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The Cryosphere Discussions

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Interactive Comment

Interactive comment on "The relation between sea ice thickness and freeboard in the Arctic" *by* V. Alexandrov et al.

V. Alexandrov et al.

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General Comments

This paper brings together in-situ measurements of sea ice to evaluate the uncertainties in the parameters used to convert satellite measurements of sea ice freeboard to thickness. The paper assesses the contribution from the uncertainty in ice density to the total ice thickness uncertainty. This is a useful exercise and suitable for publication, providing some corrections are made to the manuscript. These are detailed below, but the two most serious issues that need to be addressed are:

1) It is not clear how the uncertainty in the ice density is calculated (see comments below P647, L10)

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Interactive Discussion

Discussion Paper

Answer: The Sever measurements were used to calculate the mean density of FY-ice. Based on assumption that the sea ice is in hydrostatic equilibrium ice density was calculated for each site using eq. 2. In our calculation we used measurements of ice freeboard, ice thickness, and snow depth on runway, because ice freeboard was measured only on runways. The database contains mean values of these parameters for each landing. The uncertainty of ice density was calculated as a standard deviation for all 689 landings.

Uncertainty of ice density for MY-ice was calculated as an average weighted of uncertainties for the upper and lower layers. Due to lack of measurements these uncertainties were estimated based on scientific judgement, and amount to 50 and 20 kg/m3, respectively.

2) The motivation of this paper is to better constrain the uncertainty in satellite derived sea ice thickness measurements, as described in the abstract. However, the paper contains multiple references to constant freeboard/thickness ratios that are not used by the majority of papers that use altimeter measurements of freeboard to compute thickness (e.g. Laxon, Giles, Kwok, Zwally etc.). Constant freeboard to thickness ratios are not used due to the sensitivity of the ratio to the changes in the snow depth and density, which are accounted for when equation 4 is used, taking estimates of the snow depth and density from climatology, for example. All references to this ratio must be removed and the paper should focus on evaluating the ice density uncertainty and how it affects the total uncertainty in ice thickness using equ.5.

Answer: Constant freeboard/thickness ratios are not used due to their sensitivity to snow loading, and this is particularly relevant to laser altimetry. It is known that snow loading increases from autumn to late winter, and do not change significantly during late winter conditions. Our study also shows that snow climatology data (Warren et al., 1999) are correct for the MY-ice in the Central Arctic, but not for the FY-ice in the Eurasian Arctic shelf seas. Therefore in our paper we use constant ratios only for the late winter period, and these relations are different for the FY and MY-ice. The relations

(1), (6) and (7) cannot be used for example in autumn, when snow loading is different. We agree that in general, the isostatic equilibrium equation should be used, but for some particular cases this equation can be transformed into simple linear dependence between ice thickness and freeboard.

The paper also includes a number of grammatical errors that should be corrected.

Answer: Grammatical errors will be corrected

Specific Comments

P642, L16: The value given for the freeboard uncertainty is 0.05. Where does this number come from? I suggest taking the FB uncertainty of 0.03 m from Giles et al., (2007).

Answer: Our calculations were conducted for the freeboard errors of 0.03, 0.05, and 0.08 m. Freeboard of 0.05 m was taken as example, and this sentence will be edited correspondingly.

P642, L21: Replace CryoSat with CryoSat-2 for consistency though out the paper. The authors should check for other occurrences of this.

Answer: We agree with this comment and will replace CryoSat with CryoSat-2 throughout the paper.

P643, L5: CryoSat-2's objective is to measure trends in sea ice thickness. The uncertainty on a point measurement of sea ice thickness as described here is expected to be greater than the error in the trend.

Answer: We agree with that. According to our estimates, use of different estimates of ice density, snow depth, and other parameters significantly influences the estimates of ice thickness, and much less influences trends in ice thickness. This will be mentioned in the revised paper.

P643, L6: CryoSat-2 was launched in April 2010.

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Answer: We agree and correct the paper.

P643, L13: Beaven (1995) shows that under dry snow conditions the radar penetrates to the snow ice interface. Therefore the use of this reference here is miss-leading as it implies that Beaven's experiment shows an uncertainty in this assumption.

Answer: The editing of this sentence will be done.

P643, L14-15: The study by Giles and Hvidegaard (2006), used data from April and May in the Fram Strait, where it is likely that changes in temperature could have resulted in changes to the snow pack, effecting the penetration of the radar. CryoSat-2 will only estimate changes in the winter (defined as October to March) ice thickness to avoid possible issues with increases in temperature changing the dielectric properties of the snow pack. Therefore, it is not true that changes to the snow pack are not taken into consideration.

Answer: This sentence will be reformulated more correctly.

P643, L26: Kwok (see Kwok & Cunningham, 2008) calculates the snow depth using a combination of climatology and snow precipitation data. This method is not mentioned here.

Answer: We know this paper and it will be mentioned.

P645. L10. Remove 'yardstick'

Answer: We removed yardstick.

P645, L10: Does the fact that the survey area is being used as a runway affect the measurements of snow depth?

Answer: No, because all measurements were conducted on undisturbed surface.

P645: Equation 1: The use of constant ratios to determine sea ice thickness is not relevant to satellite altimetry as neither the IceSat or CryoSat-2 scientists use this method.

This comment also applies to equations 8 – 11 on p650.

Answer: We partly answered this question above. We agree that neither the IceSat or CryoSat-2 scientists use this method. However, these equations have been derived from direct measurements and they can be used in late winter, as well as for comparison and validation.

P646. L21: Do you mean the ‘ brine content’ of the air bubbles?

Answer: We changed “Content of air bubbles” to the “Relative volume of air bubbles”

P646. What is infiltrated snow ice? If you mean snow ice caused by sea water flooding then note that this is only relevant to Antarctic sea ice and therefore not relevant to the CryoSat-2 mission aims.

Answer: The Infiltrated snow ice is typical for the Antarctic, but also occurs in the Arctic, for example, in Fram Strait. We also observed ice flooding in the north-eastern Barents Sea.

P647, L10: Which measurements have been used to calculate the mean density of FY ice? (Sever data?) How has the uncertainty been calculated? i.e. is it the standard deviation of the individual points in the ‘large’ area? If so how do they know that the ice is in hydrostatic equilibrium at those points? Or have they divided the data into many large areas, which are assumed to be in hydrostatic equilibrium, averaged the large areas and taken the standard deviation of those large areas?

Answer: We answered this question earlier.

P647, L12: Can they be more specific as how large a “large area” is?

Answer: This depends on surface roughness. Ice thickness measurements, made at 3-5 locations 150-200 m apart should be enough for level ice floe. For deformed ice more measurements is needed, and they should be evenly distributed on ice floe, and size of the area depends on ice floe size.

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P649. L1: The paper by Tonboe et al. 2009 in Cryosphere has not been published yet, due to unaddressed issues raised by the reviewers. Please use published values for the error in freeboard (e.g. Kwok, Giles, etc.)

Answer: Here we will also refer to (Giles et al., 2007).

P650: Equation 11: Neither Laxon et al., (2003) nor Giles et al., (2007, 2008) used this equation to estimate sea ice thickness. The equation written in this form assumes that the snow depth and density are constant. Laxon and Giles do not make this assumption. N.B. comparison with Equ 6. shows that it is the choice of snow depth & density that is causing Equ. 11 to overestimate the ice thickness.

Answer: We agree that neither Laxon et al., (2003) nor Giles et al., (2007, 2008) used this equation to estimate sea ice thickness. We obtained it by means of substituting typical values of snow depth, water density, ice density, and snow density from Table 1 in the paper by Giles et al. (2007) to the isostatic equilibrium equation. Since the authors of afore-mentioned papers disagree with presentation of their results in this form, we will delete equation (11) from our paper. The corresponding correction will be done to the caption to figure 4. We agree that these authors did not make assumption that the snow depth and density are constant. We found that snow depth on MY-ice significantly exceeds that on FY-ice. Climatology data show that snow depth and density change insignificantly during late winter.

Equation 11 overestimates ice thickness for the FY-ice, because the estimate of snow depth (0.3 m) from Table 1 in (Giles et al., 2007) is typical for MY-ice in late winter, but not for the FY-ice. If to use other parameters from Table 1 in (Giles et al., 2007) and only change snow depth to 0.05 m (as it was found in Sever data) then the equation is: $H_i=9.42F_i+0.15$, which corresponds to our equation (6).

P652, Conclusions: The authors could recommend that different densities for FY and MY ice should be used routinely to calculate sea ice thickness from satellite measurements of freeboard (both in laser and radar measurements).

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Answer: We will recommend this

Figure 1. The labels on the figures are too small.

Answer: We will correct this.

Figure 2: the caption could contain the data sources. Do all the data sources estimate density in the same way? If not, how much of the measured interval is due to the error in the measurement techniques and how much is natural variability?

Answer: We will include data sources in figure caption. This figure is based on the review paper by Timco and Frederking (1996), and several other papers. Analysis of the data presented in Timco and Frederking (1996) shows that the measurements of ice density were mostly conducted using mass/volume technique. Ice densities, measured using this technique, vary substantially.

Figure 3: This is an interesting plot showing how the relative contribution of the errors change as a function of freeboard. It would be easier to read if the colours of the contributions from the errors were the same for FY and MY ice e.g. total error is currently green for FY ice and blue for MY ice, and the freeboard error is blue for FY and green for MY ice. The authors could produce the same plot for laser altimetry, using equation 4 in Giles et al., 2007.

Answer: The colours of the contribution from the errors are the same for FY- and MY-ice. It is possible to produce the same plot for laser altimetry.

Figure 4: The letters a)-e) in the caption do not relate to the figure

Answer: We have deleted the letters a)-e) from the figure caption.

Interactive comment on The Cryosphere Discuss., 4, 641, 2010.

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