The Cryosphere Discuss., 4, 641–661, 2010
www.the-cryosphere-discuss.net/4/641/2010/

The Cryosphere Discussions

This discussion paper is/has been under review for the journal The Cryosphere (TC).
Please refer to the corresponding final paper in TC if available.

The relation between sea ice thickness and freeboard in the Arctic

V. Alexandrov[1,2], S. Sandven[2,3], J. Wahlin[2], and O. M. Johannessen[2]

[1]Nansen International Environmental and Remote Sensing Center (NIERSC),
14th Line of Vasilevsky Island, 7, office 49, 199034, St. Petersburg, Russia
[2]Nansen Environmental and Remote Sensing Center (NERSC), Thormoehlensgate 47,
5006, Bergen, Norway
[3]Department of Arctic Geophysics, University of Svalbard (UNIS), 9171,
Longyearbyen, Norway

Received: 30 March 2010 – Accepted: 14 April 2010 – Published: 22 April 2010

Correspondence to: V. Alexandrov (vitali.alexandrov@niersc.spb.ru)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Retrieval of Arctic sea ice thickness from radar altimeter freeboard data, to be provided by CryoSat-2, requires observational data to verify the relation between the two variables. In this study in-situ ice and snow data from 689 observation sites obtained during the Sever expeditions in the 1980s have been used to establish an empirical relation between ice thickness and freeboard. Estimates of mean and variability of snow depth, snow density and ice density were produced based on many field observations, and have been used in the isostatic equilibrium equation to estimate ice thickness as a function of ice freeboard, snow depth and snow/ice density. The accuracy of the ice thickness retrieval has been calculated from the estimated variability in ice and snow parameters and error of ice freeboard measurements. It is found that uncertainties of ice density and freeboard are the major sources of error in ice thickness calculation. For FY ice, retrieval of ≈1.0 m (2.0 m) thickness has an uncertainty of 60% (41%). For MY ice the main uncertainty is ice density error, since the freeboard error is relatively smaller than for FY ice. Retrieval of 2.4 m (3.0 m) thick MY ice has an error of 24% (21%). The freeboard error is ±0.05 m for both the FY and MY ice. If the freeboard error can be reduced to 0.01 m by averaging a large number of measurements from CryoSat, the error in thickness retrieval is reduced to about 32% for a 1.0 m thick FY floe and to about 18% for a 2.3 m thick MY floe. The remaining error is dominated by uncertainty in ice density. Provision of improved ice density data is therefore important for accurate retrieval of ice thickness from CryoSat data.

1 Introduction

Satellite altimeter data can provide extensive spatial and temporal measurements of sea ice thickness through converting the ice freeboard measurements to thickness by assuming isostatic equilibrium (Laxon, 1994; Laxon et al., 2003; Giles et al., 2008; Kwok et al., 2009). Analysis of ERS and Envisat radar altimeter (RA) data from 1992 to present have resulted in a unique data set on ice thickness south of 81.5° N, showing a significant thinning of the ice cover from 2007 to 2008 (Giles et al., 2008). The ice thickness estimates represent monthly mean values in typically 100×100-km grid with an expected error of 0.04–0.06 m (Miller et al., 2006). These ERS/Envisat sea-ice thickness time series will be extended by CryoSat-2, whose major objectives include measuring ice thickness over most of the Arctic over a period of five years. CryoSat-2 was launched in March 2010 and carries a beam-limited radar altimeter (RA) operating in Synthetic Aperture Radar mode over sea ice, providing freeboard measurements with 250 m resolution along the satellite track (ESA, 2003).

Snow depth, snow density and ice density have a strong impact on the sea ice buoyancy and the ice freeboard. Since the ice freeboard has to be multiplied by a factor that can be up to 10 for calculation of thickness, small errors in the input data lead to large errors in the ice thickness estimates (Rothrock, 1986). Another uncertainty is the assumption that radar echo originates from the snow/ice interface (Beaven, 1995), and possible effects of layers in the snow cover and temperature variations are not taken into account (Giles and Hvidegaard, 2006). Recent studies by Connor et al. (2009), where coincident laser altimeter (LA) and RA measurements of sea ice are available, show that the radar signals are reflected from ice/snow interface, while the laser signals are reflected from the top of the snow cover.

Studies have been done to estimate ice thickness from the IceSat LA data, showing that the ice thickness has decreased significantly from 2007 to 2008, which is in agreement with analysis of RA data from Envisat (Kwok et al., 2009). Ideally, LA and RA data should be collected simultaneously in order to obtain direct estimates of the snow depth, as demonstrated in airborne campaigns (Leuschen and Raney, 2005; Connor et al., 2009). Simultaneous LA and RA satellite sensors are not planned during the CryoSat mission, thus snow data on Arctic sea ice need to be obtained from climatological estimates as well as from new field observations.

Use of the isostatic equilibrium equation to estimate ice thickness from freeboard data requires data on snow and ice density as well as snow depth, which exhibit regional and season variability. Climatological snow cover data from Russian North

Pole drifting stations have been provided by Warren et al. (1999), but there are few data sets available that provide statistics on snow and ice density, snow depth, ice freeboard and thickness over large parts of the Arctic ice cover. Therefore, the main objective of this paper is to investigate the relation between ice freeboard and ice thickness using extensive in-situ measurements from Arctic field expeditions. First, an empirical relation between the ice thickness and freeboard is derived from direct measurements during the Sever expeditions in the 1980s. Furthermore, data on snow and ice densities from literature are reviewed and error estimates are derived. These data are used in the isostatic equilibrium equation to assess the dependencies between thickness and freeboard for first-year (FY) and multiyear (MY) ice. Finally, the error sources in ice thickness retrieval from freeboard measurements are discussed and recommendations for in-situ observations in forthcoming CryoSat post-launch calibration-validation experiments are provided.

2 Ice thickness and freeboard data from the Sever expeditions

In-situ measurements of Arctic sea ice from the airborne Sever expeditions provide one of the most extensive data sets of sea ice and snow parameters collected over many years including 1928, 1937, 1941, 1948–1952, and 1954–1993 (Romanov, 1995). The total data set includes 3771 landings, here obtained from the World Data Center for Glaciology/National Snow and Ice Data Center (NSIDC), Boulder, Colorado. In this study co-located observations of ice thickness, ice freeboard and snow depth are extracted from this data set and used to establish an empirical relation between these parameters. The Sever expeditions took place mainly from mid March to early May, when landing on ice floes was possible, such that all data represent late winter conditions before melting starts. At each landing point ice and snow thickness were measured by drilling holes at 3–5 locations 150–200 m apart on the level ice where the runway was located. In addition, measurements were made at 10–20 sites on adjacent ice floes which included deformed ice (Romanov, 1995). Ice freeboard measurements were obtained only in a subset of the total data set from the Sever expeditions. In this study data from 689 landings in the period February–May of 1980–1982, 1984–1986, and 1988 have been used where freeboard measurements were included.

The data from the 689 landings were divided in two groups, the so-called runway data and the off-runway data. The former represents level ice and the latter can include ridges and various types of deformed and level ice located around the level ice. The freeboard data were obtained only on the level ice, so data from the surrounding ice could not be used to study the ice thickness-freeboard relation. The data span the entire Eurasian Russian Arctic (Fig. 1a), where FY ice is prevalent. The yardstick measurement accuracy of the ice thickness, freeboard and snow depth is 0.01 m. Comparison of ice thickness and snow depth between runway and off-runway data shows that the former has thinner ice with less snow cover than the latter. The modal ice thickness for the runway data is about 0.7 m, while it is more than 1 m for the off-runway data. Maximum thickness is about 2.60 m for the runway data and about 3.50 m for the off-runway data (Fig. 1b).

A scatterplot of ice thickness versus freeboard height is presented in Fig. 1c, showing a linear increase in thickness vs. freeboard. There is however significant spread in the ice thickness for each freeboard value, with mean standard deviation of ±0.20 m. For freeboard below 0.15 m there are more than 30 data points (N) for each freeboard interval. From 0.15 to 0.20 m, N decreases to less than 10 per interval. A few freeboard measurements above 0.20 m were collected, but these data were not included because there were only 2–3 data points in each interval. A linear regression equation, specifying the empirical relation between freeboard (F_i) and average thickness (H_i), is the following:

$$H_i = 8.13F_i + 0.37. \qquad (1)$$

A modal freeboard of 0.1 m corresponds to ice thickness of 1.18±0.20 m, using the mean standard deviation as the uncertainty estimate. This relation is based on FY ice in the period March–May. The snow depth on the runway is less than 0.20 m in more than 95% of cases, while it can be up to 0.40 m in the off-runway data. The difference in snow depth between FY and MY ice will have impact on the relation between freeboard and thickness. Equation (1) is applicable for level FY ice, and need to be modified for deformed FY and MY ice.

3 Snow and ice data

3.1 Snow depth and density

Snow depth on the Arctic sea ice increases from a minimum in July–August to a maximum in April–May before the onset of summer melt (Radionov et al., 1996; Warren et al., 1999). On MY ice in the Central Arctic the snow depth is 0.35 m in May with an uncertainty of 0.06 m (Loshchilov, 1964; Warren et al., 1999). The snow depth on level FY ice is much smaller, typically between 0.05 m for ice thinner than 1.60 m and 0.08 m for thicker ice (Romanov, 1995). Data from the Sever expeditions show a median snow depth on runways of 0.05 m. The uncertainty of the snow depth is also 0.05 m. The density of snow on MY ice in March–May is in the range of 310–320 kg m^{-3} (Romanov, 1995; Warren et al., 1999). The average and standard deviation of snow density on FY ice, calculated from the Sever data, is 324±50 kg m^{-3}. The difference in snow properties between MY and FY ice is therefore related to snow depth and not to snow density.

3.2 Ice density

The density of gas-free sea ice can vary from 919 to 974 kg m^{-3} depending on the salinity (Cox and Weeks, 1982). The most important factor determining the ice density is the content of air bubbles (Schwerdtfeger, 1963; Wadhams, 2000), which can reduce the density to 840 kg m^{-3} in normal sea ice and to 770 kg m^{-3} in infiltrated snow ice (Weeks, 1976). Figure 2 shows a composite of ice density values for thin, FY and MY ice (Malmgren, 1927; Mobley et al., 1998; Kubishkin and Skutina, 2004; Schulson et al., 2006). The density values can vary significantly, and the methods used to estimate the densities have impact on the results. The following four methods can be used to estimate ice density: (i) measurement of mass and volume of a given ice body, (ii) displacement (submersion) technique, (iii) specific gravity technique and, (iv) freeboard-thickness technique (Timco and Frederking, 1996). Each of the methods has advantages and limitations. The freeboard-thickness method used in this study to calculate density is based on the isostatic equilibrium equation, where input data are ice thickness (H_i), ice freeboard (F_i) snow depth (H_{sn}) and snow density (ρ_{sn}=324 kg m^{-3}) from the Sever data. Water density ρ_w is set to 1025 kg m^{-3}:

$$\rho_i = \rho_w - \frac{\rho_w F_i + \rho_{sn} H_{sn}}{H_i}. \tag{2}$$

The mean of the estimated ice density for FY ice is 916.7±35.7 kg m^{-3}. This technique is based on the assumption that the ice is in isostatic equilibrium. By averaging many measurements over a large area, the isostatic assumption should be valid, but on a local scale this may not be the case.

Timco and Frederking (1996) reported that FY ice density is typically between 840 and 910 kg m^{-3}, while MY ice density is between 720 and 910 kg m^{-3}. Densities of MY and FY ice samples taken below the waterline are not significantly different, and both ice types have typical values between 900 and 940 kg m^{-3}. For samples taken above the waterline, the MY ice has significantly lower density than FY ice. However, data reported by Khohlov (1978) show that the average density of the MY ice above the waterline is typically between 500–600 kg m^{-3}. This difference is mainly due to the higher volume of air-filled pores in MY ice compared to FY ice (Onstott, 1992; Eicken et al., 1995). In this study we use a density of 550 kg m^{-3} for the upper layer (ρ_u) using the data from Khohlov (1978) and a value of 920 kg m^{-3} for the lower layer (ρ_l) to calculate an averaged weighed value for the MY ice density:

$$\rho_{my} = \rho_l \left(1 - F_i/H_i\right) + \rho_u F_i/H_i. \tag{3}$$

By inserting density values for the upper and lower layers, using typical freeboard

(0.3 m) and thickness data (2.9 m) for MY ice, the bulk density of MY ice becomes 882±23 kg m^{-3}. The uncertainty was calculated from uncertainties of the density in the upper and lower layers. During winter, seawater density in the major part of the Arctic Ocean varies from 1024 to 1027 kg m^{-3} (Gorshkov, 1980; Timokhov and Tanis, 1997; Pavlov, 1998). In our calculations seawater density is 1025±0.5 kg m^{-3}.

4 Error estimates in ice thickness retrieval under isostatic equilibrium assumption

Assuming that sea ice is in isostatic equilibrium with water, ice thickness can be calculated from the following equation where all variables on the right side have prescribed values:

$$H_i = \frac{\rho_w}{(\rho_w - \rho_i)} F_i + \frac{\rho_{sn}}{(\rho_w - \rho_i)} H_{sn}. \tag{4}$$

The values of ρ_w, ρ_i, ρ_{sn}, and H_{sn} are based on statistics from many observations, while freeboard (F_i) is a variable with values between 0.01 and 0.20 m for FY ice and from 0.21 to 0.50 m for MY ice. Under the assumption that the uncertainties are uncorrelated, the error of ice thickness estimates (ε_r^2) calculated from RA measurements of ice freeboard is given by (Giles et al., 2007):

$$\varepsilon_r^2 = \varepsilon_{Fi}^2 \left(\frac{\rho_w}{(\rho_w - \rho_i)}\right)^2 + \varepsilon_{H_{sn}}^2 \left(\frac{\rho_{sn}}{(\rho_w - \rho_i)}\right)^2 + \varepsilon_{\rho_{sn}}^2 \left(\frac{H_{sn}}{(\rho_w - \rho_i)}\right)^2$$
$$+ \varepsilon_{\rho_w}^2 \left(\frac{F_i}{(\rho_w - \rho_i)} - \frac{F_i \rho_w}{(\rho_w - \rho_i)^2} - \frac{H_{sn}\rho_{sn}}{(\rho_w - \rho_i)^2}\right)^2 + \varepsilon_{\rho_i}^2 \left(\frac{F_i \rho_w}{(\rho_w - \rho_i)^2} + \frac{H_{sn}\rho_{sn}}{(\rho_w - \rho_i)^2}\right)^2, \tag{5}$$

where ε_{ρ_i}, ε_{ρ_w}, $\varepsilon_{\rho_{sn}}$ are the uncertainties in the density of ice, water and snow, $\varepsilon_{H_{sn}}$ is the uncertainty in the snow height, and ε_{F_i} is the uncertainty in the ice freeboard, assumed to be measured by RA. Typical values and uncertainties of ice freeboard

(Tonboe et al., 2009), seawater, snow and snow and sea ice parameters, estimated in Sect. 3, are presented in Table 1.

After substituting the typical values of snow, ice, and water parameters in the isostatic equilibrium equation, ice thickness is given as a linear function of freeboard for FY ice by:

$$H_i = 9.46 F_i + 0.15, \tag{6}$$

and for MY ice by:

$$H_i = 6.24 F_i + 1.07. \tag{7}$$

The uncertainty values in Table 1 are inserted in the error Eq. (5), and the results are presented in Fig. 3, where the error in ice thickness retrieval is plotted as a function of freeboard. It is found that uncertainties of ice density and freeboard measurement are the major sources of error in the ice thickness calculation, while the error in snow depth is small. The influence of changes in snow and seawater densities is insignificant. For FY ice the error in thickness retrieval is dominated by the freeboard error for thin ice, while the effect of the ice density uncertainty increases as the freeboard increases. The thickness of FY ice with a freeboard of 0.10 m is 1.10±0.61 m (error ≈ 55%), whereas a freeboard of 0.20 m gives a thickness of 2.04±0.84 m (error ≈ 40%). For MY ice, freeboards of 0.21 and 0.30 m give thicknesses of 2.38±0.56 m (error ≈ 24%) and 2.94±0.61 m (error ≈ 21%), respectively. The calculations are based on a freeboard error of 0.05 m. As the freeboard increases, the ice density error becomes the dominant error term in the thickness retrieval.

The error in thickness retrieval is smaller for MY ice compared to FY ice for two reasons: (1) the relative error in freeboard measurement is smaller for MY ice than FY ice, and (2) the uncertainty in ice density is smaller for MY ice compared to FY ice based on the data in Table 1. However, the error in MY density is not well documented. As discussed in Fig. 2, the FY ice density used in the error analysis is assumed to be in the upper range of typical values. If we include both level and deformed ice the FY density is expected to become lower.

The error estimates shown in Fig. 3 are valid for the late winter period (March–May). The snow depth and ice density have strong seasonal variability, so the error estimates will be different for the other seasons.

5 Comparison with other relations between ice thickness and freeboard

The relation between ice thickness and freeboard has been investigated by Mironov and Sen'ko (1995), who analyzed measurements of ice thickness, ice draft, snow depth and density from the North Pole-29 drifting station collecting data across the Arctic Ocean from June 1987 to August 1988. They established the following relations:

$$H_i = 11.0F_i - 0.12 \tag{8}$$

for FY ice in the period from October to May, and

$$H_i = 15.29F_i - 0.657, \tag{9}$$

for MY ice in the period December to May.

By analyzing airborne lidar data and submarine sonar data, Wadhams (1992, 2000) has found an empirical relation between the freeboard and draft of thick MY ice north of Greenland, which corresponds to the following relation between thickness and freeboard:

$$H_i = 9.04F_i. \tag{10}$$

The relation used by Laxon et al. (2003) and Giles et al. (2007, 2008), is based on prescribed values of water and ice densities and snow loading climatology from Warren et al. (1999) and is given by:

$$H_i = 9.42F_i + 0.88. \tag{11}$$

The relations in Eqs. (1), (6)–(11), combined with direct measurements of thickness and freeboard from some recent expeditions, are presented in Fig. 4. The curves show calculated ice thickness for given freeboard values up to 0.5 m. The Sever data are marked by the black line representing the linear regression Eq. (1) as well as a grey zone corresponding to ±1 standard deviation. The asterisks indicate individual measurements during the expeditions in the Barents Sea area onboard R/V Lance in 2004 and R/V M. Somov in 2006.

There is significant spread in the relations, implying that the calculation of ice thickness from freeboard data depends on which relation is used and on errors in the data used to establish the relations. For FY ice there is reasonable agreement between all the data sets and empirical relations, except the relation used by Giles et al. (2007). For example, a freeboard measurement of 0.10 m corresponds to a thickness estimate of 1.18±0.2 m, using mean and standard deviation of the Sever data. When the effect of uncertainty in freeboard measurement is included, say ±0.05 m, the overall error in thickness retrieval will be about ±0.5 m. This is in agreement with the error analysis based on Eq. (5).

For MY ice there is more spread between the relations. Since there is no data analysis behind the comparison, it is difficult to assess the validity of the various relations. The relation by Wadhams et al. (1992) is based on data north of Greenland where the MY ice is heavily deformed, while the relation by Mironov and Sen'ko (1995) is based on data from the Central Arctic where ice is less deformed. Estimation of thickness from a freeboard of 0.3 m gives 3.93 m according to Eq. (9). This estimate seems to be in the upper range of expected values. If Eq. (7) is assumed to be more realistic and the effect of an uncertainty in freeboard measurement of ±0.05 m is included, the thickness retrieval will be 2.94±0.61 m.

6 Conclusions

In this study the technique of ice thickness retrieval from freeboard measurements, which will be provided by the CryoSat RA, has been validated and developed using in-situ data from field expeditions and other published results. The empirical relation,

TCD
4, 641–661, 2010

derived from measurements on 689 sites in the period March–May, allows calculating FY ice thickness from freeboard values in the range of 0.01–0.20 m. Analysis of the Sever data revealed that the average snow depth on the FY ice is 0.05 m, which is significantly less than that on MY ice. Snow density was 324±50 kg m^{-3}, which is in good agreement with other studies including both FY and MY ice.

Data on snow and ice density have been reviewed in order to estimate mean values and typical variability for assessment of errors in thickness retrieval from freeboard data. The density of level FY ice was estimated to be 916.7±35.7 kg m^{-3}, using the isostatic equilibrium equation and the Sever data. This estimate is in the upper part of the density range for FY ice according to the published results. The density of MY ice, calculated as the weighted average of its upper and lower layers, decreases from 887 to 876 kg m^{-3} with increase of its thickness from 2.4 to 4.2 m. Results from previous studies show that FY ice density has realistic values between 840 kg m^{-3} and 910 kg m^{-3}, while MY ice covers a wider range from 720 kg m^{-3} to 910 kg m^{-3} (Timco and Frederking, 1995).

The mean values and uncertainties of snow depth, and ice and snow densities, determined for FY ice and MY ice, were used to calculate the total error in ice thickness retrievals from freeboard measurements using the isostatic equilibrium equation. The uncertainties in snow depth have much less impact on the thickness retrieval than those in ice density and freeboard, using estimates representing late winter conditions (March–May). The ice density error increases with increasing freeboard, while the error in freeboard is nearly constant. Uncertainties of thickness retrieval amount to ≈60% for ≈1.0 m thick FY ice and to ≈24% for ≈2.4 m thick MY ice. If the MY thickness increases to ≈3.0 m the error is reduced to ≈21%. These estimates are based on a ±0.05 m error in the freeboard data. The error in freeboard measurements is the main uncertainty factor for FY ice thinner than 1.5 m, while ice density becomes the main error source for thicker FY ice and all MY ice. If the freeboard error can be reduced to 0.01 m, the error in thickness retrieval is reduced to about 32% for a 1.0 m thick FY floe and to about 18% for a 2.3 m thick MY floe.

A synthesis of investigated relations between ice freeboard and thickness has been established based on direct measurements from several field campaigns. There is a general linear increase in thickness as function of freeboard, but the spread of the relations is significant. For FY ice the relations are fairly consistent, whereas for MY ice there are inconsistencies among several of them. These relations are based on data obtained in different parts of the Arctic, where the amount and size of ridges significantly vary. Further studies are needed to clarify the freeboard-thickness relation for MY ice, which implies that more data on freeboard, thickness, density and snow cover need to be collected.

The results of the error analysis of the freeboard-thickness relation are directly applicable to the retrieval of ice thickness from IceSat and CryoSat altimeter data. The present analysis is based on data for the winter months only, and similar analyses should be conducted for the other seasons. There is general lack of in-situ snow and ice measurements in the Arctic, and new observing systems are therefore needed to provide data for validation of the ice thickness retrievals from CryoSat, expected to be in operation for five years from 2010.

Acknowledgements. This work was supported by the EU FP6 project DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environment Studies, no. 018509), the Research Council of Norway (project No. 178916/S30 Ice-ocean-atmosphere research in Svalbard using satellite and field data – promotion of Russian and Norwegian PhD cooperation), and the ESA Prodex project "CryoSat sea ice validation and process studies in the European Arctic" (contract No. C90318). The Sever data are provided by World Data Center for Glaciology/National Snow and Ice Data Center, University of Colorado, Boulder, Colorado.

References

Beaven, S. G., Lockhart, G. L., Gogineni, S. P., Hosseinmostafa, A. R., Jezek, K., Gow, A. J., Perovich, D. K., Fung, A. K., and Tjuatja, S.: Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets, Int. J. Remote Sens., 16(5), 851–876, 1995.

Connor, L. N., Laxon, S. W., Ridout, A. L., Krabill, W. B., and McAdoo, D. C.: Comparison of Envisat radar and airborne laser altimeter measurements over Arctic sea ice, Remote Sens. Environ., 113, 563–570, 2009.
Cox, G. F. N. and Weeks, W. F.: Equations for determining the gas and brine volumes in sea ice samples, CRREL Report 82–30, Hanover, NH, 1982.
Eicken, H., Lensu, M., Lepparanta, M., Tucker, W. B., Gow, A. J., and Salmela, O.: Thickness, structure and properties of level summer multiyear ice in the Eurasian sector of the Arctic Ocean, J. Geophys. Res., 100, 22697–22710, 1995.
ESA: CryoSat Science Report, ESA SP-1272, 56 pp., 2003.
Giles, K. A. and Hvidegaard, S. M.: Comparison of spaceborne radar altimetry and airborne laser altimetry over sea ice in the Fram Strait, Int. J. Remote Sens., 27(15), 3105–3113, 2006.
Giles, K. A., Laxon, S. W., Wingham, D. J., Wallis, D. W., Krabill, W. B., Leuschen, C. J., McAdoo, D., Manizade, S. S., and Raney, R. K.: Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002, Remote Sens. Environ., 111, 182–194, 2007.
Giles, K. A., Laxon, S. W., and Ridout, A. L.: Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum, Geophys. Res. Lett., 35, L22502, doi:10.1029/2008GL035710, 2008.
Gorshkov, S. G. (Ed.): Atlas of the oceans. The Arctic Ocean, USSR Navy Publishing House, 1980 (in Russian).
Khohlov, G. P.: Physico-chemical characteristics of the upper layers of different sea ice types in the area near of "NP-22" drifting station, Trudy Arkticheskogo i Antarkticheskogo Instituta, 359, 4–12, 1978 (in Russian).
Kubishkin, N. V. and Skutina, Y. A.: Changes of temperature, salinity, and density of level sea ice in spring period according to expedition studies in the Pechora Sea, Trudy Arkticheskogo i Antarkticheskogo Instituta, 449, 104–123, 2004 (in Russian).
Kwok, R., Cunningham, G. F., Wensnahan, M., Rigor, I., Zwally, H. J.. and Yi, D.: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008, J. Geophys. Res., 114, C07005, doi:10.1029/2009JC005312, 2009.

Laxon, S. W.: Sea ice altimeter processing scheme at the EODC, Int. J. Remote Sens., 15(4), 915–924, 1994.
Laxon, S. W., Peacock, N., and Smith, D.: High interannual variability of sea ice thickness in the Arctic region, Nature, 425, 947–949, 2003.
Leuschen, C. J. and Raney, R. K.: Initial results of data collection by the APL D2P Radar Altimeter over land and sea ice, J. Hopkins APL Tech. D., 26, 114–122, 2005.
Loshchilov, V. S.: Snow cover on the ice of the central Arctic, Problemy Arktiki i Antarktiki, 17, 36–45, 1964 (in Russian).
Malmgren, F.: On the properties of sea-ice, in: The Norwegian North polar expedition with the "Maud" 1918–1925, A/s John Griegs Boktrykkeri, Bergen, Scientific results, 1(5), 1–67, 1927.
Miller, P. A., Laxon, S. W., Feltham, D. L., and Cresswell, D. J.: Optimization of sea ice model; using basinwide observations of Arctic sea ice thickness, extent and velocity, J. Climate, 19, 1089–1108, 2006.
Mironov, Y. U. and Sen'ko, N. P.: About relation between ice thickness and ice draft, Trudy Arkticheskogo I Antarkticheskogo Instituta, 435, 47–54, 1995 (in Russian).
Mobley, C. D., Cota, G. F., Grenfell, T. C., Maffione, R. A., Scott Pegau, W., and Perovich, D. K.: Modeling light propagation in sea ice, IEEE T. Geosci. Remote, 36(5), 1743–1749, 1998.
Onstott, R. G.: SAR and scatterometer signatures of sea ice, in: Microwave Remote Sensing of Sea Ice, Geophysical Monograph No. 68, American Geophysical Union, Washington DC, 73–104, 1992.
Pavlov, V. K.: Circulation in ice-covered waters, in: Physics of ice-covered waters, vol. 2, Helsinki University Printing House, Helsinki, 447–482, 1998.
Radionov, V. F., Bryazgin, N. N., and Aleksandrov, Y. I.: The snow cover of the Arctic Basin, Gidrometeoizdat, St. Petersburg, 1996 (in Russian).
Romanov, I. P.: Atlas of ice and snow of the Arctic Basin and Siberian Shelf seas, Backbone Publishing Company, 1995.
Rothrock, D. A.: Ice thickness distribution – measurement and theory, in: The Geophysics of Sea Ice, Plenum Press, New York and London, 551–576, 1986.
Schulson, E. M., Fortt, A. L., Iliescu, D., and Renshaw, C. E.: Failure envelope of first-year Arctic sea ice: The role of friction in compressive fracture, J. Geophys. Res., 111, C11S25, doi:10.1029/2005JC003235, 2006.

Schwerdtfeger, P.: The thermal properties of sea ice, J. Glaciol., 4, 789–907, 1963.
Timco, G. W. and Frederking, R. M. W.: A review of sea ice density, Cold Reg. Sci. Technol., 24, 1–6, 1996.
Timokhov, L. and Tanis, F. (Eds.): Arctic Climatology Project, Environmental Working Group Joint U.S.-Russian Atlas of the Arctic Ocean – winter period, Environmental Research Institute of Michigan in association with the National Snow and Ice Data Center, Ann Arbor, MI, CD-ROM, 1997.
Tonboe, R. T., Pedersen, L. T., and Haas, C.: Simulation of the satellite radar altimeter sea ice thickness retrieval uncertainty, The Cryosphere Discuss., 3, 513–559, 2009, http://www.the-cryosphere.net/3/513/2009/.
Wadhams, P., Tucker III, W. B., Krabill, W. B., Swift, R. N., Comiso, J. C., and Davis, R. N.: Relationship between sea ice freeboard and draft in the Arctic Basin, and implication for ice thickness monitoring, J. Geophys. Res., 97(C12), 20325–20334, 1992.
Wadhams, P.: Ice in the Ocean, Gordon and Breach Science Publishers, 2000.
Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., and Colony, R.: Snow depth on Arctic Sea Ice, J. Climate, 12, 1814–1829, 1999.
Weeks, W. F.: Sea ice properties and geometry, AIDJEX Bulletin, 34, 137–172, 1976.

Table 1. Typical values and uncertainties of snow and ice density and snow depth for late winter conditions. The freeboard data are prescribed input to the isostatic equilibrium equation.

Parameter	Ice type			
	FY ice		MY ice	
	Typical value	Uncertainty	Typical value	Uncertainty
Ice freeboard, m	0.01–0.2*	0.05**	0.3	0.05**
Snow depth, m	0.05	0.05	0.35	0.06
Ice density, kg m^{-3}	916.7***	35.7***	882****	23****
Snow density, kg m^{-3}	324	50	320	20

* The freeboard varies with thickness and age of the FY ice,
** freeboard is a free variable and the uncertainty estimates are used as example of realistic numbers,
*** analysis of level FY ice from the Sever data,
**** based on data from literature.

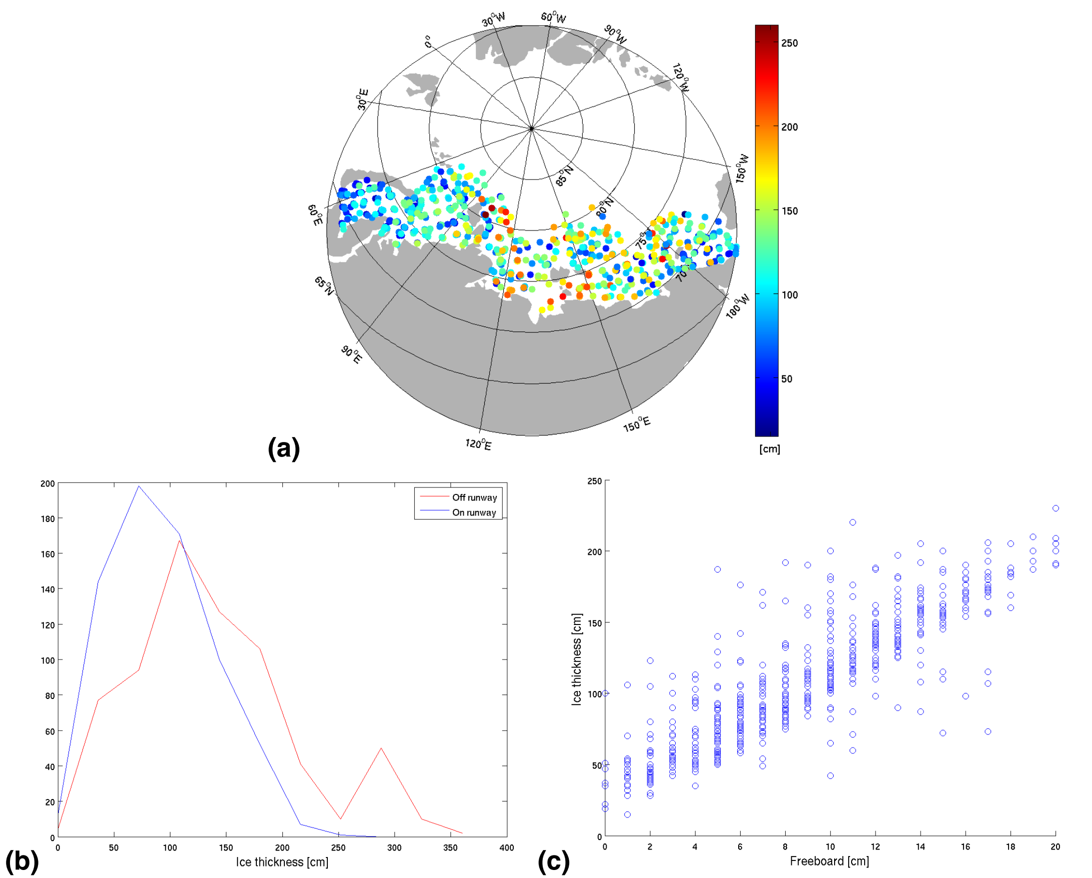

Fig. 1. **(a)** Location of 689 ice thickness and freeboard measurements during the Sever aircraft landings on the Arctic sea ice in 1980s, where colours indicate thickness of level ice on runways; **(b)** histogram of ice thickness on level ice (on runway) and on characteristic ice types around the landing sites (off runway), and **(c)** a scatterplot of ice thickness versus ice freeboard measurements on level ice.

TCD

4, 641–661, 2010

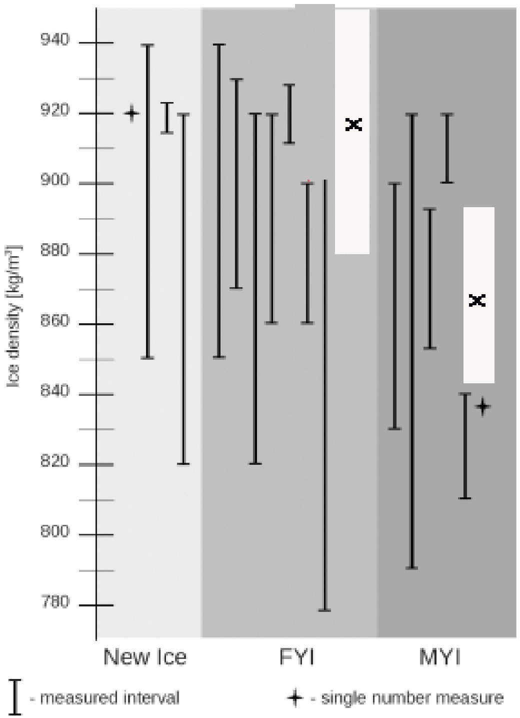

Fig. 2. A composite of sea ice density data measurement ranges obtained from Timco and Frederking (1995) and other published material. The white column under FY ice represents the mean and standard deviation of density retrieved from the Sever data. The white column under MY ice represents the best estimate of mean and standard deviation of density from published material.

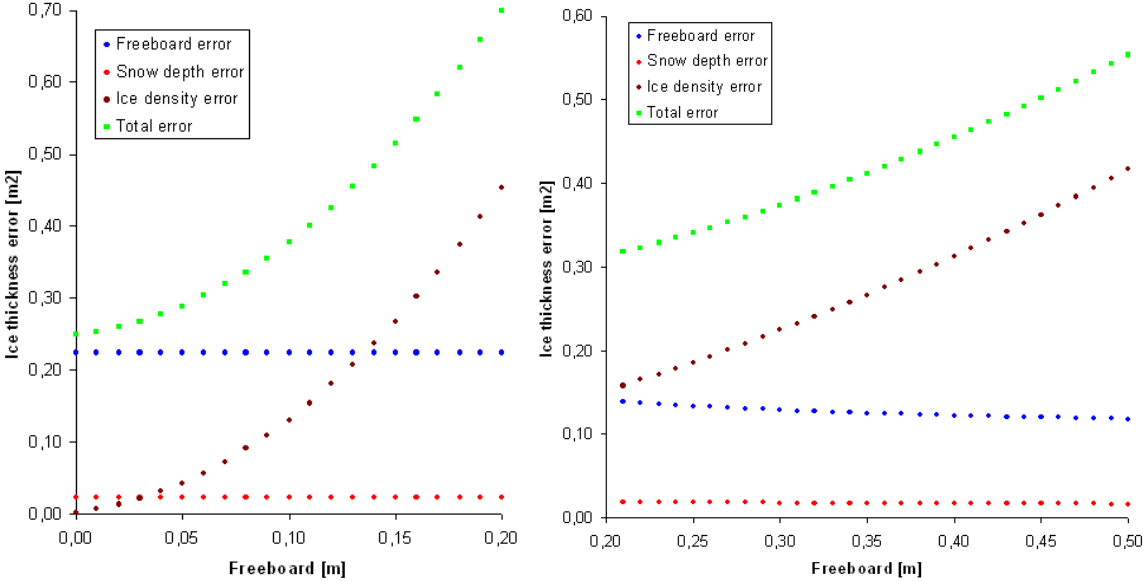

Fig. 3. Error terms contributing to uncertainty in ice thickness retrieval from freeboard measurements for first-year (left) and multiyear (right) ice. The prescribed error of ice freeboard is 0.05 m.

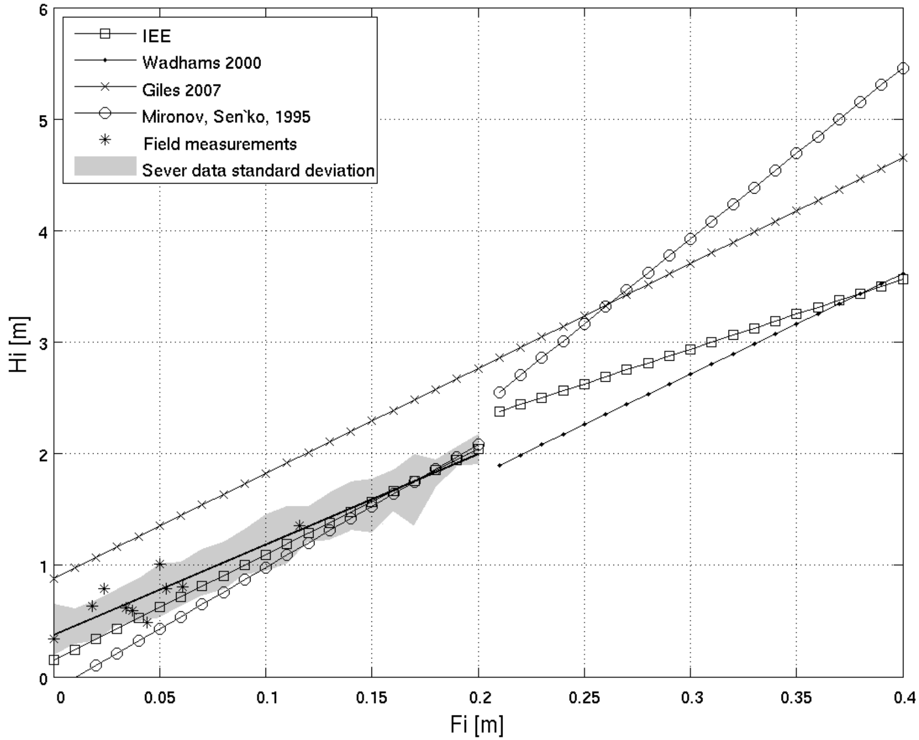

Fig. 4. Relation between ice thickness and ice freeboard based on measurements from **(a)** the Sever expeditions (Eq. 1, standard deviation is shown as the grey zone); **(b)** North Pole-29 drifting station (Mironov and Sen'ko, 1995) (Eqs. 8 and 9); **(c)** Wadhams et al. (1992) (Eq. 10); **(d)** isostatic equilibrium equation used by Laxon et al. (2003) (Eq. 11), and **(e)** isostatic equilibrium equation (IEE) for FY and MY ice used in this study (Eqs. 6 and 7). The asterisks represent other direct measurements of thickness and freeboard obtained by the authors in 2004 and 2006.