

Response to Editor

Editor's comments are in blue, our responses are in black

"The current size of the paper exceeds these requirements, as the length is too long (by about one third)" ... "There are too many figures and tables (1 table, 5 figures). In my view, figs. 3-5 are not not essential to the manuscript. I also think that the error analysis can be substantially shortened."

We thank the editor for reconsidering his decision to reject this paper and allowing submission of a revised version incorporating minor corrections. This new manuscript has been greatly reduced in length (from 3462 words to 2676 words), in particular the error section has been significantly shortened. Figures 3-5 have been removed. We hope this revised version will be suitable for final publication in The Cryosphere.

Many thanks, Tom Watts (on behalf of all authors)

Response to Reviewer 1

Reviewer's comments are in blue, our responses are in black

The authors reported on a new technique to measure ice layer density of snowpack in the field. To discuss the accuracy of their technique, they evaluated each error resulting from their technique in detail. Thus, their results should be more accurate than the previous studies. Although the scientific discussion is not satisfied due to the small number of observation cases, their method has a potential to contribute the future studies of ice layer of snowpack. The contents and length of the manuscript are reasonable for Brief communication of TC. For this reason, this paper is worth publishing. Before acceptance, several things, which is shown in comments, should be considered.

L89-90: Is there any reason to choose the volume value of the theoretical sample as 4.89 cm³? If there are any reasons, please add the information.

Added "(chosen as it was the estimated smallest sample volume taken during field trials)"

L133-134: What does significant difference mean?

Changed to "The Kolmogorov-Smirnov test showed natural ice layers were significantly less dense than artificial ones, although the difference was within methodological error"

L136-141: It is difficult to follow the logic of these sentences. Please clear the logical process.

This has been reworded to "The results from Inuvik show some physically unreasonable high outlying measured densities (Fig. 3). Mass measurements at Inuvik were made outside, and whilst care was taken to ensure the balance was level and condensation was cleaned from the balance as it formed, these cannot be ruled out as sources of error."

L139: What does (2) indicate?

Corrected to "(Fig. 2)"

Response to Reviewer 2

Reviewer's comments are in blue, our responses are in black

The paper in its revised form as a brief communication reads very well and nicely introduces this new method to measure the density of ice layers. However, the authors ought to be extremely careful in introducing an effective porosity that they too often abbreviate by porosity alone. The latter is ambiguous and misleading. On p. 5, lines 151- 157, you need to make clear that you are after that volume on the edges of your broken samples that is wetted after submersion, correct? This may be loosely related to effective porosity that is more commonly defined as, That portion of porosity which is readily accessible to a fluid moving through the porous medium. In that sense I understand that effective porosity can increase, but not porosity itself. You definitely have to make a clear distinction between these two terms and call your parameter effective porosity throughout the paper. Note that it is not before p. 6, lines 171-172, that I start to understand why you use the term effective porosity even though it is hardly aligned with definitions found in literature. I recommend accepting the paper after the authors addressed the porosity issue and do some minor revisions as suggested below.

This section was shortened at the request of the editor, however we have reworded the introductory paragraph of section 3.3. It now reads "The measured ice layers had a closed porosity, where layers contained bubbles they were not connected in a porous structure. A greater volume of bubbles in the sample reduces the external dimensions and volume of the sample. Here we refer to this reduction in volume caused by the presence of bubbles as effective porosity, represented by a dimensionless fraction which represents the proportion of sample volume which is available for liquid to flow through.". Additionally we have made our references to effective porosity consistent.

Minor comments

abstract, line 3: "...on 87 **samples taken from 4 ice layers, both natural and artificial, in...**"

Changed to : "The method was used on 87 ice layer samples, taken from natural and artificial ice layers in the Canadian Arctic and mid-latitudes".

p. 1, line 14: "ice crust" I guess these layers involved some melting followed by refreezing. Today these layers would more properly be noted as melt-freeze crusts. Thus the term ice crust sounds ambiguous to me in the context of your paper and I'd suggest you make a note on this here.

Changed to: "Ice layers differ from melt-freeze crusts (often referred to as 'ice crusts') and ice lenses; melt-freeze crusts are always permeable and have a coarse grained granular snow-like structure." later instances of 'ice crust' were also updated to "melt-freeze crust".

p. 2, line 50: "and that repeat images" wording unclear to me. Is there something missing in that sentence?.

Corrected to: "Each camera image was centred on a visible datum on the mounting system to ensure the camera was correctly focused. Images were captured before and after each ice sample was submerged as shown in Fig 1."

p. 6, lines 179-180 : Use ϕ_{eff} instead of ϕ .

This has been updated

p. 7, line 204: No doubt the ice layers were porous. The question about permeability remains open though.

Removed mention of 'porous'

Figures

Figure 3: Replace "porosity" by **effective porosity** in the caption.

This figure has been removed at the suggestion of the editor to fit length requirements

Figure 5: Here you are showing "Effective porosity of sample (1)" vs "Density (kg m^{-3})", not the contrary.

This figure has been removed at the suggestion of the editor to fit length requirements

Replace "porosity" by **effective porosity** in the caption.

This figure has been removed at the suggestion of the editor to fit length requirements

Tables

Table 1: Caption, line 271: replace "diameter" with **bubble diameter**.

Corrected

The overall numbers for both Layer Thickness and Density are not consistent with the sum of the above columns.

Corrected

Replace all "0" with dashes

Corrected

Brief communication: Improved measurement of ice layer density in seasonal snowpacks

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Abstract. The microstructure and density of ice layers in snowpacks is poorly quantified. Here we present a new field method, for measuring the density of ice layers caused by melt or rain-on-snow events. The method was used on 87 ice layer samples, taken from natural and artificial ice layers in the Canadian Arctic and mid-latitudes; ~~the mean~~. Mean measured ice layer density was 5 909 ± 28 kg m⁻³ with a standard deviation of 23 kg m⁻³, significantly higher than values typically used in the literature.

1 Introduction

Ice structures form in snowpacks during melt or rain-on-snow events (Colbeck, 1991). Rain either freezes on contact with the surface of the snowpack, or water refreezes within the snowpack to 10 form ice layers, lenses, crusts, columns, or basal ice layers (Gray and Male, 1981). Strong intercrystalline bonds created from refreezing of liquid water, lead to the formation of cohesive ice structures (Fierz et al., 2009). Permeability of ice layers to liquid water and gas is vastly reduced compared to snow (Albert and Perron Jr., 2000; Colbeck and Anderson, 1982). Impermeable layers are identifiable because pores do not connect within the ice formation, and the granular snowpack structure is 15 missing (Fierz et al., 2009). Ice layers differ from ~~ice crusts~~ melt-freeze crusts (often referred to as ‘ice crusts’) and ice lenses; ~~ice-melt-freeze~~ crusts are always permeable and have a coarse grained granular snow-like structure (Colbeck and Anderson, 1982). Ice lenses can be impermeable, do not have a granular structure and are spatially discontinuous. Similarly to ice lenses, ice layers can be impermeable, and do not have a granular structure, however, ice layers are continuous (Fierz et al., 20 2009).

Ice layers introduce uncertainty into the performance of snow microwave emission models (Rees et al., 2010), which are an important component of satellite derived snow water equivalent (SWE) retrieval algorithms (Takala et al., 2011). The radiometric influence of even thin ice layers poses a significant challenge for physical and semi-empirical snow emission models, which can either

25 treat ice layers as coarse grained snow (Mätzler and Wiesmann, 1999) or as planar (flat and smooth) ice layers (Lemmetyinen et al., 2010). Uncertainties attributed to not knowing the density of ice layers are greater than any other parameter in snow emission models (Durand et al., 2008). Consequently, development and evaluation of snow emission models are hindered by poorly quantified field measurements of microstructure and properties of ice layers (Montpetit et al., 2012).

30 Pure ice density ranges from 916 kg m^{-3} at 0°C (Lonsdale, 1958) to 922 kg m^{-3} at -40°C (La Placa and Post, 1960). Only limited field measurements of ice layer densities have previously been attempted. Ice layer density measurements taken in the Canadian Arctic by submerging pieces of ~~ice-melt-freeze~~ crust into oil resulted in a range of densities from 630 to 950 kg m^{-3} (Marsh, 1984). Ice layer densities of 400 to 800 kg m^{-3} were measured using a snow fork, which measures
35 the dielectric properties of snow around 1 GHz (Sihvola and Tiuri, 1986) in seasonal snow on the Greenland ice sheet (Pfeffer and Humphrey, 1996). The results from these studies vary drastically and a quantitative assessment of the error in measurement techniques is absent. Consequently, the aim of this paper is to describe a newly developed field measurement technique for measuring ice layer density, and present density measurements made in Arctic and mid-latitude snowpacks.

40 2 Method

2.1 Development of ice density measurement method

A new laboratory and field-based method (Fig. 1) was developed to measure the density of ice layers found in seasonal snow, based on volumetric displacement. The basic principle is that when an ice layer sample is submerged in a vessel of liquid, calculating the volume displacement and sample
45 mass will yield an estimate of density. The mass of a sealed 50 ml centrifuge tube with 2.5 ml graduations containing white spirit (sometimes termed “mineral spirits”), was measured with a precision of $\pm 0.001 \text{ g}$ under laboratory conditions before entering the field. White spirit is immiscible with water and has a low freezing point (-70°C), eliminating potential sample melt. White spirit also has a low density (650 kg m^{-3}), making it likely that the ice sample would sink and be completely
50 submerged. In the field the centrifuge tube was held by a fixed, levelled, mounting system within the macro setting range of a compact camera. Each camera image was centred on a visible datum on the mounting system to ensure the camera was correctly focused, ~~and that repeat images~~. Images were captured before and after each ice sample was submerged as shown in Fig. 1.

In each image three positions were identified during post processing: the liquid level, the graduation above the liquid level and the graduation below the liquid level. Pixel co-ordinates of these
55 positions were recorded and the proportional height of the liquid level between the upper and lower graduation was translated to a volume at a higher resolution than the centrifuge tube graduations alone would allow. ~~The top of the liquid level was located rather than the meniscus for ease of identification; as relative volume change was used no error was introduced.~~ After images were taken,

the centrifuge tube containing the sample was sealed and the change in mass was measured on return to the laboratory. ~~Only samples where the liquid in the tube was level in both images were considered.~~

2.2 Methodological error

Ice layers found in snowpacks are very difficult to accurately and consistently re-create under laboratory conditions. Therefore to assess the accuracy of the ice density measurement technique, ball bearings of known volume were measured. Stainless steel ball bearings were used (manufactured to a diameter of $1 \pm 2.5 \times 10^{-5}$ cm), resulting in a volume of 0.5236 ± 0.0004 cm³. The volume of ~~the~~ ball bearings was calculated from before and after images of 10 ball bearings submerged in the centrifuge tube. The expected total volume of all ball bearings of approximately 5.236 cm³ is comparable to the mean volume of ice samples collected. Of 134 samples, each consisting of 10 ball bearings, the mean volume was 5.045 cm³. ~~The volume~~ Volume measurements were normally distributed and an error value based on ± 1 standard deviations was calculated, resulting in a systematic volume measurement error or bias of -0.19 cm³.

~~The largest source of error is in reading the height of the liquid in the centrifuge tube from the camera photos.~~ Identifying the precise height of the surface of the liquid between the graduation markings on the cylinder is limited by the quality of the camera focus and resolution of the camera. ~~If the camera focus is not perfect it is difficult to locate the height of the liquid, which result in error and uncertainty.~~ Based on carrying out 10 repeat measurements on 10 centrifuge tube photos the (mean) error was found to be ± 0.125 cm³ in each volume measurement photo, equating to a random root mean squared error in the measurement of the ice sample volume of ± 0.18 cm³ ($error = \sqrt{0.125^2 + 0.125^2}$), as each volume measurement involves reading the volume from two photos.

~~To calculate the optimum sample volume, the number of ball bearings used in each volume measurement was increased from 1 to 24, a volume range of 0.52 to 12.57. Correlation between standard deviation and sample volume was not statistically significant (confidence > 99), demonstrating that the error in volume measurement was independent of sample volume. Field trials suggested that 10 was the maximum sample volume routinely possible to use due to the diameter of the centrifuge tube. Although no minimum sample volume was set, the largest possible sample was obtained.~~

~~To~~ estimate the potential impact of the uncertainty in volume measurement on samples taken in the field, the random (± 0.18 cm³) volume measurement error from the ball bearing experiment was applied to a theoretical ice sample of volume 4.89 cm³ (chosen as it was the estimated smallest sample volume taken during field trials) and mass 4.53 g (equating to a density of 916 kg m⁻³). This volume error from the ball bearing experiment translated into an observed volume of 4.53–4.89 cm³ (i.e. 4.71 ± 0.18 cm³). Assuming no error in the mass balance (precision of ± 0.001 g), the upper

density value (minimum volume) was 951 kg m^{-3} and the lower density value (maximum volume) was 881 kg m^{-3} , representing an uncertainty in density of $\pm 35 \text{ kg m}^{-3}$ or 4 %.

2.3 Field measurements

During the winter of 2013, ice layer density measurements were collected at three sites in Canada:
100 North Bay, Ontario (46.33° N , 79.31° W) between 8–9 February, Canadian Centre for Atmospheric Research (CARE), Egbert, Ontario (44.23° N , 79.78° W) on 25 February, and Trail Valley Creek, Inuvik, North West Territories (68.72° N , 133.16° W) on 9 April. Ice layers were removed from the surrounding snow and broken to size using a scraper.

In North Bay ~~, snow stratigraphy, density and the mean maximal extent of individual snow grains were measured in a woodland clearing. An (NB), an~~ artificial ice layer was created ~~on by spraying water onto~~ the surface of the snowpack ~~and compared with naturally formed ice layers~~. Artificial ice layers have been created in previous work (Montpetit et al., 2012) so it is important to know if their characteristics differ from naturally occurring ice layers. ~~To create the ice layer a very thin top layer of undulating recent snow (less than 6h old) was swept from the snowpack to expose a melt crust below, this was done to maintain an ice layer of even thickness across the site. After the removal of recent snow, water was sprayed onto the snowpack to create a surface ice layer. The ice layer was distinct to the melt-freeze crust and was removed from it when the layer was extracted.~~ A natural ice layer covering the entire clearing was also present lower within the snowpack (formed by 2 mm of rain on 30 January). Density, bubble diameter, and thickness measurements
115 of both natural and artificial ice layers were made; whenever bubbles were visible their diameters were measured using a field microscope and snow grain card, at a resolution of 0.1 mm. Very small bubbles, with a diameter of $< 0.1 \text{ mm}$ were recorded as being visible although a diameter could not be applied to them. Layer thickness was measured to a resolution of 1 mm for each sample. ~~Density measurements were made of 15 natural and 15 artificial ice layer samples.~~

120 At CARE, measurements were conducted in an open, grass-covered field. A spatially continuous ice layer formed over an area of at least $200 \times 100 \text{ m}$ in the 10 cm deep snowpack as a result of above-freezing daytime temperatures for a period of 4 days prior to measurement. Ice layer thickness and densities were measured in the same manner as in North Bay, ~~29 measurements of ice density and thickness were made.~~

125 In Inuvik, water was sprayed onto a 30 cm tundra snowpack when air temperatures were approximately -25° C to form an artificial ice layer on the surface of the snowpack ~~as no natural ice layer was present~~. Water was sprayed over an area of 1 m^2 , concentrating the spraying towards one edge ~~, creating which created~~ ice thicknesses between 1 ~~to and~~ 6 mm ~~which allowed 28 measurements of ice layer density across a range of ice layer thicknesses.~~

130 3 Results

3.1 Ice layer density

Mass, volume and density measurements were made of 86 samples of ice layers and are summarised in Table 1 and Fig. 2. After measurements were corrected for bias the mean sample volume was 6.4 cm^3 and when, After the random error of $\pm 0.18 \text{ cm}^3$ was applied to the volume measurements an uncertainty of $\pm 28 \text{ kg m}^{-3}$ was calculated. Ice layer densities varied between 841 and 980 kg m^{-3} , with an overall mean of 909 kg m^{-3} and standard deviation of 23 kg m^{-3} . Analysis using the A Kolmogorov-Smirnov test showed ~~all ice layers to be significantly different. Natural ice layers were on average~~ natural ice layers were significantly less dense than artificial ones, although the difference was within methodological error. The ~~measurements in results from Inuvik show some physically unreasonable high~~ outlying measured densities (Fig. 2). Mass measurements at Inuvik were made outside, and whilst care was taken to ensure the balance was level and condensation was cleaned from the balance as it formed, these cannot be ruled out as sources of error and could be a reason why some of the high outlying measured densities (2) are physically unreasonable at the Inuvik site. The air temperature was so cold that the water source for creating the artificial layers was freezing up, therefore it is considered unlikely that the artificial ice layers were wet when measured.

3.2 Ice layer bubble size and thickness

Table 1 summarises the measurement of ice layer thickness and bubble size. In some cases bubbles were visible in the ice layer, but were not large enough to be measured using the field microscope. These were noted as $< 0.1 \text{ mm}$ in Table 1. For the purpose of calculating the mean and standard deviation of the bubble distribution a value of 0.05 mm was applied to these bubbles. There was no significant correlation between ice layer thickness and bubble diameter ($p < 0.01$).

3.3 Error analysis

Three sources of error were quantified in the measurement of ice layer density: (1) systematic error and (2) random error in the volumetric measurement of the ice samples, which would apply to any object measured using this method (both discussed in Sect. 2.2), as well as (3) error from sample porosity, which applies only to the measurement of ice layer density. The measured ice layers had a closed porosity, where layers contained bubbles they were not connected in a porous structure. However, due to the presence A greater volume of bubbles in the ice layers some increase in porosity would occur as more bubbles are exposed when the ice layer was broken and placed in the centrifuge tube. The exposure of the bubbles causes effective porosity and is sample reduces the external dimensions and volume of the sample. Here we refer to this reduction in volume caused by the presence of bubbles as effective porosity, represented by a dimensionless fraction which represents the proportion of a sample volume which is available for liquid to flow through.

The influence of effective porosity on the ice layer density measurements was quantitatively evaluated by numerically modelling the bubbles ~~within ice layers. Air bubbles within the ice layer were represented using spheres, scattered randomly, without any overlap within an ice sample of size x, y, z and density d . The sizes of the spheres were determined by taking a random sample from a normal distribution of bubble sizes based on the mean and standard deviation of bubble diameter measurements. A sphere size was chosen randomly from the distribution and located randomly within the x, y, z axes. If the sphere overlapped another sphere then the location was changed until no overlap occurred. If after 1000 attempts a location for the sphere could not be found its radius was changed to another random sample from the normal distribution and the process repeated. After each sphere was placed, the total volume of all the spheres and the density of the ice sample was calculated. Spheres were added to the sample until the desired density was reached starting from an initial pure ice density of 916 kg m^{-3} . Examples of the ice layers with bubbles distributed in them are shown in Fig. ??.~~

~~Slices were taken through the modelled ice sample and the volume of the spheres that would be open to the surface and allow liquid to penetrate the ice surface was calculated. For example, if the slice went through a sphere at exactly the halfway point, half of the volume of that sphere would be added to the porosity value for that sample (Fig. ??).~~ as spheres within cuboid ice layer samples. This method assumes that the ice layer is solid ice containing bubbles rather than a granular snow-like structure. For a theoretical ice sample of size $10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$ the sample density was increased in increments of 0.01 kg m^{-3} from 600 to 916 kg m^{-3} , and effective porosity was measured through the sample by taking slices at 0.1 cm intervals.

The relationship between effective porosity and density (ρ) for this bubble and sample size is linear (Fig. ??), and the effective porosity (ϕ_{eff}) is found using:

$$\phi_{eff} = -0.00016\rho + 0.14. \quad (1)$$

~~assuming the same porosity on all edges of the ice sample (where the sample was broken). The mean~~

Mean bubble diameter and standard deviation were calculated from all samples. The root-mean-squared-error of Eq. (1) was 0.0007 with an r squared value of 0.998.

The impact of effective porosity on the samples was calculated by assuming a sample width of 2 cm (the width of the centrifuge tube). ~~Sample thickness and volume were measured (with known methodological error) and used to estimate the maximum and minimum dimensions of each sample. The relationship in Eq. (1) was used to estimate the porosity of each sample based on the measured density.~~ As the density of the sample decreased, volume error from effective porosity in the sample ranged from 6.5×10^{-5} to $1 \times 10^{-3} \text{ cm}^3$. The mean increase using either the maximum or minimum value for density in the effective porosity calculations was $1.42 \times 10^{-6} \text{ cm}^3$. The maximum random error ($\pm 0.18 \text{ cm}^3$), the volume measurement bias reflecting systematic error (-0.19 cm^3), and the effective porosity correction were applied to each volume measurement. The maximum range of

density was calculated for each sample and the ~~samples'~~^{effective} porosity was negligible (less than 0.001 cm^3). Overall the measurements of ice layer density ($909 \pm 28 \text{ kg m}^{-3}$) were not significantly different to the actual density of pure ice $916 - 922 \pm 28 \text{ kg m}^{-3}$ between 0 to -40°C (Lonsdale, 1958; La Placa and Post, 1960).

205 4 Discussion and Conclusion

New laboratory and field protocols were used to produce direct measurements of ice layer density including a thorough assessment of measurement uncertainty. Measurements of natural and artificially made ice layers produced an average density of $909 \pm 28 \text{ kg m}^{-3}$, where uncertainty is a function of the random error in the method used to measure the volume of the ice samples. Effective porosity of
210 ice layers was estimated using observations of bubble size and was deemed to be too low to impact the accuracy of the method. Our measured density values are higher than those previously measured by Marsh (1984) (mean 800 kg m^{-3}), and Pfeffer and Humphrey (1996) (400 to 800 kg m^{-3}). It is unclear whether previous studies measured the density of ice layers that were permeable~~and porous~~, including thin, non-continuous ice layers. Here only impermeable ice layers were measured and this
215 may explain the density differences between studies. In addition, artificially created ice layers had a higher density than natural ice layers (Table 1). A possible reason for this is that the artificial ice layers were created on the surface of the snowpack, which is likely to experience lower air temperatures than naturally formed ice layers within the snowpack.

Densification and ice formation impacts passive microwave brightness temperatures at the satellite
220 scale (Grody, 2008). Consequently, the evolution of ice structures is important in characterisation of snowpack microwave signatures, and may play an important role in ice layer detection algorithms. However, snow microwave emission models are currently unable to accurately model ice layers (Rees et al., 2010). Some snow emission models (e.g. Wiesmann and Mätzler (1999); Picard et al. (2013)) include a parameter for ice layer density, which has previously been very poorly constrained
225 and is a large source of uncertainty in emission models (Durand et al., 2008) and remote sensing data assimilation applications (Langlois et al., 2012). Consequently, new ice layer density measurements presented here provide a means to reduce uncertainty in future snow radiative transfer modelling.

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230 and Andrew Rees for support during data collection in North Bay, Dave Halpin and Dave Thomas for help facilitating field and lab work and James Reeve for support with experiment design. This work was supported by a Northumbria University RDF studentship (Tom Watts) and the Natural Science and Engineering Research Council (Discovery Grant: Chris Derksen); field activities were funded by Environment Canada.

References

- Albert, M. R. and Perron Jr., F. E.: Ice layer and surface crust permeability in a seasonal snowpack, *Hydrol. Process.*, 14, 3207–3214, 2000.
- Colbeck, S. C.: The layered character of snow covers, *Rev. Geophys.*, 29, 81–96, 1991.
- Colbeck, S. C. and Anderson, E. A.: The permeability of melting snow, *Water Resour. Res.*, 18, 904–908, 1982.
- Durand, M. T., Kim, E. J., and Margulis, S. A.: Quantifying uncertainty in modeling snow microwave radiance for a mountain snowpack at the point-scale, including stratigraphic effects, *IEEE T. Geosci. Remote*, 46, 1753–1767, 2008.
- Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K., and Sokratov, S. A.: The international classification for seasonal snow on the ground, UNESCO/IHP, Paris, 2009.
- Gray, D. M. and Male, D. H.: *Handbook of Snow*, The Blackburn Press, Caldwell, New Jersey, 1981.
- Grody, N.: Relationship between snow parameters and microwave satellite measurements: Theory compared with advanced microwave sounding unit observations from 23 to 150 GHz, *J. Geophys. Res.-Atmos.*, 113, 1–17, 2008.
- La Placa, S. J. and Post, B.: Thermal expansion of ice, *Acta Crystallogr.*, 13, 503–505, 1960.
- Langlois, A., Royer, A., Derksen, C., Montpetit, B., Dupont, F., and Goïta, K.: Coupling of the snow thermodynamic model SNOWPACK with the Microwave Emission Model for Layered Snowpacks (MEMLS) for subarctic and arctic snow water equivalent retrievals, *Water Resour. Res.*, 48, 819–821, doi:10.1029/2012WR012133, 2012.
- Lemmetyinen, J., Pulliainen, J., Rees, A., Kontu, A., and Derksen, C.: Multiple-layer adaptation of HUT Snow Emission Model: comparison with experimental data, *IEEE T. Geosci. Remote*, 48, 2781–2794, 2010.
- Lonsdale, D. K.: The structure of ice, *P. Roy. Soc. Lond. A Mat.*, 247, 424–434, 1958.
- Marsh, P.: Wetting front advance and freezing of meltwater within a snow cover: 1. Observations in the Canadian Arctic, *Water Resour. Res.*, 20, 1853–1864, 1984.
- Mätzler, C. and Wiesmann, A.: Extension of the microwave emission model of layered snowpacks to coarse-grained snow, *Remote Sens. Environ.*, 325, 317–325, 1999.
- Montpetit, B., Royer, A., Roy, A., Langlois, A., and Derksen, C.: Snow microwave emission modeling of ice lenses within a snowpack using the microwave emission model for layered snowpacks, *IEEE T. Geosci. Remote*, 51, 4705–4717, 2012.
- Pfeffer, W. T. and Humphrey, N. F.: Determination of timing and location of water movement and ice-layer formation by temperature measurements in sub-freezing snow, *J. Glaciol.*, 42, 292–304, 1996.
- Picard, G., Brucker, L., Roy, A., Dupont, F., Fily, M., Royer, A., and Harlow, C.: Simulation of the microwave emission of multi-layered snowpacks using the Dense Media Radiative transfer theory: the DMRT-ML model, *Geosci. Model Dev.*, 6, 1061–1078, doi:10.5194/gmd-6-1061-2013, 2013.
- Rees, A., Lemmetyinen, J., Derksen, C., Pulliainen, J., and English, M.: Observed and modelled effects of ice lens formation on passive microwave brightness temperatures over snow covered tundra, *Remote Sens. Environ.*, 114, 116–126, 2010.
- Sihvola, A. and Tiuri, M.: Snow fork for field determination of the density and wetness profiles of a snow pack, *IEEE T. Geosci. Remote*, GE-24, 717–721, 1986.

- Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J.-P., Koskinen, J. T., and Bo-
275 jkov, B.: Estimating northern hemisphere snow water equivalent for climate research through assimilation
of space-borne radiometer data and ground-based measurements, *Remote Sens. Environ.*, 115, 3517–3529,
2011.
- Wiesmann, A. and Mätzler, C.: Microwave emission model of layered snowpacks, *Remote Sens. Environ.*, 70,
307–316, 1999.

Table 1. Measurements of ice layer density bubble size and thickness (all sizes in mm, all densities in kg m^{-3}). n is number of samples, $n < 0.1$ is the number of samples with a bubble diameter of less than 0.1 mm. All ice layer density values have been corrected to account for the measured -0.19 cm^3 bias in volume.

		Bubble Diameter				Layer Thickness			Density		
	Type	n	n<0.1	Mean	SD	n	Mean	SD	n	Mean	SD
Care	Natural	0 <u>~</u>	-	-	-	29	8	0.6	29	906	17
North Bay	Natural	14	4	0.16	0.12	15	3	0.6	15	890	21
	Artificial	12	6	0.08	0.03	15	5	0.9	15	921	18
Inuvik	Artificial	0 <u>~</u>	0 <u>~</u>	-	-	28	2	0.5	18 <u>28</u>	915	26
Overall	-	26	10	0.12	0.1	86 <u>87</u>	5	2.7	86 <u>87</u>	909	23

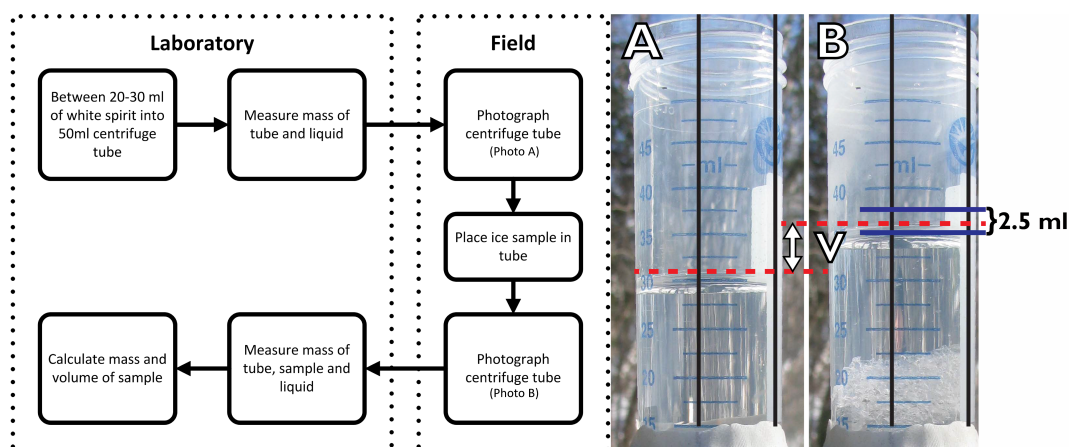


Figure 1. Flow chart describing the methodology to measure densities of ice layers from a snowpack. Photographs show an example pair of photos used in the calculation of ice sample volume. **A** taken before the sample was added and **B**, taken after. **V** is equal to the volume of the ice sample. Black lines are guides added to help assess the quality of the photos.

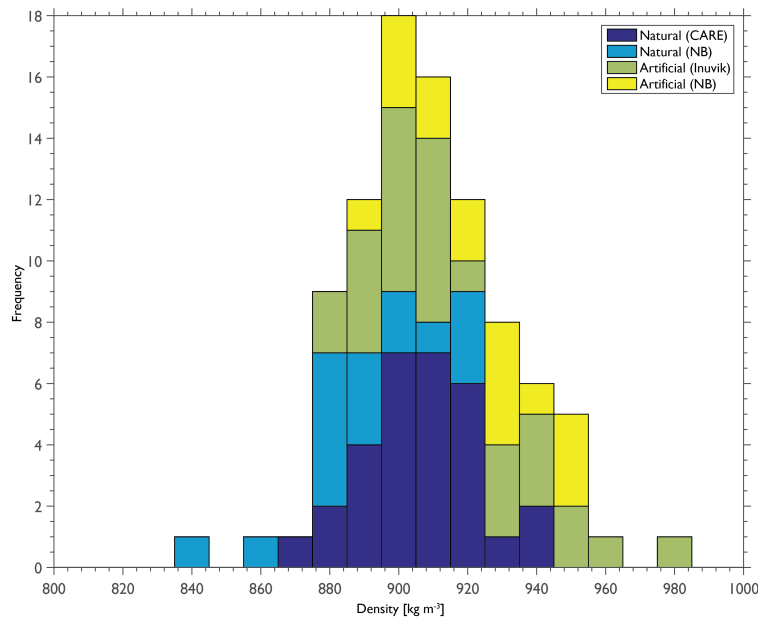


Figure 2. Summary of ice layer density measurements. Stacked histogram showing frequency of each density measurement, colours show distribution of artificial and natural ice layers across multiple sites.

Examples of the numerical representation of ice layers used to investigate porosity, (a) shows a sample with simulated density of 800 and (b) shows a sample with density 909.

Schematic representation of slicing technique to measure porosity. Air bubbles (shaded in blue) are shown in an ice sample, the theoretical slice was made at the location of the dashed line. The left hand side was chosen as the side to be sampled, and so all of the diagonally striped areas marked “A” were calculated and summed to calculate the overall porosity of the sample.

Sample density vs mean simulated sample porosity. Mean sample porosity (blue line) was calculated at 0.1 intervals throughout the sample, shaded area shows mean ± 1 standard deviation. Red dashed fitted linear trend line (Eq. 1) was calculated using a least squares regression.