upward looking sonar (ULS) observes sea ice draft which can be converted into sea ice thickness in a similar way as the sea ice freeboard. In the RRDP we use data from the Beaufort Gyre ExPeriment (BGEP) where three, sometimes four moored ULS measured sea ice draft. The approximate location of these moorings is denoted by the diamond in Fig. 2. BGEP ULS data are taken for years 2003 to 2008 from WHOI:
20 <http://www.whoi.edu/page.do?pid=66559>. Accuracy of the data is estimated by Krishfield and Proshutinsky (2006) to be between 0.05 m and 0.1 m. This data is extremely valuable as it provides an independent measure of the seasonal cycle of sea ice draft and thus thickness. Another source of ULS data in the RRDP are those carried onboard submarine. Submarine ULS draft data were successfully used by Laxon et al. (2003)
25 for a first assessment of Arctic Ocean sea ice thickness distribution obtained from ERS-1/2 data. The RRDP contains submarine ULS data from three cruises. Data from two of the cruises from US submarines (April 1994 and October 1996) are available from NSIDC: <http://nsidc.org/data/g01360.html>. Data from the third cruise from a UK submarine (March/April 2007) are available from University of Cambridge (UCAM), see

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also (Wadhams et al., 2011). Submarine ULS data are in general less accurate than the BGEF data but are the only information about draft distribution over a larger region. Rothrock and Wensnahan (2007) report a bias of 0.29 m and a standard deviation of 0.25 m. An assessment of the UK submarine data used in the RRDP reveals a standard deviation of 0.29 m and a bias of 0.4 m; these numbers are worse compared to the US submarine data due to classified submarine positions.

3 Methods

It is assumed that satellite radar altimetry measures the sea ice freeboard. By assuming isostasy, sea ice freeboard can be used to compute sea ice thickness z_i as follows:

$$z_i = \frac{z_s \rho_s + f_b \rho_w}{\rho_w - \rho_i} \quad (1)$$

with snow depth z_s , sea ice freeboard f_b , and the densities of sea water, sea ice and snow: ρ_w , ρ_i , and ρ_s , respectively. Figure 3 illustrates the parameters used in Eq. (1).

The main objectives of the RRE are

- To characterize the uncertainties in the sea ice thickness product based on the uncertainties of the input parameters.
- To evaluate Eq. (1) for freeboard-to-thickness conversion.
- To select the best snow depth (product) for freeboard-to-thickness conversion.
- To investigate validity and influence of retrieval assumptions, like using constant sea ice density, on the sea ice thickness retrieval.

In order to achieve these goals the following investigations were carried out:

1. Snow depth data of the different data sets involved are inter-compared.

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2. RA-2 sea ice freeboard is converted to snow freeboard and compared with OIB and CryoVEx snow freeboard.
3. RA and RA-2 sea ice freeboard is used to compute sea ice draft using different input data and compared to ULS sea ice draft data.
4. RA-2 sea ice freeboard is used to compute sea ice thickness with Eq. (1) using variable sea ice density and/or snow depth (Kurtz and Farrell, 2011; Laxon et al., 2013) and is also compared with OIB data.

For the standard computations as given above under (3) and (4) the following values are used: $\rho_i = 900 \text{ kg m}^{-3}$ and $\rho_w = 1030 \text{ kg m}^{-3}$. For multiyear and first-year ice we use sea ice densities published elsewhere (e.g., Timco and Frederking, 1996; Alexandrov et al., 2010): 882 kg m^{-3} and 917 kg m^{-3} , respectively. Snow density varies over space and time in the W99 data set (see Fig. 1 e, f). For (3) we additionally use snow density values of 240 kg m^{-3} and 340 kg m^{-3} . Note that the sea ice and water density values differ from those used, e.g., in Kwok et al. (2009) for sea ice thickness retrieval using ICESat data: $\rho_i = 925 \text{ kg m}^{-3}$ and $\rho_w = 1024 \text{ kg m}^{-3}$. Depending on the type of sensor, laser or radar altimeter, the retrieved sea ice thickness is sensitive to the choice of snow and ice density as well as snow depth (e.g., Kwok et al., 2009, Kwok and Cunningham, 2008, Spreen et al., 2006; Alexandrov et al., 2010; Giles et al., 2007; Forstrom et al., 2011). For sea ice thickness retrieval using CryoSat-2 radar altimetry data Laxon et al. (2013) varied sea ice density with ice type and snow density according to W99.

4 Results

In the following we present the results of comparing the various data sets. We start with snow depth and (sea ice) freeboard and then continue with sea ice draft and thickness.

4.1 Snow depth

Snow depth is crucial for sea ice thickness estimation from altimeter data. Figure 4 shows snow depth data available for CryoVEx (Fig. 4a and c) and from OIB data (image b) in the Fram Strait area. Because ASIRAS and ALS both sensed the snow–air interface (see discussion below) no additional snow depth observations other than W99 and those retrieved using AMSR-E data over FYI are available for 2008 and 2011. Mean snow depth values given underneath Fig. 4 illustrate that W99 snow depth values are more than twice as large as OIB or AMSR-E snow depths.

Figure 5 shows the distribution of OIB snow depth (image a) and its difference to W99 (Fig. 5c) and AMSR-E (image e) snow depths for 2010 for the Arctic Ocean. It illustrates that over FYI (Fig. 5e) OIB and AMSR-E snow depth agree within 0.05 m while OIB underestimates W99 snow depth over FYI by about 0.21 m and over MYI by about 0.11 m (Fig. 5c). These results are summarized in Table 2 together with the results for 2009. In 2009 OIB underestimates W99 snow depth over FYI by a similar amount to 2010: 0.19 m while the agreement with W99 snow depth over MYI is much better with a difference of just 0.02 m. Figure 5e illustrates that two different regimes of FYI are covered in 2010, one in the Arctic Ocean and one in the Canadian Archipelago. We investigated data from these two regions separately because of the potentially different sea ice and snow properties.

The right hand column of images in Fig. 5 compares snow depth over FYI of the Arctic Ocean, obtained from AMSR-E with OIB snow depth. Figure 5b suggests that W99 snow depths are twice as large as AMSR-E ones; the difference is 0.18 m (Table 2). However, even though AMSR-E and OIB snow depths seem to agree well, a linear regression analysis points to a correlation of -0.121 , i.e. a poor agreement. Figure 5d suggests two different snow density regimes. Agreement improves substantially when we limit the comparison to data pairs with W99 snow density above 320 kg m^{-3} with a correlation of 0.83, a slope of 1.19 and bias of 0.0 m. AMSR-E snow depth retrieval reliability increases with increasing FYI fraction. Figure 5f illustrates how much the FYI

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fraction varies for the data set considered. If we limit the comparison to cases with > 95 % FYI fraction, agreement between AMSR-E and OIB snow depth increases substantially compared to using all data pairs, with a correlation of 0.76, a slope of 0.74, a bias of 0.06 m and a mean difference of 0.03 m. We carried out the same procedure for the OIB 2009 data (maps and graphs not shown) with similar results: the correlation increases from 0.33 to 0.81 (snow density limitation) and 0.70 (FYI fraction limitation), slope and bias of the regression line change from 0.12 and 0.14 m to 1.00 and 0.01, respectively, and the mean difference is 0.01 m.

Our comparison of OIB and AMSR-E snow depth for the Canadian Archipelago results in a similar picture. The agreement between OIB and AMSR-E snow depth is already quite reasonable: the correlation is 0.70 and the mean difference is 0.01 m (see Table 2, rightmost column), however slope and bias of the linear regression are 0.43 and 0.08 m. A limitation to certain W99 snow density values cannot be done because all density values are essentially the same. A limitation to FYI fraction > 95 % would not change the regression results. In addition, the land-spill over effect, i.e. grid cells with contributions from both sea ice and land to the measured brightness temperatures which can influence AMSR-E snow depth retrieval was investigated by means of the land fraction per 100 km grid cell. A limitation to grid cells with low or zero land fraction would not improve the result of the regression. Note that in this region the W99 snow depth and density values are less based on measurements themselves but rather a product of an extrapolation of Arctic Ocean values. The W99 values given in Table 2 for the Canadian Archipelago should therefore not be over-interpreted.

The results of our snow depth comparison agree with Kurtz and Farrell (2011) and Kurtz et al. (2013): over FYI AMSR-E data give a much better measure of the actual snow depth than W99; the latter are about twice as large as AMSR-E and OIB snow depths over FYI. Over MYI, OIB and W99 differ by only 0.02 m in 2009 but by 0.12 m in 2010. Only grid cells with at least 65 % MYI have been used here. One possible explanation for the different degree of agreement could be inter-annual variation in

snow depth over MYI. While in 2009 OIB snow depth was 0.36 m it was just 0.23 m in 2010. Mean W99 snow depth was 0.35 m and 0.34 m, respectively.

4.2 Sea ice and snow freeboard

During the CryoVEx campaigns in 2008 and 2011 in the Fram Strait ASIRAS and ALS essentially sensed the snow surface. Radar penetration into the snow cover on sea ice in the Fram Strait during CryoVEx campaigns was close to zero although the radar is supposed to sense the ice–snow interface. Both freeboard measurements (ASIRAS and ALS) linearly agreed with an RMSE of 0.02 m, a bias of about 0.05 m, a slope close to 1 and a linear correlation coefficient of 0.99 for 2008 and 2011. Therefore from CryoVEx only the snow freeboard measurements can be used for this study. For 2011, CryoVEx ALS snow freeboard underestimates RA-2 snow freeboard computed using W99 snow depth by 0.06 m; for 2008, this underestimation is about 0.16 m. These values are within the uncertainties given for the ALS data we note that. We look at 21 and 11 data pairs only, respectively, and that W99 data might be less reliable in the Fram Strait region because, like in the Canadian Archipelago, they are based on extrapolation rather than measurements (Warren et al., 1999).

Mean OIB snow freeboard in the Arctic Ocean agrees overall within 0.02 m with RA-2 snow freeboard computed from RA-2 sea ice freeboard when using collocated observed OIB snow depths (see Table 3). If instead W99 snow depth is used the agreement remains fine for 2009 but for 2010 RA-2 underestimates the overall mean OIB snow freeboard by 0.11 m. This is illustrated in the histograms shown in Fig. 6 and can be explained by the difference between OIB and W99 snow depth (see Sect. 4.1) but also by the different fraction of MYI in these data sets. For 2009 snow depth and snow freeboard are available from OIB only over MYI while for 2010 about one third of the OIB data were obtained over FYI (see Fig. 5). As shown in Sect. 4.1, OIB snow depth agrees much better with W99 snow depth over MYI than over FYI.

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4.3 Sea ice draft

The results of the comparison of sea ice draft between ULS and radar altimeter is summarized in Table 4. Sea ice draft observed by US submarine ULS in October 1996 is overestimated by ERS-1 RA by 0.13 m which is within the ULS uncertainty of 0.25 to 0.3 m. For April 1994, however, ERS-1 RA underestimates the observed sea ice draft by 0.45 m which is outside the uncertainty range given for these ULS data. This discrepancy is illustrated by Fig. 7c and d: while both data sets show maximum probability in the same draft bin of 1.5 to 2.0 m for 1996, the histograms are shifted relative to each other for 1994 with largest probability in bin 2.5 to 3.0 m for the ULS data but 2.0 to 2.5 m for RA data. The scatterplot in Fig. 7e underlines that the agreement is much better for 1996 than for 1994; in particular the RMSD for 1996 is less than half the one for 1994.

The sea ice draft as observed by UK submarine ULS in April 2007 is underestimated by RA-2 by 0.12 m (Table 4). However, the majority of this cruise took place north of the northern limit of RA-2 data coverage and therefore is based on only 15 data pairs, compared to about 90 and 40 for the US submarine cruises.

The mean winter sea ice draft observed by BGEP ULS agrees within 0.05 m with sea ice draft computed from RA-2 data using W99 snow depth and density and standard sea ice and water density values. However, the seasonal range in sea ice draft is much lower for RA-2 than for BGEP ULS (Table 4, Fig. 8). Only for winters 2005/2006 and 2006/2007 does the seasonal range of sea ice draft agree in both data sets. The area considered here was covered by almost 100 % MYI from 2003 to 2007 (first four winters), whereas FYI entered the region in winter 2007/2008. Therefore, for the first four winters, one might need to use the MYI density instead of the value of 900 kg m^{-3} . By doing so the RA-2 draft decreases by between 0.1 m and 0.4 m, depending on season and year. This results in a better agreement between BGEP ULS and RA-2 draft early in the winter season, but it does not improve agreement in the seasonal range. Note that usage of AMSR-E snow depth, possible for winter 2007/2008, results in RA-2 draft

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values that would be typical for 100 % MYI and a snow density of about 290 kg m^{-3} (see green dots in Fig. 8). However, AMSR-E snow depth can only be obtained over FYI so one might need to use the FYI density of 917 kg m^{-3} . This would shift the green dots by 0.3 m towards larger ice draft values and would thus cause a slightly better agreement between ULS and RA-2 drafts. More investigations are needed to confirm this.

4.4 Sea ice thickness

By using Eq. (1) sea ice thickness is computed from RA-2 data using different snow depth data sets and compared to OIB (2009, 2010) and to CryoVEx (2008, 2011) sea ice thickness observations. Snow depth data sets used are W99 only, W99 over MYI and $0.5 \times W99$ over FYI (Kurtz and Farrell (2011), henceforth abbreviated KF11), OIB only, and W99 over MYI but AMSR-E over FYI. The results of this comparison are summarized in Table 5 for the Arctic Ocean and in Table 6 for the Fram Strait.

For the Arctic Ocean, for OIB 2009 data none of the four snow data sets reveals a sea ice thickness correlated with the observed one better than 0.54. Using OIB snow depth gives the highest correlation and the smallest RMSE of 0.73 m; largest RMSE and lowest correlation is obtained using W99: 1.12 m and 0.29, while using the other two snow data sets results in values between those. For the Arctic Ocean for OIB 2010 data again using OIB snow depth gives highest correlation and smallest RMSE, however, agreement is worse than for 2009: 0.18 and 1.16 m (see Table 5). Practically no correlation is obtained with the observed sea ice thickness when using the other snow data sets. This is illustrated by Fig. 9 which shows scatter plots of the sea ice thickness computed using the mentioned snow depth data sets vs. the observed sea ice thickness during OIB for 2010. Note that if we would restrict the replacement of W99 by AMSR-E snow depth values to grid cells with 90 % FYI fraction or more would most likely not make any difference because the data pairs with high FYI fraction (red/brown dots in Fig. 9b and d) do not align along the 1-to-1 relationship line. Using W99 in combination with AMSR-E and KF11 results in a similar statistics because AMSR-E

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March 2005) between draft calculated from RA-2 sea ice freeboard with typical FYI density and typical MYI density.

The W99 snow depth is twice as large as OIB snow depth over FYI. This is confirmed by AMSR-E snow depth estimates, agreeing with OIB snow depth within 0.02 m. This confirms the results of Kurtz and Farrell (2011) and Kurtz et al. (2013). There is also an indication that even over MYI W99 might be over-estimating the actual snow depth, as is the case for April 2010. More snow depth inter-comparisons are required to further investigate this finding. The Envisat RA-2 sea ice freeboard obtained in the Arctic Ocean agrees within 0.02 m with OIB snow freeboard when OIB snow depth is added. This is better than the accuracy of 0.05 m which is given for RA-2 and OIB freeboard data (Kurtz et al., 2013). We are not able to carry out a similar comparison with ERS-1/2 data. We note that the discrepancy between the draft data obtained for the two US submarine cruises (Sect. 4.3) could partly be caused by a W99 snow depth that does not match the actual snow depth. Also a mismatch between snow densities can contribute to the observed discrepancy (see next paragraph).

An investigation of the W99 snow density was not carried out and this may be an important factor regarding the difference between using W99 or other snow observations to derive the sea ice thickness. According to the W99 climatology and other studies, e.g. Alexandrov et al. (2010), the snow density varies seasonally. Fresh snow has very low densities, even less than 100 kg m^{-3} , while processes like snow compaction by wind and/or melt can increase the snow density substantially, e.g. to over 400 kg m^{-3} . In addition snow density can vary on short spatial scales. However, in this study satellite radar altimetry is used and therefore we deal with a spatial scale of 100 km and a temporal scale of a month. Therefore we feel confident to refer to Fig. 8 where the snow density is varied over the range of average snow densities known: 240 to 340 kg m^{-3} ; these are similar to the snow density range given in W99. The change in mean ice draft associated with a snow density change over this full range is about 0.2 to 0.3 m maximum. This translates into a possible bias in ice thickness of about 0.3 m. This is a substantial impact and therefore it is recommended to take into account

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the seasonally varying snow density when retrieving ice thickness from satellite radar altimetry.

Upward looking sonar data of the sea ice draft are compared with sea ice draft computed from radar altimetry sea ice freeboard using six different realizations of the freeboard-to-draft conversion which is similar to the freeboard-to-thickness conversion: one uses fixed ice density at 900 kg m^{-3} and W99 snow depth (A1); one used ice type dependent ice densities and parameterized W99 snow depth following (Laxon et al., 2013) (A2); one uses fixed first-year ice density at 910 kg m^{-3} combined with freeboard dependent multiyear ice density (Ackley et al., 1974) and W99 snow depth (A3); one uses fixed ice density at 900 kg m^{-3} with full and half W99 snow depth over multiyear and first-year ice, respectively (A4); one uses fixed multiyear and first-year ice snow depth and ice type dependent ice densities (Alexandrov et al., 2010) (A5); one follows the empirical approach for thick multiyear ice with including any snow depth (Wadhams et al., 1992) (A6). Table 7 summarizes the difference in the mean and median observed minus computed sea ice draft (SID) for the six realizations and the ULS data sets listed in Table 1.

The main conclusion from this comparison is that A1, A3 and A4 are agreeing equally well with the ULS SID data within their uncertainty bounds (about 0.3 m for BS and BSS and 0.05 m for BGEP), and that A5 and A6 show the largest discrepancies. Why is A2 (Laxon et al., 2013) biased low? Almost all ULS data are obtained under MYI. A2 uses a MYI density of 882 kg m^{-3} while A1 and A4 use 900 kg m^{-3} and A3 some other value. Such a difference in ice density can easily account for a negative bias in the obtained SID by 0.2 m (see Fig. 8). However, the good agreement between A1 and A4 with regard to the mean and median SID does not mean that these use the perfect input parameter combination. The agreement between observed and computed SID varies from month to month and RA-2 based monthly mean sea ice draft values do not very well capture the increase in sea ice draft during winter periods between 2003 and 2008; generally the increase in RA-2 draft is smaller than the increase in ULS draft. Draft was calculated from RA-2 data using W99 snow depth and density. If W99 snow depth

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is over-estimating actual snow depth and/or density at the beginning of winter and under-estimating actual snow depth and/or density at the end of winter, then sea ice thickness and consequently sea ice draft would be over-estimated during early winter and under-estimated during late winter. In this context sea ice density changes need to be taken into account. For winter 2007/08 the agreement between observed and calculated draft does not increase when using AMSR-E snow depth instead of W99 snow depth. However, AMSR-E snow depth retrieval is only possible properly over FYI and the green dots in Fig. 8 are computed with a sea ice density of 900 kg m^{-3} which is too low for FYI. If we use instead 917 kg m^{-3} (black lines in Fig. 8) the agreement between observed and calculated draft improves substantially. We note further that the area covered by the moorings used (A, B, C and D) is approximately 4° in latitude by 10° in longitude while the RA-2 draft is computed from an area of 12° in latitude by 30° in longitude. RA-2 draft data are thus averaged over an almost 10-fold larger area which could explain the smaller seasonal amplitude.

Our results with regard to sea ice thickness calculated from RA-2 sea ice freeboard suggest that using a contemporary measured snow depth, like from OIB, increases the correlation and decreases the RMSE between observed (OIB) and calculated (RA-2) mean sea ice thickness. A substantial over-estimation (under-estimation) occurs for thin (thick) sea ice. Using W99 alone results in the worst agreement in the few cases investigated. All these cases are from the period 2008 to 2011, a time period where the MYI fraction in the Arctic Ocean has substantially decreased compared to the time for which the W99 climatology can be considered valid (Comiso, 2012). If results from recent studies and approaches are considered (Kurtz and Farrell, 2011; Laxon et al., 2013) and a modified version of the W99 is used, the RMSE between OIB and RA-2 sea ice thickness decreases. In this context it is important to mention the different spatiotemporal scales which are involved. OIB data is obtained at fine spatiotemporal resolution along one transect. RA-2 data, as are used here, comprise all measurements over one month within at disc of 100 km diameter. In addition the footprint of a single RA-2 measurement is 1–2 orders of magnitude larger than the footprint of a single OIB

measurement. Therefore it can be expected that RA-2 data represent the average ice thickness rather than the actual range in ice thickness values (see Fig. 9).

Besides the effect of the snow cover the ice density plays a key role. Unfortunately, OIB sea ice thickness values were obtained with a fixed sea ice density value of 915 kg m^{-3} (Kurtz et al., 2013). This density value represents FYI but is going to provide a positive bias in draft and thickness for MYI because it is about 30 kg m^{-3} higher than the average MYI density value suggested, e.g., by Alexandrov et al. (2010). This makes an assessment of the obtained sea ice thickness values a difficult task, in particular if the aim is to quantify the impact of different sea ice density values on the obtained sea ice thickness. Currently, OIB data are the only airborne data source for contemporary data of freeboard and snow depth. This information can be used to obtain an estimate of the sea ice density along the flight track on the spatial scale of 50 km as used here. For this we solved Eq. (1) for the sea ice density and inserted OIB sea ice thickness, freeboard and snow depth; snow density was taken from W99. The resulting sea ice densities are 923 kg m^{-3} and 934 kg m^{-3} for MYI for 2009 and 2010, respectively, and 930 kg m^{-3} for FYI for 2010. These values are larger than the density value used to compute the OIB sea ice thickness. Note that for 2010 sea ice density values computed for MYI and FYI are similar to each other within the standard deviation of about 10 kg m^{-3} . If instead of the OIB snow depth we use the W99 snow depth, obtained ice density values change little for MYI: 926 kg m^{-3} and 922 kg m^{-3} , but substantially for FYI: 898 kg m^{-3} . We interpret this to be caused by the over-estimation of the actual snow depth by W99 over FYI. We recommend to study the impact of sea ice density more thoroughly and to carry out similar investigations with the available submarine ULS sea ice draft data.

We note that the interpretation of the CryoVEx data remains inconclusive because the ASIRAS instrument, which is supposed to sense the ice–snow interface and thus provide an independent sea ice freeboard measurement, failed to do so and instead provided snow freeboard like the ALS sensor. Therefore CryoVEx ASIRAS data could not be used as an additional source of sea ice freeboard data and, in combination with

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the ALS instrument, of snow depth. The cause for this remains unknown. Environmental conditions (melt) are identified as a possible reason for the 2011 CryoVEx data but not for the 2008 CryoVEx data. This suggests that even under apparent freezing conditions sensors like Envisat RA-2 or Cryosat-2 might not sense the sea ice surface. This can be due to various reasons which to explain is beyond the scope of this study.

6 Summary and recommendations

Satellite radar altimetry has been providing surface elevation measurements of the Arctic Ocean for about two decades. With the assumption that these elevation measurements represent the sea ice freeboard these are used to derive sea ice thickness (Laxon et al., 2013, 2003). In order to derive a consistent and quality-controlled sea ice thickness data set spanning two decades from satellite radar altimetry in the Arctic Ocean a careful investigation of the uncertainties involved in the freeboard-to-thickness conversion needs to be done. Here we report about results of such an investigation carried out within the European Space Agency Climate Change Initiative sea ice Essential Climate Variable project. Within this project sea ice freeboard data derived from satellite radar altimetry are collocated with a suite of validation data from various sources: observations of snow and sea ice freeboard from Operation Ice Bridge (OIB) and Cryosat Validation Experiment (CryoVEx) air-borne campaigns, observations of sea ice draft from moored and submarine Upward Looking Sonar (ULS), and observations of snow depth from OIB campaigns, Advanced Microwave Scanning Radiometer aboard EOS (AMSR-E) and the Warren Climatology (W99) (Warren et al., 1999).

It is found, in agreement with earlier studies (Kwok et al., 2011; Kurtz and Farrell, 2011), that W99 is outdated. Over multiyear ice, the W99 snow depth agrees with snow depth from OIB within 0.02 m in 2009 but only within 0.12 m in 2010. Over first-year ice, W99 snow depth is twice as large as snow depth from OIB in both years. OIB snow depth over first-year ice agrees within 0.02 m with AMSR-E snow depth. Therefore, AMSR-E snow depth over first-year ice is a valuable alternative for current conditions

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in the Arctic Ocean. This result is confirmed by a comparison of measured snow freeboard (OIB) with snow freeboard computed from radar altimetry sea ice freeboard plus snow depth. If OIB snow depth is used, mean snow freeboard agrees within 0.02 m. If W99 snow depth is used, mean snow freeboard over-estimates the observed one by 0.12 m in 2010. The results obtained using CryoVEx campaign data point into the same direction.

Upward looking sonar data of the winter (October–March) sea ice draft are compared with sea ice draft computed from radar altimetry sea ice freeboard using different realizations of the freeboard-to-draft conversion. Considering the mean and the median sea ice draft those realizations, that allow a spatiotemporally variable snow depth and snow density, reveal agreement between observed and computed sea ice draft within the uncertainty bounds. None of the realizations is able to re-produce the seasonal range in sea ice draft. Low sea ice drafts at the beginning of the freezing season are over-estimated while large sea ice drafts at the end of the freezing season are under-estimated. A change of sea ice densities and/or snow depths as a function of ice type can improve the agreement at the beginning or end of the freezing season but seems not to have an impact on the obtained sea ice draft range.

A comparison of OIB and CryoVEx sea ice thickness estimates with radar altimetry sea ice thickness obtained using four different freeboard-to-thickness conversion approaches reveals a similar picture for all four approaches: low (high) ice thickness values are over- (under-) estimated by the radar altimetry. In addition an improvement from using ice type dependent snow depth is not that evident. This contrasts our sensitivity study which reveals that the sea ice freeboard uncertainty needs to be as small as possible to avoid sea ice thickness uncertainties of the order of 0.5 m or more. This study further reveals that using an appropriate ice density is as important as using an appropriate snow depth. For example, uncertainties of up to 0.8 m can be avoided if over multiyear ice the respective lower ice density and larger snow depth is used. The choice of the snow density is less important but can still contribute to ice thickness uncertainties of the order of 0.3 m, particularly during early winter or spring.

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We note that almost all sea ice draft data and many of the validation data of our data base are from regions with multiyear ice. A real assessment of those approaches which include ice-type dependent ice density and snow depth could therefore not be carried out in a systematic enough way. More work and more data sets are required here.

More emphasis needs to be put on the choice of the scales involved. Some of the independent data used in our study point towards a larger range in sea ice draft and thus thickness than observed by satellite radar altimetry. Averaging over a track length of 50 km or 100 km of a submarine or an airborne sensor can only be an approximation of the variability in sea ice freeboard obtained from satellite radar altimetry over a disc with diameter 100 km. Also, data from submarine and airborne campaigns cover a few days while satellite RA data are averages over a month.

The airborne data sets which allow sea ice thickness retrieval suffer from (i) environmental conditions – like the CryoVEx campaign data (see below), (ii) from the fact that not all uncertainty sources are well understood yet (Kurtz et al., 2013), and (iii) usage of sea ice thickness retrieval input parameters like snow depth and densities which are not state-of-the-art in view of recent literature (Alexandrov et al., 2010; Laxon et al., 2013). In particular point (ii) suggests that the results of the inter-comparison between RA-2 sea ice thickness and OIB sea ice thickness need to be interpreted carefully and only in view of our sensitivity study.

7 Recommendations

We formulate the following recommendations for freeboard-to-thickness and freeboard-to-draft conversion using radar altimetry for the Arctic Ocean:

1. The Warren Climatology has to be used carefully. It is not valid over first-year ice and it is of limited use in the Fram Strait as well as other regions outside of the central Arctic Ocean. It is recommended to use the Warren Climatology in combination with a second data set of snow depth over first-year ice.

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2. Using radar altimetry, the impact of sea ice density on sea ice thickness retrieval is as large as the impact of snow depth. Recent studies indicated that the difference in sea ice densities of multiyear ice and first-year ice is large enough to explain sea ice thickness under- or over-estimations of the order of 0.5 m or more. It is recommended to use an ice-type dependent set of ice densities. This requires a (re-)evaluation of existing ice-type data sets of the Arctic Ocean. In addition it is important to also consider the density difference between ridged and level ice. We need many more measurements of ice density and isostasy across FY and MY ridges, then possibly parameterise the degree of ridging in order to derive an appropriate area-averaged ice density. Much remains to be done here.
3. For a sophisticated inter-comparison and validation of the final sea ice thickness product it is mandatory to use the same input parameters for the freeboard-to-thickness conversion. Otherwise a potential improvement in performance which might result from utilizing a new set of input parameters cannot be quantified.
4. The amount of contemporary sea ice draft, snow depth and sea ice thickness data is clearly sub-optimal and needs to be improved for a sophisticated, long-term validation of sea ice thickness retrieved from satellite radar altimetry in the Arctic Ocean.

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Table 1. Validation data used in the RRDP for sea ice thickness.

Year	Location	Parameter	Source	Acronym
2003–2008	Beaufort Sea	Ice draft, snow depth	BGEP moored ULS, AMSR-E	BGEP
Apr 1994	Beaufort Sea	Ice draft	NSIDC US submarine ULS	BS
Oct 1996				
Mar 2007	Fram Strait, Beaufort Sea	Ice draft, snow depth	UCAM UK submarine ULS, AMSR-E	BSS
May 2011	Fram Strait	Ice freeboard, thickness, snow depth	DTU ALS, ASIRAS, AMSR-E	FS
Apr 2008				
Oct 2009	Western Arctic	Ice freeboard, thickness, snow depth	NSIDC IceBridge	OIB

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Table 2. Summary of the comparison between OIB, W99, and AMSR-E snow depth in the Arctic Ocean. Absolute values are only given for OIB; all other values are differences. All values are given together with one standard deviation.

Data set	All	MYI (> 65 %)	FYI (> 95 %)	Can. Arch.
OIB 2009	(0.26 ± 0.11) m	(0.36 ± 0.04) m	(0.16 ± 0.02) m	–
OIB – W99	(-0.07 ± 0.11) m	(0.02 ± 0.04) m	(-0.19 ± 0.02) m	–
OIB – AMSR-E	–	–	(-0.01 ± 0.02) m	–
W99 – AMSR-E	–	–	(0.18 ± 0.03) m	–
OIB 2010	(0.21 ± 0.07) m	(0.23 ± 0.05) m	(0.13 ± 0.02) m	(0.13 ± 0.04) m
OIB – W99	(-0.13 ± 0.07) m	(-0.12 ± 0.05) m	(-0.21 ± 0.01) m	(-0.15 ± 0.04) m
OIB – AMSR-E	–	–	(-0.03 ± 0.02) m	(-0.01 ± 0.03) m
W99 – AMSR-E	–	–	(0.18 ± 0.02) m	(0.15 ± 0.03) m

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Table 3. Summary of overall mean observed (OIB) and computed (RA-2) snow freeboard using OIB or W99 snow depth; given are mean values plus/minus one standard deviation.

Data set	Snow freeboard (OIB)	Snow freeboard (RA-2 + OIB snow depth)	Snow freeboard (RA-2 + W99 snow depth)
OIB 2009	(0.52 ± 0.15) m	(0.51 ± 0.10) m	(0.52 ± 0.07) m
OIB 2010	(0.42 ± 0.16) m	(0.40 ± 0.12) m	(0.53 ± 0.08) m

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Table 4. Summary of observed and computed sea ice draft values using standard settings and W99 snow parameters; given are mean values plus/minus one standard deviation.

Data set	Observed draft (ULS)	Derived draft (RA, RA-2)
BS 1994	(2.92 ± 0.41) m	(2.47 ± 0.57) m
BS 1996	(1.68 ± 0.51) m	(1.81 ± 0.41) m
BSS 2007	(2.48 ± 0.46) m	(2.36 ± 0.54) m
BGEP 2003–2008	(1.59 ± 0.42) m	(1.64 ± 0.25) m

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Table 5. Summary of comparison between RA-2 sea ice thickness computed using different snow depth data sets and OIB sea ice thickness for the Arctic Ocean.

Year	Snow data set	R	RMSD [m]	Year	Snow data set	R	RMSD [m]
2009	OIB	0.54	0.73	2010	OIB	0.18	1.16
	W99	0.29	1.12		W99	0.08	1.52
	AMSR-E + W99	0.45	0.94		AMSR-E + W99	0.03	1.28
	KF11	0.43	0.97		KF11	0.05	1.28

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Table 6. Summary of comparison between RA-2 sea ice thickness computed using different snow depth data sets and CryoVEx as well as OIB sea ice thickness for the Fram Strait.

Year	Snow data set	R	RMSE [m]
2010	W99	0.73	2.30
	OIB	0.71	0.89
2008	W99	-0.66	1.83
	AMSR-E + W99	-0.72	1.38
	KF11	-0.72	1.38
2011	W99	0.05	1.36
	AMSR-E + W99	-0.44	2.02
	KF11	-0.36	1.86

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Table 7. Differences of mean and median observed minus computed sea ice draft from submarine and moored ULS (see Table 1) and algorithms A1 to A6 applied to radar altimeter data for the Arctic Ocean. Algorithms giving the smallest difference are highlighted in bold font.

	Data set	A1	A2	A3	A4	A5	A6
Difference in mean (median) SID [m]	BS, Oct 1996	0.13 (0.03)	-0.12 (-0.23)	0.06 (0.04)	0.13 (0.03)	0.49 (0.35)	0.01 (-0.13)
	BGEP, Mar 2002–Aug 2007	-0.01 (0.05)	-0.22 (-0.19)	0.02 (0.09)	-0.04 (0.05)	0.16 (0.27)	-0.43 (-0.35)
	BSS, Mar 2007	0.00 (0.01)	-0.22 (-0.24)	0.08 (-0.15)	-0.36 (-0.33)	-0.46 (-0.40)	-0.69 (-0.70)

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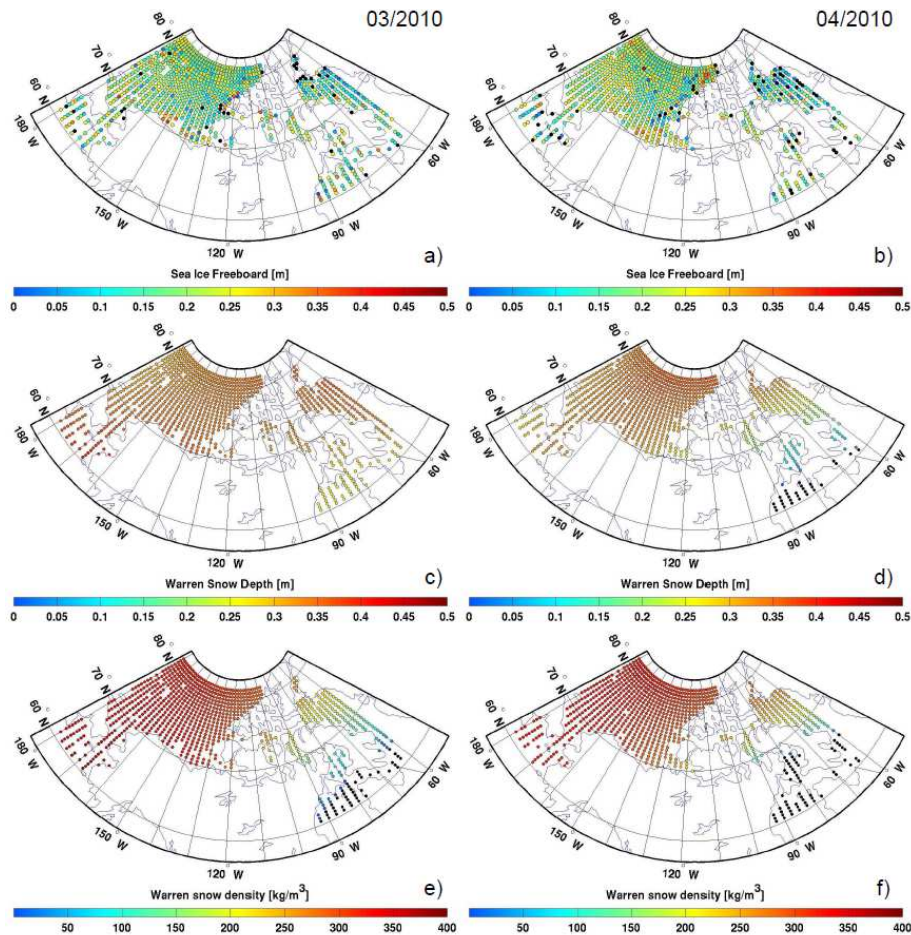


Fig. 1. Maps of the collocated Envisat RA-2 sea ice freeboard for March and April 2010 (a, b), of the Warren Climatology snow depth (c, d) and of the Warren Climatology snow density (e, f). Negative values are flagged black.

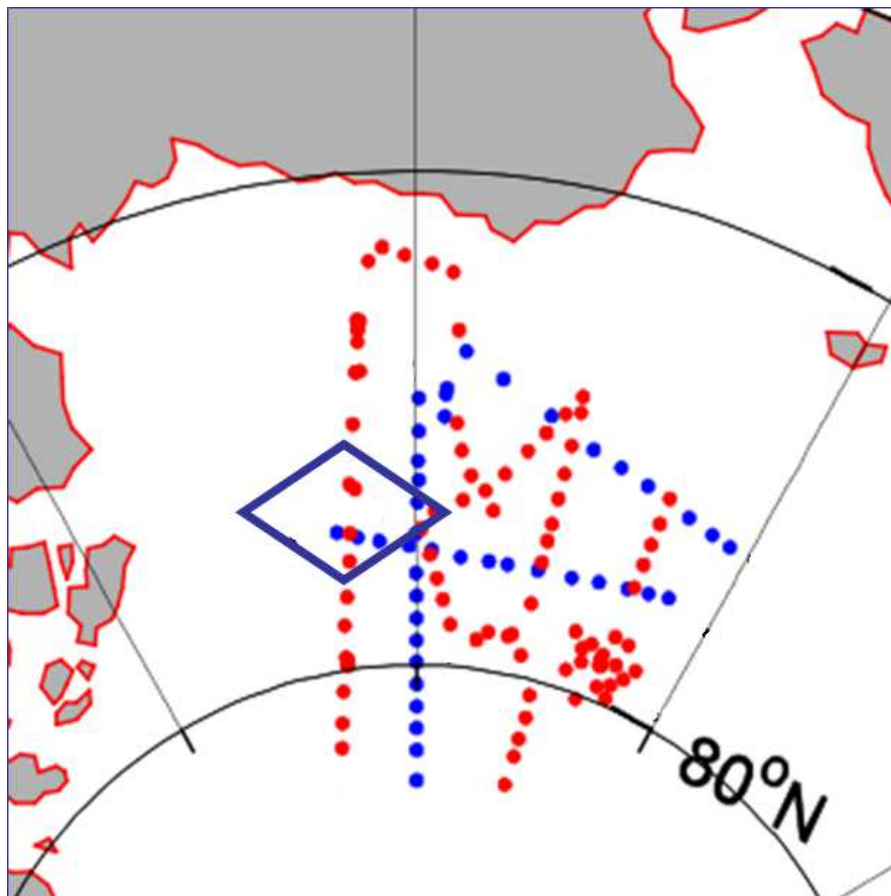


Fig. 2. Location of US submarine ULS draft measurements in blue (1994) and red (1996) together with the approximate location of the BGEP mooring (diamond).

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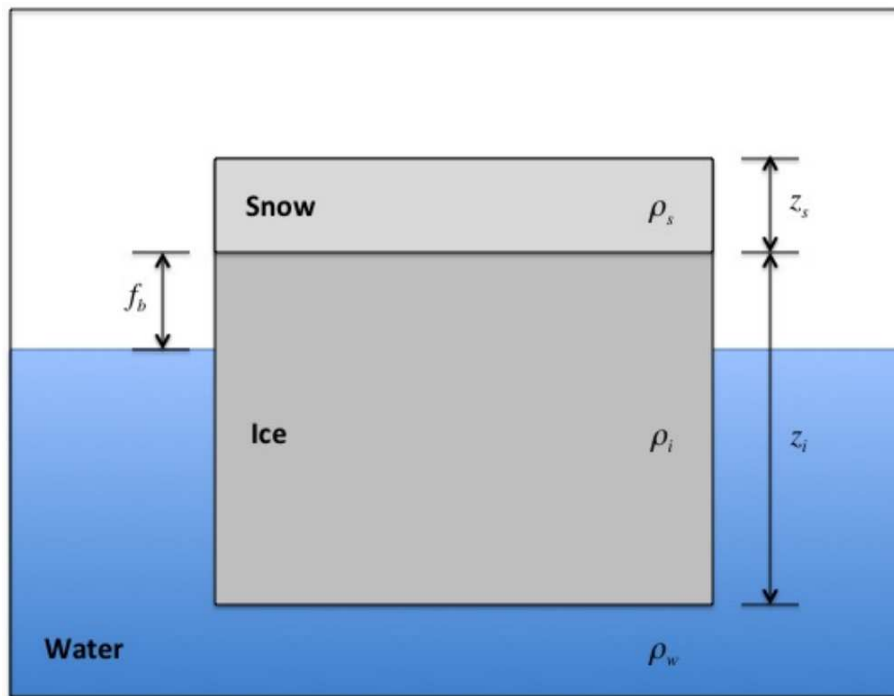


Fig. 3. Illustration of the parameters involved in sea ice thickness computation using sea ice freeboard.

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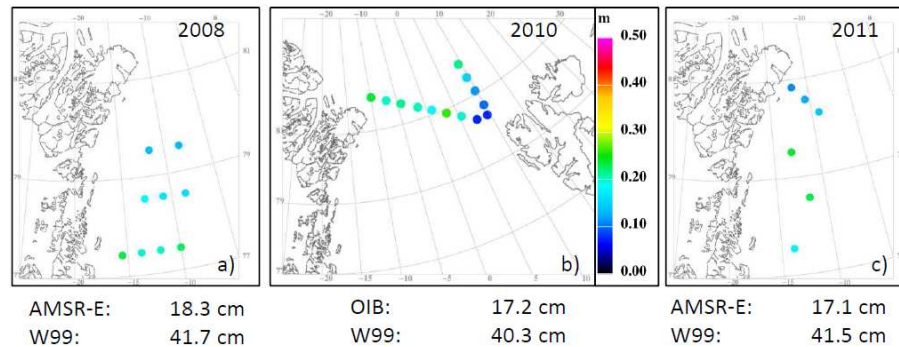


Fig. 4. Locations and values for snow depth data sets in the Fram Strait for CryoVEx **(a, c)** and OIB **(b)**. For CryoVEx only AMSR-E snow depths are shown as these are only available for FYI; for 2008 this is 9 out of 11 and for 2011 this is 6 out of 21 data points. In 2010 no FYI was present according to AMSR-E ice classification.

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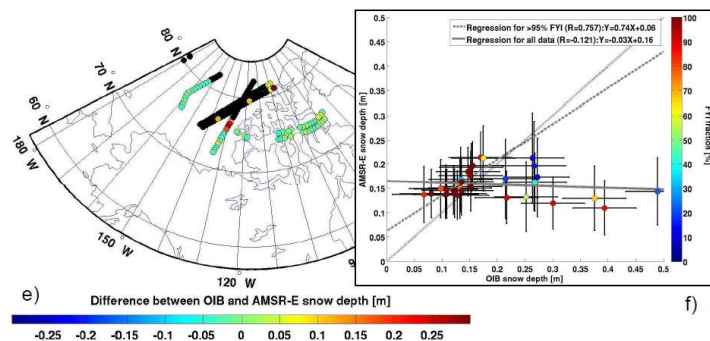
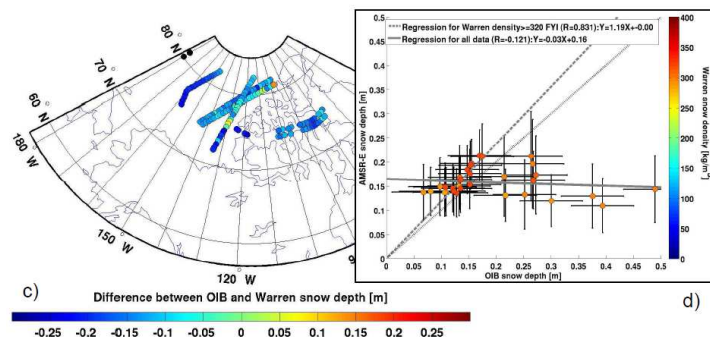
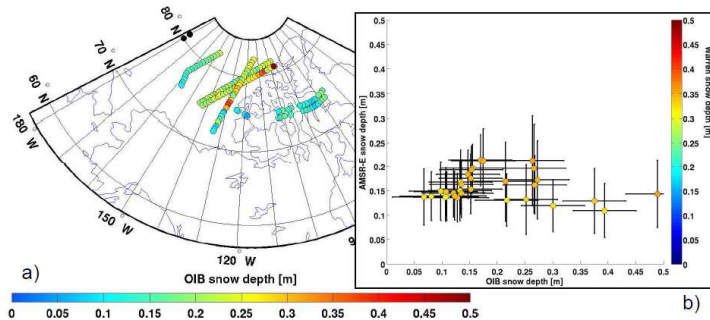
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Fig. 5. Left column: OIB snow depth and its difference to W99 and AMSR-E snow depth for April 2010. Grid cells with FYI fraction of 0% are flagged black in **(e)**. Right column: scatter plots of AMSR-E vs. OIB snow depth with symbols color coded with W99 snow depth **(b)**, W99 snow density (image **(d)**), and FYI fraction **(f)**. The grey solid line represents the 1-to-1 relationship; black solid and dashed lines are the regression lines using all data pairs or in limitation to the given density **(d)** and FYI fraction **(f)** values. Note that the parallel tracks visible in images **(a)**, **(c)** and **(e)** are actually on top of each other. They have been separated by 0.4° latitude for better visibility.

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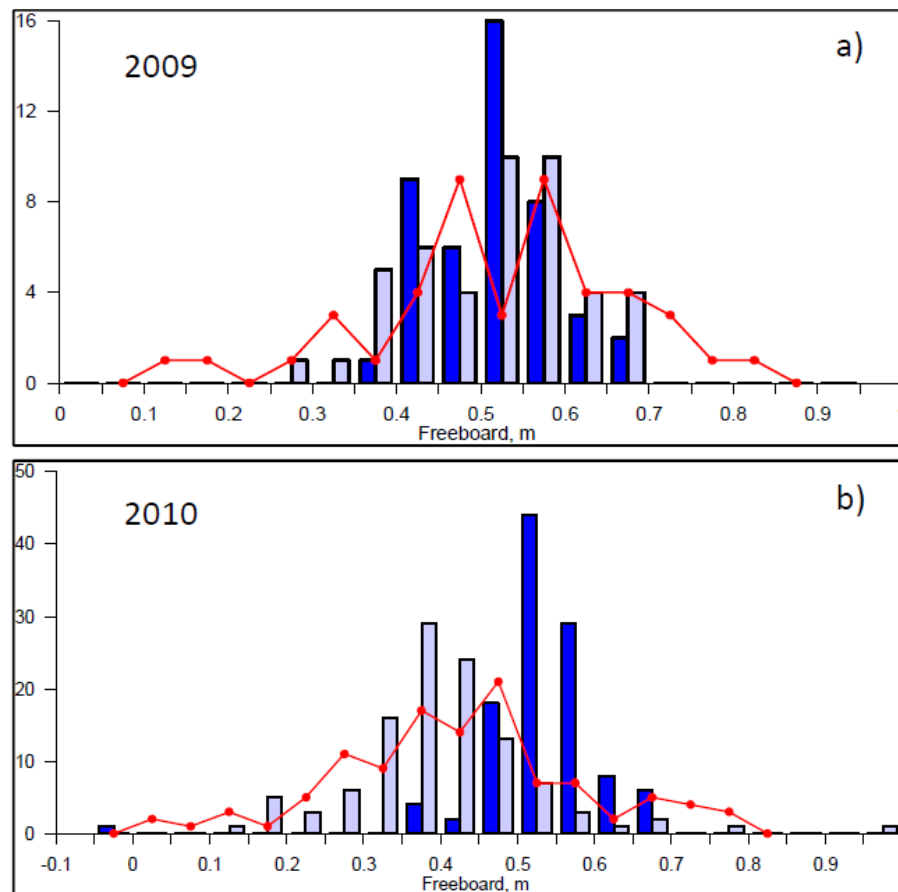


Fig. 6. Histograms of OIB (red) and RA-2 (blue) freeboard. RA-2 freeboard is derived using OIB snow depth (light blue bars) and W99 snow depth (dark blue bars). Both MYI and FYI data are included. Note the different y-axis scaling.

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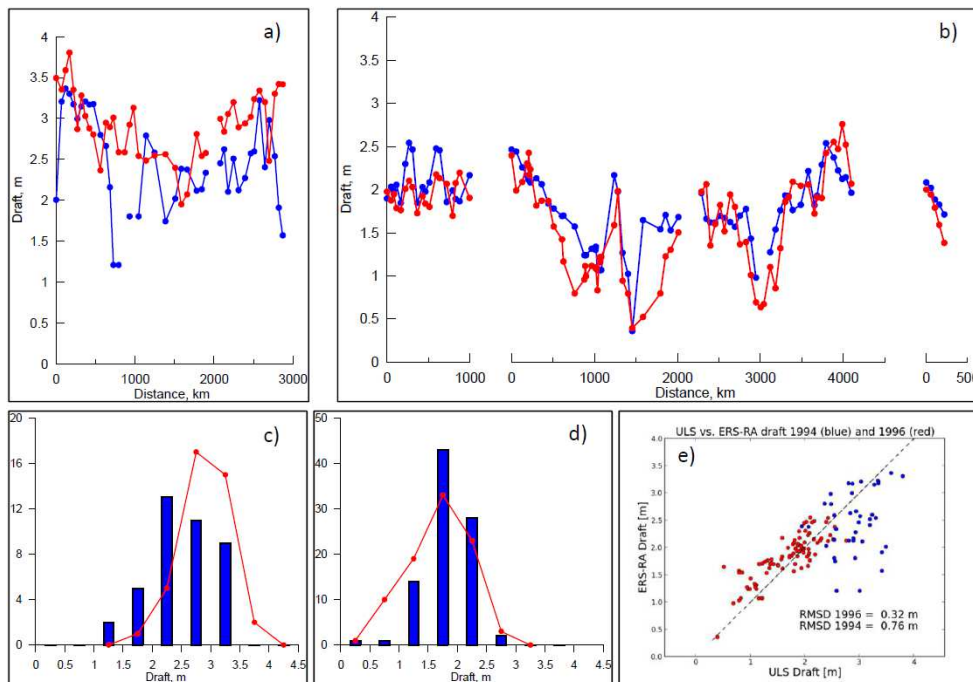


Fig. 7. Comparison between sea ice draft observed from US submarine ULS (red) and computed from ERS-1 RA sea ice freeboard using W99 snow data (blue). **(a)** and **(b)** are profiles along submarine track for April 1994 and October 1996, respectively (see also Fig. 2); **(c)** and **(d)** show corresponding histograms. Image **(e)** compares data from both cruises for 1994 (blue) and 1996 (red) together with the RMSD.

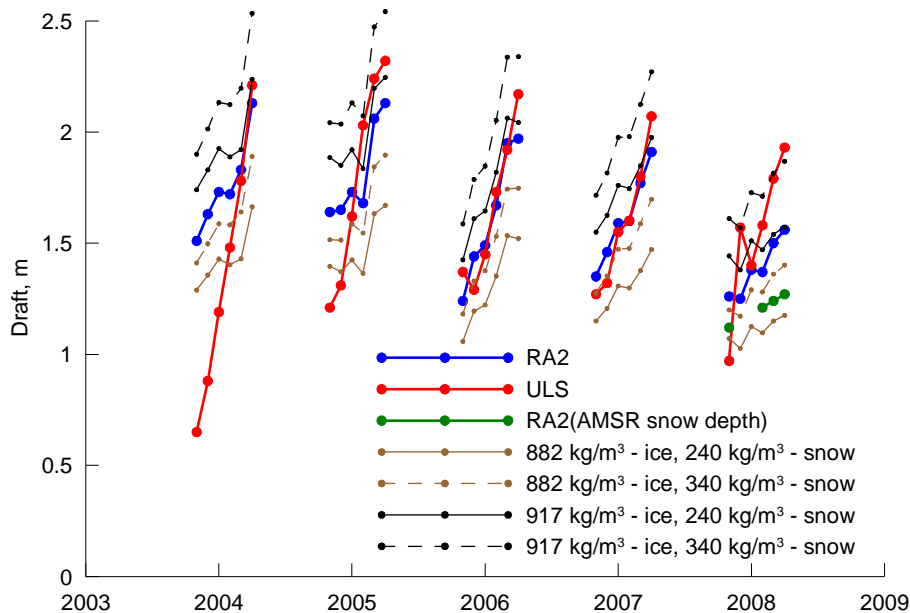


Fig. 8. BGEF ULS draft data, averaged to monthly mean for the winter months October to March (red) compared to monthly mean draft computed from RA-2 sea ice freeboard using **(a)** W99 snow depth and density and standard values: $\rho_i = 900 \text{ kg m}^{-3}$ and $\rho_w = 1030 \text{ kg m}^{-3}$ (blue); **(b)** W99 snow depth but MYI density: $\rho_i = 882 \text{ kg m}^{-3}$ (brown); **(c)** W99 snow depth and FYI density: $\rho_i = 917 \text{ kg m}^{-3}$ (black); and **(d)** AMSR-E snow depth (green). Note that the latter is only possible for FYI areas. For **(b)** and **(c)** snow density is set fixed to either 240 kg m^{-3} (solid lines) or 340 kg m^{-3} (broken lines).

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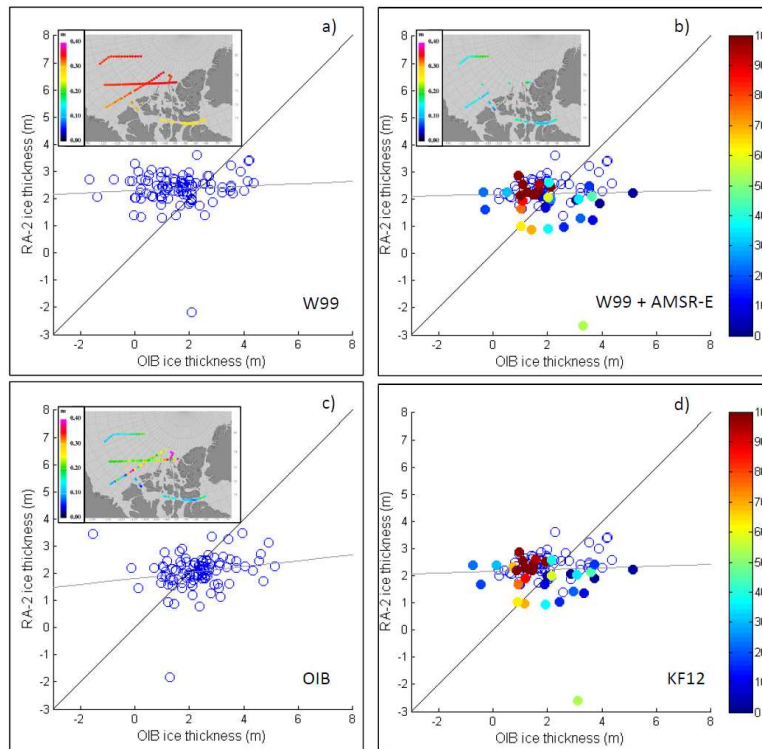


Fig. 9. RA-2 sea ice thickness computed using different snow depth data sets vs. OIB sea ice thickness. Black and blue lines denote the 1-to-1 relationship and the obtained linear regression, respectively. Insets in images (a) to (c) denote locations of flights used and give an idea about the snow depth variability in these data sets. Color coding of the symbols in images (b) and (d) denotes ice type fraction with open blue = 100 % MYI, dark filled blue = 1 % FYI and brown/red = 100 % FYI.

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