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An investigation of relative thermal expansion and contraction of ice and steel

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We report the results of a number of experiments conducted by changing the temperature of a steel pipe containing ice. We measure the strain in the ice and the temperature at a frequency of 1Hz using sensors based on fiber Bragg gratings. When the temperature of the apparatus changes, the steel and ice expand or contract at different rates, and so there is the potential for the ice and steel to move relative to each other. The steel pipe constrains the expansion of the ice in two dimensions. Further, cohesion and friction between the ice and steel may limit the movement of the ice in the third dimension. The measured strain therefore allows us to make inferences about the interaction between the ice and the pipe. We find a coefficient of thermal expansion in free ice comparable to literature values (around 51x10-6K^{-1}) but that the effective expansion coefficient varies depending on how the ice is constrained. We also report on the results of similar experiments with saline ice.

1. Introduction

The thermal expansion coefficient of ice is important to Arctic engineers. Structures in ice must be designed to withstand pressures exerted by expanding ice sheets; sensors in ice may lose contact with their surrounding ice in warming conditions and so show incorrect results; debonding of ice frozen onto steel fixtures may occur under high thermal stresses. The thermal expansion of ice has been studied in detail. Malmgren (1927) studied the thermal expansion of sea ice on board the *Maud*. Based on experiments enclosed in an iron tube, and a theoretical model which assumes that all salinity is captured in enclosed brine pockets inside the ice, Malmgren found that the thermal expansion coefficient of sea ice drops (relative to that of fresh ice) and then changes sign (becomes negative) as the temperature approaches zero. Butkovich (1959) reports on experiments which show that thermal expansion in fresh ice shows memory dependence, and that the coefficient can decrease over successive contraction-expansion cycles. Cox (1983) reassesses Malmgren's (1927) explanation of the thermal expansion of sea ice, but suggests that the assumption of a *closed* system is false in sea ice. Cox (1983) suggests an *open* model in which both brine and ice are free to expand or contract independently. This view is supported by the results of Johnson and Metzner (1990). The authors of this paper argue in a related presentation (Marchenko and Lishman, 2014) that the truth may lie between Cox and Malmgrens' arguments, and that brine in sea ice is partly open and partly confined to pockets with limited permeability.

In this paper we are particularly interested in the expansion of ice when it is constrained by steel, which has a lower thermal expansion coefficient (the linear coefficient for steel is $13 \times 10^{-6} K^{-1}$, or roughly a quarter of the linear expansion coefficient of ice). When ice and steel expand and contract together under thermal variations, several physical processes must be considered:

- heat is conducted through both steel and ice;
- the steel and ice both expand and contract;
- the ice may adhere to the steel, in which case expansion may cause creep in the ice;
- the ice may slip relative to the steel, perhaps smoothly or perhaps in a stick-slip motion;
- if the ice is saline, then phase changes may occur within brine pockets in the ice;
- water, salt, and trapped gas may be expelled from the ice (or in some cases impelled into the ice);
- local temperature variations within the ice may cause differential expansion, local strains, and cracking;
- if the ice is constrained in some directions, it may expand preferentially in other directions, and so the relation between linear and volumetric expansion may be complicated.

Here we compare results for both fresh and saline ice under varying degrees of confinement, with the aim of isolating some of these processes. We are particularly interested in two questions. First, does frictional slip between ice and steel play any role in the relative thermal expansions? Second, if we constrain the brine drainage, does the expansion coefficient change? The experimental method discussed below allows us to answer these questions.

2. Experimental method

A series of experiments were undertaken in the cold rooms of University College London. A fiber-Bragg extensiometer was used to measure the linear strain in ice samples under various conditions. This device consists of a grating (within an optical fiber) which reflects light of a particular wavelength, and transmits all other light. The wavelength of light reflected is a function of the strain and temperature in the grating. A grating with fixed strain (i.e. mounted so as not to expand or contract with temperature) can therefore be used for reliable temperature measurement. For a free grating in an optical fiber under tension, once the wavelength variation due to temperature changes is known, the remaining wavelength variation must be attributable to strain in the tense fiber. The equipment is therefore well suited to simultaneous measurements of temperature and strain, as well as being reliable and robust, and hence is ideal for measuring the thermal expansion coefficient of ice. The system used in these experiments was provided by Advanced Optics Limited, of Dresden, Germany.

The ice was formed between two steel pipes: an outer pipe with inside diameter 11cm, and an inner pipe with outside diameter 2cm. Fresh ice was made from London tap water; saline ice from the same, with 8ppt NaCl added. The samples were formed in layers, so that up to 1cm depth of water was added and allowed to freeze before the next layer was formed. No evidence was seen of supercooled water or large bubbles within these layers. The experiments are conducted in air.

Ice samples were tested in three conditions: unconstrained, constrained within one pipe, and constrained between two pipes (in the first two cases, pipes were removed after forming by briefly warming). These conditions are illustrated in figure 1. The pipe has length 180mm, and the samples are milled 5mm from either end of the pipe, such that the initial ice sample has two flat parallel ends 190mm apart. On these flat ends we place an aluminium spacer of width 4mm which supports the fiber-Bragg sensor such that expansion in the ice in the along-pipe (z) direction stretches the extensiometer.

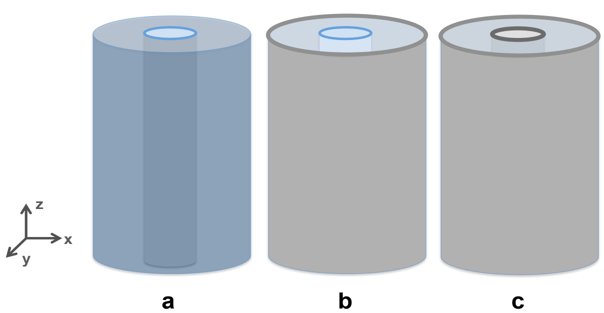

Figure 1. Schematic of experimental configurations: (a) unconstrained ice sample; (b) toroidal ice sample constrained by external steel pipe (but free to expand into central cavity); (c) toroidal ice sample constrained by external and internal steel pipes.

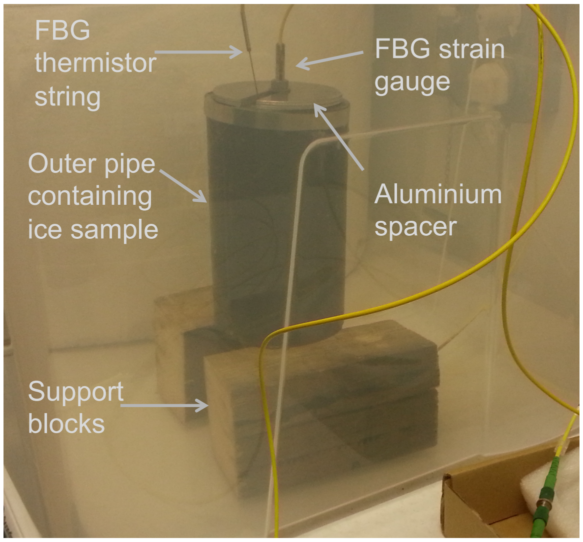

Figure 2. Photograph of experimental setup. The steel pipe shown is 180mm high.

Temperatures are measured using a fiber-Bragg 12-thermistor string inserted through a drilled hole in the ice (or ice and pipe), such that temperatures are recorded through the sample in the x-direction. The temperature used for calibration of the strain sensor is that closest to the sensor: in this case, thermistor 7. For calculation of thermal expansion, we use the average of thermistors 1-5, which gives a mean value through the ice, but eliminates the thermistors in the air, which respond much faster to temperature changes in the room. Temperature and extension are measured at 1 sample/s. The entire apparatus is shown in a photograph in figure 2.

3. Results

In total, 27 tests were conducted, across the three geometries shown in figure 1, and for both fresh and saline ice (i.e. 6 different experimental configurations). Due to the complications of sharing working spaces, and running long experiments (often >24h), tests were not conducted according to a rigorous schedule but rather on an ad-hoc basis which allowed for both warming and cooling to be investigated in all configurations.

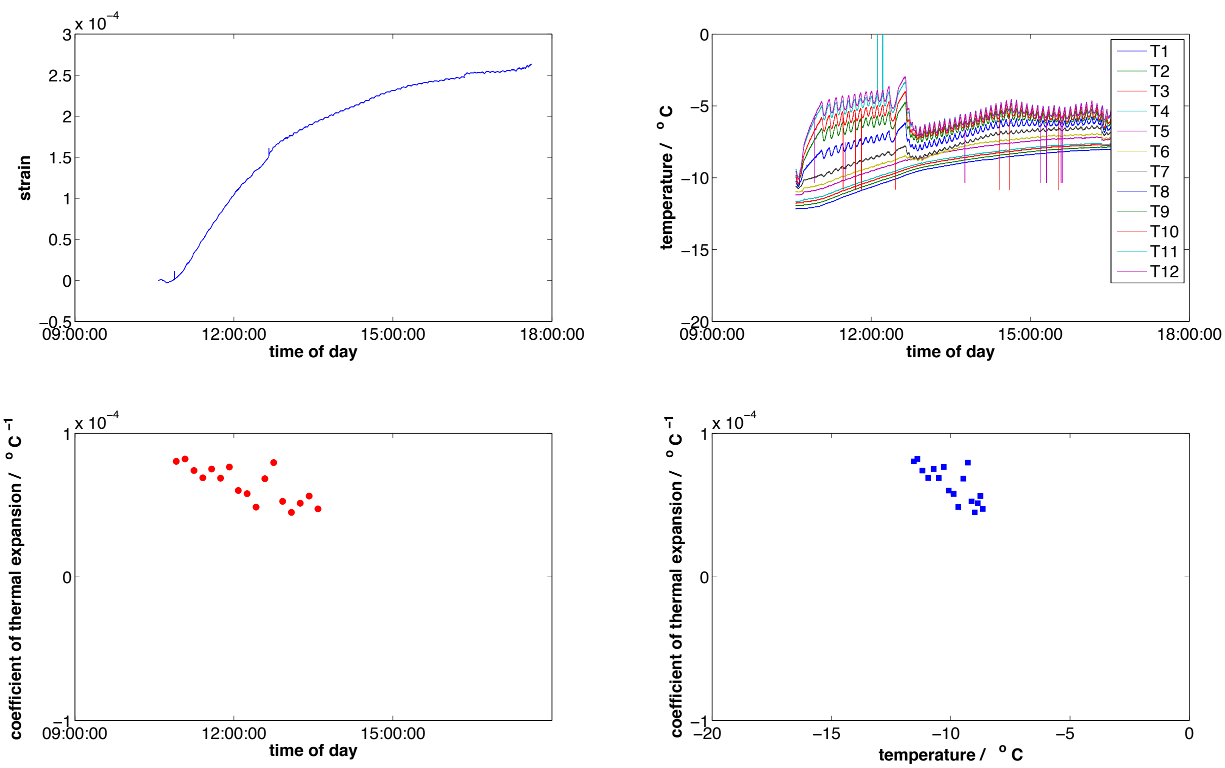

Figure 3. Results from a typical thermal expansion experiment. Strain and temperature measurements are shown in the top two figures. Calculated thermal expansions are shown as a function of time and then of temperature in the lower two figures. The results shown are for unconstrained fresh ice.

Figure 3 shows the results of a typical experiment. The measured strain and temperature are calculated directly from the fiber-Bragg wavelengths, using known calibration coefficients and measured wavelengths for the thermistors submersed in 0°C iced water. These measurements are shown at the top of figure 3. In the temperature plot we can see two minor sources of error;

variations in the air temperature due to the cold room fan cycle (duration 5 minutes), and a sudden cooling (just after 12.00) when the door to an adjoining cold room was opened. Neither of these processes has a strong effect on the observed in-ice temperatures (the lowest six lines on the top right plot) but both will have some effect on overall results. Calculated thermal expansion coefficients are shown in the bottom half of figure 3. For these, ice temperature and strain are averaged over 600s periods. If the temperature difference in this window is less than 0.1°C then the measurement is ignored, since slight residual strains at constant temperatures can lead to high anomalous expansion coefficients. The results shown are therefore those for which the temperature difference across the measurement window was sufficiently high. These are then shown as a function of time and temperature.

Figure 4 shows results combined across all experiments. For fresh ice (top figure) there is a range of positive values of thermal expansion coefficient, with a few negative outliers. We see no clear trend with temperature. Average (linear) coefficients are $46.9x10^{-6}K^{-1}$ for unconstrained fresh ice, $26.9x10^{-6}K^{-1}$ for ice constrained by an external pipe, and $64.3x10^{-6}K^{-1}$ for ice constrained by both internal and external pipes. The average for the unconstrained pipe is within 10% of the literature value. For saline ice with no pipe (RHS, squares, average value $52.4x10^{-6}K^{-1}$) and with 1 pipe (RHS, crosses, average $50.6x10^{-6}K^{-1}$) we see similar behaviour. For saline ice with two pipes the values over the first eight hours of the test are similar (average $54.2\ x10^{-6}K^{-1}$) results are similar, but then we see a clear trend towards negative expansion coefficients with rising temperature (above around -10°C). We hypothesise that the dual pipes constrain the brine, leading to Malmgren-type behaviour.

4. Modelling and discussion

The presence of the steel pipes in our experiments appears to have two competing effects. With only one pipe, measured expansion along the pipe seems to be reduced. We explain this as an effect of the ice adhering to the pipe, while still unconstrained to expand inwards. With two pipes, the ice is constrained so that it can only expand lengthways, and the measured expansion is then higher.

These interpretations of our results are hypothetical. In order to better understand them, we model the expansions in Comsol Multiphysics. We model a cylinder of ice (axial symmetry) of the same dimensions as our experiments, with either one or two constrained boundaries. We consider two cases: one in which the ice deforms elastically, and one in which the ice is also allowed to creep (this creep then occurs relative to the fixed boundary). The ice is assumed to have an elastic modulus of 1GPa, a specific heat capacity of 2000 kJ/kg K, a Poisson ratio of 0.33, and a thermal conductivity of 2 W/mK. The thermal expansion coefficient is set at $50x10^{-6}$ K^{-1}. The creep follows a Norton model of the form

$$\dot{\varepsilon} = A\left(\frac{\sigma}{\sigma_{crit}}\right)^{n} \qquad \textbf{[1]}$$

where $A=10^{-4}s^{-1}$, σ_{crit} = 1MPa, and n=4. There is no temperature dependence to the modeled creep. The temperature is modeled as tanh(t/3600), giving roughly a one degree temperature increase in an hour. The simulation runs for 10000s. Results are shown in figure 5.

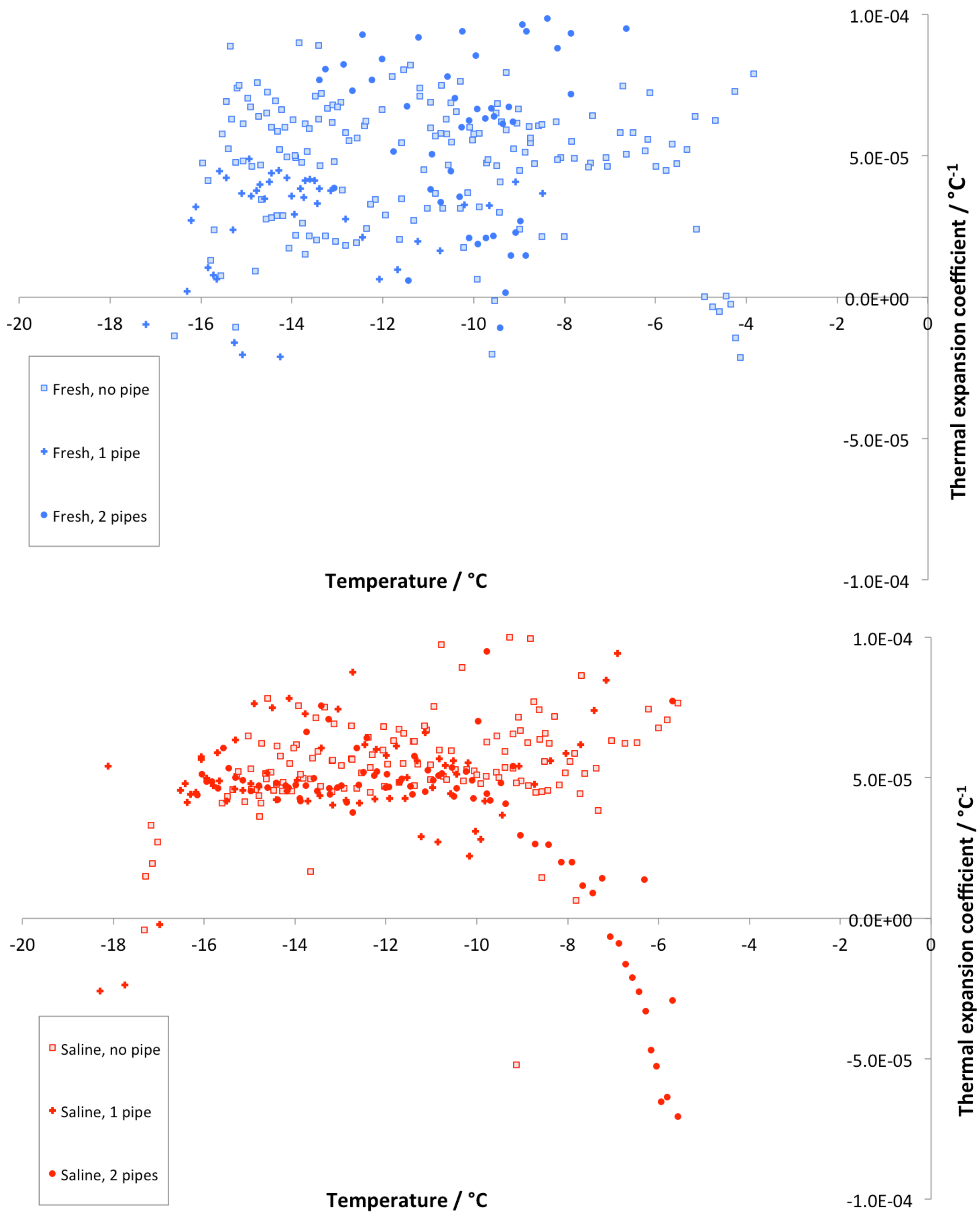

Figure 4. Experimentally measured thermal expansion coefficients, plotted as a function of temperature. The upper figure shows values for fresh ice (unconstrained as squares; with one pipe as crosses; and with two pipes as circles), and the lower figure shows similar results for saline ice.

We note in regard to figure 5 that our experimental setup is unable to measure variations in expansion across the top surface, and will only measure the maximum expansion (at the inside boundary for lines 1 and 3, and around 3cm in for lines 2 and 4). Table 1 shows a comparison of the measured expansion to the maximum modeled expansion for each ice configuration. The results shown in figure 5 show an opposite effect to our measured results: with only one pipe, ice expansion is highest, while with two pipes it is lowest. The high modeled values of expansion with one pipe are explained by the absence of inwards expansion (into the internal void) in our model. The low modeled values of expansion with two pipes are unexplained, and we hypothesize that some slip at the ice/steel interface occurs.

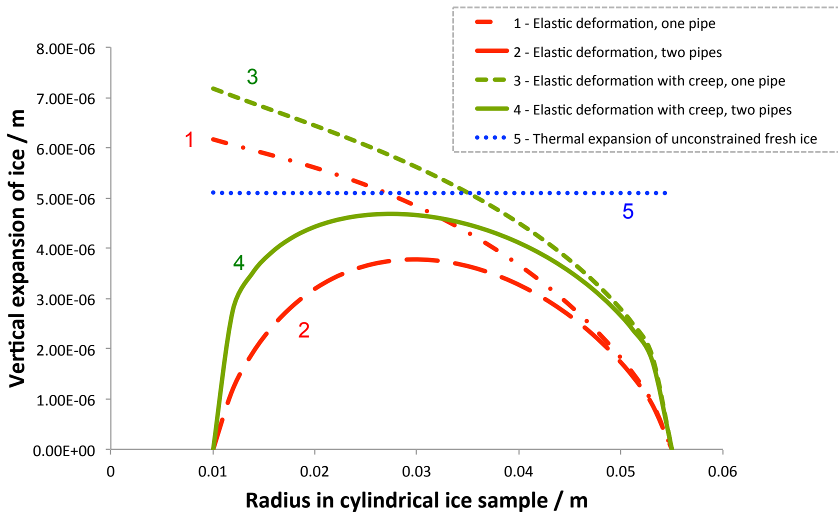

Figure 5. Modelled deformation of ice constrained by external and internal pipes (solid and long-dash) and by an external pipe only (short dash and dot-dash). Lines 1 and 2 (red) show purely elastic behaviour; 3 and 4 (green) show behaviour with creep, modelled as described above. The blue dotted line shows the predicted expansion of unconfined ice.

Confinement	Thermal expansion coefficient (x 10^{-6} $^{o}C^{-1}$)		
	Measured (fresh/saline)	Modelled (elastic) (maximum)	Modelled (elastic + creep) (maximum)
Unconfined	46.9 / 52.4	51	51
External Pipe	26.9 / 50.6	61.7	71.8
External and Internal Pipes	64.3 / 54.2	37.8	46.9

Table 1. A comparison of measured and modeled maximum expansion.

The frictional slip between the ice and steel occurs at extremely low slip rates (on the order of $10^{-9}ms^{-1}$). At these speeds there is no frictional melting and hence little thermal control on friction (Akkok et al., 1987) and so friction is in a velocity strengthening regime, where faster slip leads to higher friction. Further experiments are planned to investigate whether any frictional sliding occurs, and whether this sliding is smooth or stick-slip.

The conflicting models of sea ice thermal expansion discussed in the introduction have conflicting descriptions of brine expulsion from the ice. The salinity of the ice samples is therefore key to understanding whether saline ice behaves differently from fresh ice. Our samples have an initial bulk salinity of 8ppt, and final salinities of 3-4ppt. The experiments do not show whether the steel pipes limit the expulsion of brine from the saline ice. Later experiments conducted at UNIS, Svalbard, on fjord ice, suggest that brine drainage during thermal expansion and contraction is small compared to overall salinity, but these experiments are not discussed in depth here.

The results of figure 4 show a large scatter. We ascribe this to variations in temperature throughout the ice: as the ice in the cold rooms warms and cools, the temperature in the ice does not change instantaneously, and so some parts of the ice may be expanding as other parts contract. The averaged values presented alongside our results are likely therefore to give a good approximation to the expansion coefficient of ice under various constraints.

5. Conclusions

Ice, both saline and fresh, has a linear thermal expansion coefficient around $50\text{x}10^{-6}\text{K}^{-1}$. If the ice is constrained by steel, which has a lower thermal expansion coefficient, then this constraint may lead to higher linear expansion in some directions due to the non-zero Poisson's ratio of ice. However, the adhesion between ice and steel can also reduce the linear expansion in some directions. Frictional sliding between ice and steel may occur at the very low slip rates which occur under thermal expansion. Creep within the ice may allow expansion in the bulk of the ice even when the boundary is fixed to the steel. Individual results for the linear coefficient, recorded over ten minutes of expansion or contraction, show a wide scatter, although averaged values correspond well to the literature. The scatter is assumed due to temperature inhomogeneity in the ice: this is likely to occur in real-life cases as well as laboratory experiments. Different analytical models for the expansion of saline ice contain different assumptions about the evolution of salinity within the ice. The results of this work suggest that some but not all brine is expelled during thermal cycling, and ice confinement may lead to brine retention and varying thermal expansion with temperature. Further measurements of salinity variation may lead to a more precise understanding of any differences between the thermal expansion of fresh and saline ice.

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