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Sea ice density measurements. Methods and uncertainties

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ABSTRACT

Sea ice density is an important engineering and geophysical parameter. However, it lacks a standard method of measurement. In this paper, we show that the hydrostatic weighing method is the best available method that can capture the natural variation of the ice density throughout the ice thickness below the water line. The hydrostatic weighing method has a lower measurement uncertainty (0.2%) in comparison with the most common mass/volume method, which has an uncertainty of 4% when applied to ice samples with lengths and diameters of ~70 mm. The density of first-year level ice below the waterline measured by the hydrostatic weighing method in the present study lies in a range of 894–921 kg m^{-3}. The density of rafted multiyear ice and the ice above the waterline had a wider range, 863–929 kg m^{-3}.

1. Introduction

Sea ice density is an important engineering parameter. When ice is submerged under water by a structure or a vessel, the buoyant force on the structure is proportional to the density difference of sea water and ice (Timco and Weeks, 2010). A 10% (~100 kg m^{-3}) underestimation of ice density may cause approximately 100% overestimation of the buoyancy force. From a geophysical perspective, ice density is used for monitoring sea ice volume. The ice volume is calculated based on the ice surface area, ice freeboard retrieved from the radar altimetry and assumed ice density (Alexandrov et al., 2010; Kern et al., 2015). A 4% (~40 kg m^{-3}) uncertainty in the ice density may result in ~30% error in the ice thickness estimation for first year ice that is 1.1–2 m thick (Alexandrov et al., 2010).

An extensive review of sea ice density measured before 1996 is presented in Timco and Frederking (1996). According to this review, the density of the sea ice above the waterline is in a range of 720–910 kg m^{-3} and below the waterline it lies in a narrower range of 900–940 kg m^{-3}. It should be noted that the largest part of the ice is below the waterline. Therefore, the expected average density of the sea ice should vary within a narrow range. More recent sea ice density data are reported in Alexandrov et al. (2010) and Hutchings et al. (2015). However, the mean density of the rafted first-year ice presented in Hutchings et al. (2015) is 800 and 870 kg m^{-3}, which is below the range reported by Timco and Frederking (1996) for the first-year ice.

The wide spread in measured values can be due to two fundamental types of uncertainty: natural and epistemic (Merz and Thieken, 2004). The natural variation reflects the true heterogeneity of the ice density including spatial (horizontal and vertical) and temporal variation The spatial variation covers both small-scale variation across the ice cores collected at the same field site and large-scale variation, which implies field studies in different regions. The temporal variation in its turn is associated with the seasonal changes in the weather conditions and other natural processes. The epistemic uncertainty arises from poor measurement technique or equipment. It also includes the error caused by the brine loss due to the gravity drainage during sampling and the brine expulsion during storage (Cox and Weeks, 1986). The natural variation of the ice density can be measured only if the epistemic uncertainty is less than the natural variation.

Sea ice density measurement uncertainties associated with the most common methods, including mass/volume, liquid/solid and freeboard methods, have been recently reported in Hutchings et al. (2015). According to them the mass/volume method is the most accurate of the three. Its measurement uncertainty is 3–8% depending on the size of the ice sample. However, Hutchings et al. (2015) did not cover the hydrostatic weighing method, which has an even lower measurement uncertainty, 0.05–1.3%, according to other studies (Nakawo, 1983; Kulyakhtin et al., 2013; Pustogvar and Høyland, 2015). In the present study, we compare the mass/volume and the hydrostatic weighing methods, focusing on their epistemic uncertainties: limiting measurement uncertainty and the errors related to the brine loss. The natural vertical variation of sea ice density is also discussed.

2. Measurement methods and their epistemic uncertainties

In the mass/volume method, the density is calculated from the measured mass of the sample and its volume. The volume is calculated

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based on the assumed geometry and linear dimensions of the sample measured with a caliper or similar instrument.

The limiting measurement uncertainty is defined as the sum of maximum positive errors of all measurements. For the mass/volume method, the limiting measurement uncertainty is expressed as:

$$\Delta\rho_{ice} = \frac{\partial\rho_{ice}}{\partial M}\Delta M + \frac{\partial\rho_{ice}}{\partial D}\Delta D + \frac{\partial\rho_{ice}}{\partial L}\Delta L \quad (1)$$

$$\frac{\Delta\rho_{ice}}{\rho_{ice}} = \frac{\Delta M}{M} + 2\frac{\Delta D}{D} + \frac{\Delta L}{L} \quad (2)$$

where M is the mass of the sample, and D and L are the diameter and the length, respectively, with the assumption of a cylindrical sample shape, which is the typical shape of an extracted core. This type of uncertainty, however, does not take into account the uneven surface of the sample and the deviation of the sample shape from a cylindrical shape.

The hydrostatic weighing method is based on Archimedes' law. The sample mass is measured both in the air and when it is submerged in any liquid having a density less than the density of the ice sample (paraffin in the present study; in previous studies, the submersion liquid was petroleum (Malmgren, 1927), 2,2,4-trimethylpentane (Nakawo, 1980, 1983) or paraffin (Kulyakhtin et al., 2013)). The ice density in hydrostatic weighing is derived as:

$$\rho_{ice} = \frac{M_{air}}{M_{air} - M_{par}}\rho_{par} \quad (3)$$

where M_{air} and M_{par} are the masses of the sample suspended in the air and in the paraffin, respectively, and ρ_{par} is the density of the paraffin.

The limiting measurement uncertainty of the hydrostatic weighing method is:

$$\Delta\rho_{ice} = \frac{\partial\rho_{ice}}{\partial M_{air}}\Delta M_{air} + \frac{\partial\rho_{ice}}{\partial M_{par}}\Delta M_{par} + \frac{\partial\rho_{ice}}{\partial\rho_{par}}\Delta\rho_{par} \quad (4)$$

$$\frac{\Delta\rho_{ice}}{\rho_{ice}} = \frac{M_{par}}{(M_{air} - M_{par})}\frac{\Delta M_{air}}{M_{air}} + \frac{M_{par}}{(M_{air} - M_{par})}\frac{\Delta M_{par}}{M_{par}} + \frac{\Delta\rho_{par}}{\rho_{par}} \quad (5)$$

The hydrostatic weighing method is commonly considered to be more time consuming than the mass/volume method. However, in the mass/volume method, substantial time is spent for thorough measurements of sample dimensions using a caliper. In the case of the hydrostatic weighing method, no size measurements are required, the mass measurements are fast and most of the time is spent to tie a thread around a sample; the thread is further used to hang the sample on weight scales. Based on our experience, the time spent on the hydrostatic weighing measurements is comparable with the time spent on the mass/volume method.

Brine drainage during sampling is another component of epistemic uncertainty. Both methods are core-based methods and result in a brine loss when the core is lifted out of the water. In this case, the water in open brine channels is replaced by the air, which artificially increases the air content. This is especially significant for the lower part of an ice core with high permeability. In the hydrostatic weighing method, the brine channels drained during the core retrieval are filled with paraffin during submersion. Therefore, the volume of open brine channels is excluded from the measurements.

To demonstrate the uncertainty related to the brine loss due to gravity drainage, we use the data on the brine/air volume fractions and bulk density of ice published in Crabeck et al. (2015). The brine volume fractions of the ice samples from the bottom of the core sampled on January 25 were 16 and 19%. To evaluate the upper limit of the measurement uncertainty, let's make an assumption that these volumes fully corresponded to the volumes of the brine channels, i.e., that there was no brine trapped in brine pockets. The reported bulk density of the samples was 920 kg m^{-3} and the air volume was ~1.5% at −2 °C. Based on the air volume fraction and temperature, the density of brine-free ice that is the part of the sample with excluded brine channels can be calculated as (Cox and Weeks, 1983; Leppäranta and Manninen, 1988):

$$\rho_{bf} = \left(1 - \frac{V_a}{V}\right)\left(0.917 - 1.403 \cdot 10^{-4}T\right) \quad (6)$$

where ρ_{bf} is the density of the brine-free ice, $\frac{V_a}{V}$ is the air volume fraction and T is the temperature. In our example, the brine-free density is equal to 904 kg m^{-3}. The brine free density is the density obtained by the hydrostatic weighing method (ρ_{HW}) for the considered case of complete brine loss. A comparison of this density estimate using the hydrostatic weighing method with the reported bulk density of 920 kg m^{-3} indicates an error equal to ~2% for ice density measurements due to the brine loss.

In the case of the mass/volume method, the bulk density is estimated as follows:

$$\rho_{MV} = \left(1 - \frac{V_b}{V}\right)\rho_{bf} + \frac{V_b}{V}\rho_a \quad (7)$$

where $\frac{V_b}{V}$ is the brine volume fraction and ρ_a is the density of the air (~1.3 kg m^{-3}). Here, unlike the hydrostatic weighing method, the brine channel volume is included in the bulk density calculations but the channels are filled with air. So, for our example, the estimated densities using the mass/volume method are 757 and 727 kg m^{-3}, which, respectively correspond to the initial brine volumes of 16 and 19%. Therefore, the error of the ice density measurements due to the brine loss (if such happens) in the case of the mass/volume method is substantially greater than in the case of hydrostatic weighing method when samples are subjected to brine drainage. For given above example the error is ~20% for mass/volume and only ~2% for hydrostatic weighing. To achieve the above-described accuracy of the hydrostatic weighing method, we need to assure that all the air in the brine channels is replaced by paraffin. Otherwise, the density is underestimated; however, the underestimation is less than that by the mass/volume method.

It is believed that sample storage is another source of epistemic uncertainty due to the brine loss. Cox and Weeks (1986) theoretically investigated this question and showed that no porosity change would be expected for samples with in-situ temperatures below −10 °C. They claimed that cycling an ice sample from a near-melting temperature to a cold storage temperature and back to in-situ temperature for testing can result in up to 15% porosity change due to the brine expulsion. However, the underlying assumptions are unrealistic, such as the assumptions that the ice is completely air-free at the time of extraction and that there is no resistance to the brine expulsion through the sample. Additionally, the theoretical estimates of porosity changes are not supported in the experiments. Nakawo (1983) sampled two cores with adjacent locations and measured the density and air porosity of one core immediately following the extraction and measured the other core after six months of storage at −40 °C. Although the cores were extracted at an air temperature of −23 °C, the temperature of the lower part of the core that was similar to the ice/seawater interface temperature of −2 °C. No porosity changes had been observed (Nakawo, 1983), which leads to a conclusion that the effect of brine loss due to storage is negligible.

3. Data description

The data presented in this paper were collected at two field sites. The first site was on the 1.6- to 1.7-m thick ice in the vicinity of an ice ridge in the Fram Straight, Greenland. The measurements were performed as a part of the ice investigation program during the Oden Arctic Technology Research Cruise (OATRC2013) in August 2013. Two pairs of cores were