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Salt transport in artificial snow on sea ice: laboratory experiments

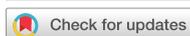
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Supplementary material for this article is available [online](#)

Abstract

Salt within snowpacks on first-year sea ice affects snow properties by reducing the melting point, which can increase liquid water content and alter snowpack evolution. These changes lead to modifications in dielectric properties, which in turn influence snow and sea ice geophysical retrievals from radar remote sensing. In this study, we conducted laboratory experiments with artificial sea ice to examine how brine, originating from sea ice, influences the salinity of overlying snow. Our results reveal strong positive correlations ($0.80 < r < 1.00$) between the initial water salinity and volume of the created sea ice discs, and the overlying bulk snow salinity. The impact of brine migration as a function of snow grain size (0.710–1 mm, 0.355–0.710 mm and < 0.35 mm) and snow structure was explored, with grains less than 0.35 mm diameter leading to a basal snow salinity value seven times higher than grains in the 0.710–1 mm range. Furthermore, the presence of an ice layer within the snowpack was found to limit upward brine movement. These findings improve understanding of snow–ice brine interactions and provide critical insights towards enhancing the accuracy of remote sensing retrievals over sea ice regions.

1. Introduction

The Arctic has warmed at nearly four times the global average rate over the last forty years (Rantanen *et al* 2022) and the same period has also seen radical reductions in the summer minimum sea ice extent (Stroeve *et al* 2007, Parkinson and Comiso 2013), the thickness of the sea ice cover (Kwok 2018, Sumata *et al* 2023), and the age of the ice cover (Stroeve and Notz 2018, Babb *et al* 2023). The Arctic sea ice is therefore transitioning from a primarily second-year ice (SYI) and multi-year ice (MYI) cover to a thinner, relatively smoother and younger cover of first-year ice (FYI; (Babb *et al* 2023)) which has different physical properties (e.g., Weeks and Ackley (1982)). FYI typically has salinity values of 6–15 parts per thousand (ppt) (Nakawo and Sinha 1981) whilst SYI and MYI range between 0.1 ppt and 3 ppt (Schwarzacher 1959, Cochran *et al* 2019). FYI is often overlaid by partially to completely saline snow cover, with bulk snowpack salinity values often exceeding 10 ppt in the basal snow layers (~6–8 cm) above the sea ice surface (Nandan *et al* 2017). Salinity values of several ppt can persist within the snowpack up to ten centimetres above the sea ice surface (Barber *et al* 1995, Drinkwater and Crocker 1988, Geldsetzer *et al* 2009, Nandan *et al* 2017). When concentrated in these quantities, the salt can induce the presence of small quantities of liquid water at temperatures below 0°C (Geldsetzer *et al* 2009).

The presence of saline liquid brine fundamentally alters the physical properties of the snow by increasing its bulk dielectric permittivity and electrical conductivity, which in turn have a direct and significant impact on microwave propagation (Crocker 1984, Barber and Nghiem 1999). The challenges posed by saline snow to remote sensing have been investigated in the contexts of microwave scatterometry (Barber and Nghiem 1999, Nandan *et al* 2017) and radar altimetry (Nandan *et al* 2017, 2020). The microwave range of electromagnetic radiation is often used in satellite remote sensing observations, such as Ku-band radar (12–18GHz) to retrieve ice freeboard and subsequently sea ice thickness data. This relies on the assumption that Ku band radar penetrates the snow and reflects from the sea ice surface. However, it has been shown that microwave penetration into snow on sea ice is impacted by a range of physical properties of the snowpack, such as grain size, salinity, density, surface roughness and wetness, and that such assumptions do not always hold in the natural environment (e.g. Jutila and Haas (2023), Willatt *et al* (2010), Stroeve *et al* (2022)). The dielectric constant of liquid water is around 40 times greater than snow, and subsequently the presence of liquid water in the snowpack causes the dielectric properties to increase by several factors, leading to higher backscatter of the signal and decreasing the microwave penetration (Barber *et al* 1995, Willatt *et al* 2010). Picard *et al* (2022) exploited the sensitivity of microwave brightness temperature to snow liquid content with the aim to better develop models that can detect liquid water such as melt ponds. Merkouriadi *et al* (2024) used a snow evolution model to investigate liquid sources in the snow and their effect on measurements of freeboard by CryoSat-2, finding that in the central Arctic freeboards from CryoSat-2 were much larger when compared to model simulations, suggesting the possibility that the radar signal penetration depth was affected by flooding of sea water at the snow/ice interface, though further research is required to confirm this.

Salt in snow on sea ice also plays a crucial role in polar atmospheric chemistry through the release of sea salt aerosols during blowing snow events, which can significantly influence cloud condensation nuclei concentrations, atmospheric chemical reactions, and regional climate feedbacks (Yang *et al* 2008).

This study seeks to improve our understanding of how physical snow and ice conditions influence salinity and hence liquid water content in snow on sea ice. In situ data allowing investigation of these independent variables is lacking due to the difficulty of accessing snow-covered sea ice with appropriately varied sea ice salinity and snow grain size. Measurements over multiple timescales with controlled temperatures are unlikely to be possible under natural conditions. We are also able to replicate different grain size layering configurations, whilst a study of natural snow would be very unlikely to observe these with all other variables held constant. We now discuss what has been learned in the field, where knowledge gaps remain and how laboratory experiments, within controlled environments, can help to examine these relationships.

While field observations have identified key overall patterns in the dynamics of snow-sea ice salinity, the mechanisms that underpin the transfer of brine from sea ice to snow are uncertain (Domine *et al* 2004). For sea ice with a positive freeboard, an important source of available salt to the snowpack begins with the upward rejection of brine from within the sea ice to the upper surface (Perovich and Richter-Menge 1994, Vancoppenolle *et al* 2006). This brine ‘skim’ can be extremely saline, with values sometimes exceeding 50 ppt (e.g., Martin (1979), Barber *et al* (2014)). Once snow covers the sea ice and its highly saline upper surface, it acts as a medium for transfer, wicking the brine upwards through capillary action (Sturm and Massom 2016, Shokr and Sinha 2023). It is observed that snow salinity tends to be higher on FYI with higher salinity levels (Cox and Weeks 1973, Frey *et al* 2020), and observations have shown that snow salinity increases nearer to the ice-snow interface, and depending on the snow depth may sometimes exist throughout the snowpack (Petrich and Eicken 2010, Frey *et al* 2020, Nandan *et al* 2020). Due to delayed freeze up, snow covers are likely to become thinner (Stroeve *et al* 2020, Webster *et al* 2014), which could result in an increase in salinity at the bottom layers and the presence of salinity throughout the snowpack (Nandan *et al* 2017).

Two likely controls on the transfer of salt from sea ice into overlying snow are the sea ice salinity and the properties of the snowpack such as grain size (Colbeck 1974, Coléou and Lesaffre 1998, Calonne *et al* 2012, Mallett *et al* 2024). Stratification with layers of different grain sizes have been observed in field studies (Colbeck 1983, Domine *et al* 2008) where wind redistribution creates alternating grain size layers, such as smaller grains atop larger grains when fresh snow falls over older, coarsened snow, depth hoar forms at the base of the snow pack increasing grain size there, or larger grains sit atop a finer basal layer due to surface growth. However, there are limited experiments on salt transfer processes in this context, and these controls have not been systematically varied in a laboratory controlled environment. The transfer of liquid in snow with varying grain size structures has been predominantly studied in freshwater contexts, while studies in saline environments are lacking (Colbeck 1974, Coléou and Lesaffre 1998, Calonne *et al* 2012). Recent laboratory and natural environment experiments were conducted by Mallett *et al* (2024), who observed salt transfer into snow. Their laboratory experiment sampled snow from the natural environment, so did not offer controlled variation of the snow structure, and used brine salinity of 100 ppt which is far higher than natural values.

Our confirmatory experiments isolate these variables using artificial sea ice, rather than brine only, with realistic salinity values, and artificial snow, permitting examination of the control of sea ice and snow properties

on salt transfer from ice into snow. Comprehensive quantitative data on brine transfer processes are still lacking, and the effects of physical characteristics and environmental factors on these processes remain understudied. In the laboratory, controlled and reproducible experimental setups can be created to isolate and investigate specific variables affecting brine transfer, which is challenging in natural environments where interactions between uncontrollable factors can impact observations. This study quantitatively verifies field-derived hypotheses by controlling parameters for how initial sea ice salinity, volume and snow grain size distribution determine snow salinity and vertical transport of brine on different time scales. These controlled experiments establish causal relationships that were previously inferred from field correlations.

2. Methods

2.1. Experimental approach

This study investigates brine transfer from artificial sea ice discs into overlying artificial snow. The reported experiments were conducted in the University College London Ice Physics Laboratory during 2023 and 2025, following preliminary experiments in 2022 to refine experimental techniques. We consider upward brine expulsion from the ice and subsequent upward movement into the overlying snowpack. The experimental approach is grounded in the understanding of ‘brine expulsion’, a phenomenon where brine, initially trapped within the sea ice during its formation, is expelled (Perovich and Richter-Menge 1994, Tschudi *et al* 2016), and upward wicking, which describes the process of brine transfer to the snowpack above through capillary action (Barber *et al* 2003).

Artificial sea ice and snow were produced in the lab and assembled into snow-covered sea ice analogues. Sea ice and snow properties, and time elapsed, were varied, to explore their effects on the salinity of the snowpack. Experiments on all variations of the independent variable were run simultaneously to ensure that the environmental conditions were the same. The lab can produce air temperatures between 0 and -30°C ; in these experiments air temperature ranged between -9.9 and -5°C (please see Supplement section on Temperature for details).

Throughout the study, salinities were measured using the Hanna HI-98319 Waterproof Salinity Meter, which can measure from 0 to 70 ppt within an operating temperature range of 0 to 50°C , both of which cover the relevant values for our study.

The following section details the experimental procedures (figure 1).

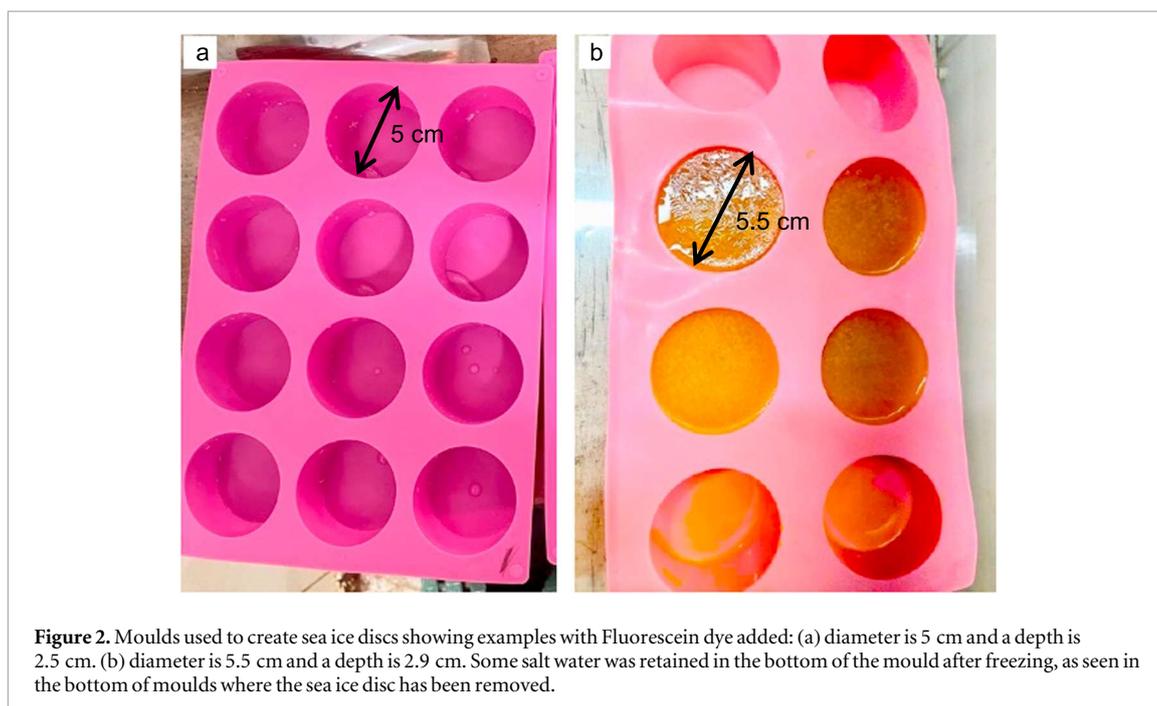
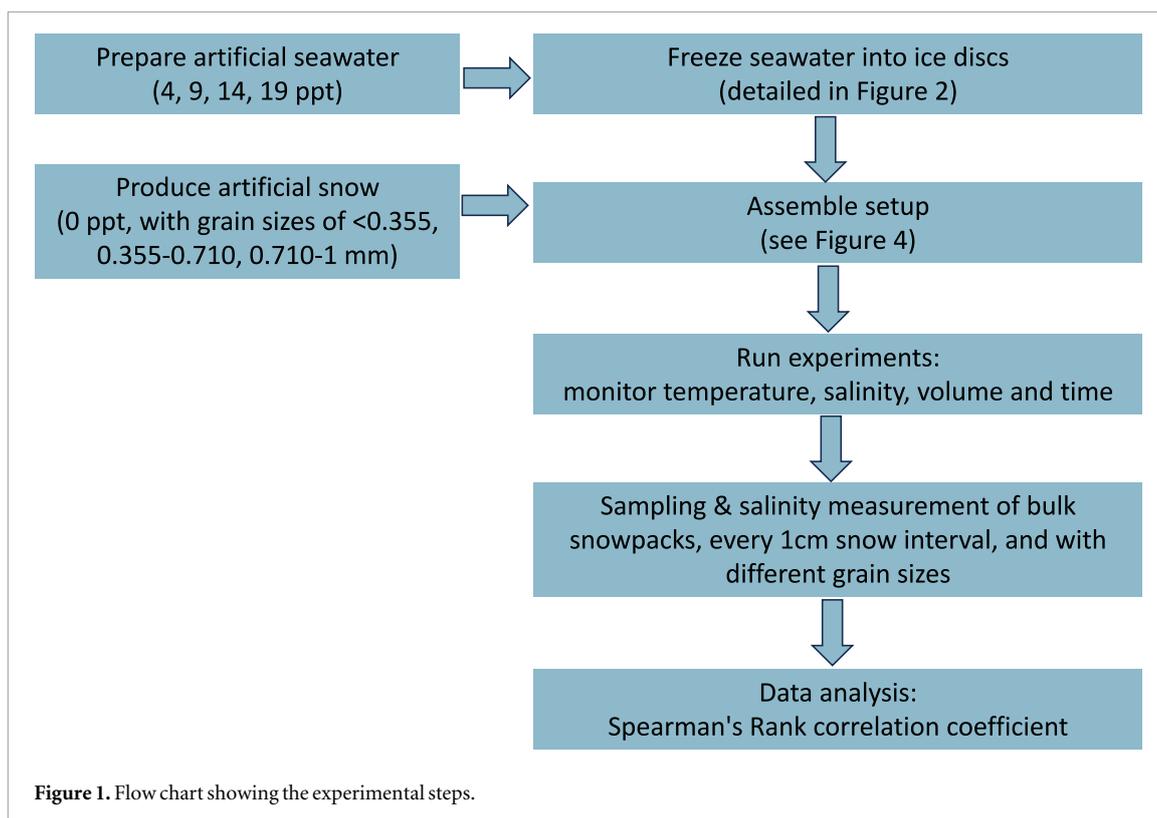
2.1.1. Sea ice disc formation

Working at room temperature, artificial sea water was made using ‘Instant Ocean’, a powder sea salt mix commonly used in aquariums and research facilities to replicate sea water. This provided an inexpensive and practical way to produce a sea water analogue with the ability to vary salinity. Instant Ocean was added incrementally to water and the salinity measured until it reached the desired value. Specific volumes of the artificial sea water were then measured out into silicone cylindrical moulds using a pipette. These were then frozen to form artificial sea ice discs.

The salinity and volume of the water used to form the sea ice discs were varied during Experiments 1 and 2 (detailed below), ranging from 4 ppt to 19 ppt and 25 to 70 ml, respectively. Two sizes of silicone mould were used; the first was of 5 cm diameter and 2.5 cm depth and the second was of 5.5 cm diameter and 2.9 cm depth (figure 2). The larger diameter mould allowed a larger range of sea ice disc volumes to be used when studying the effect of sea ice disc volume and snowpacks structure on brine transfer, for Experiments 2 and 3.

All sea ice discs froze within 20-24 hours. During the first few hours, a thin layer of ice became visible on the surface of the liquid, indicating that the exposed upper surface froze first due to the insulating effect of the silicone mould around the sides and base. Once entirely frozen, it was noted that a thick brine skim could be observed at the surface of ice discs. The salinity of the resulting sea ice discs was therefore slightly lower than that of the initial salt water. A skim of liquid salt water was also observed at the bottom of the mould, with more of this liquid observed for sea ice discs made with higher salinity sea water (figure 2). These observations can be attributed to the drainage of brine during the freezing process (Weeks and Ackley 1982). It was unfortunately not possible to measure the salinity of this liquid due to the salinity meter requiring a larger liquid volume for measurement.

For Experiments 1 and 2 (detailed below), no dye was added to the artificial sea ice prior to freezing. For Experiment 3, Fluorescein dye was added to provide a visual indication of the salt transfer. We measured the salinity of water with, and without, the addition of Fluorescein dye, and observed that for the quantities added for tracing in these experiments, Fluorescein increased measured salinity by ~ 2 ppt.



2.1.2. Production of artificial snow

Artificial snow (figure 3) was produced from pure water (0 ppt salinity) frozen into ice cubes. The cubes were run through an ice crusher machine and then placed into a blender which chopped them into small pieces of varying sizes. Sieves and a vibrating machine were then used to sort snow into three different grain sizes: 0.710–1 mm, 0.355–0.710 mm, and less than 0.355 mm. It is important to note that the snow does not replicate the structure (shape/orientation) of natural snow, but resulted in grains with a relevant range of sizes. The diameters of these grains are significantly larger than typical natural precipitation-fresh snow (typically 50–500 μm) (Jäkel *et al* 2021) and wind-redistributed snow (1–300 μm after sublimation) (Dai and Huang 2014, Huang *et al* 2016), and the particles themselves are denser (compared to the density of natural snow, which is 0.01–0.3 g cm^{-3}) (Fierz *et al* 2009, Sturm and

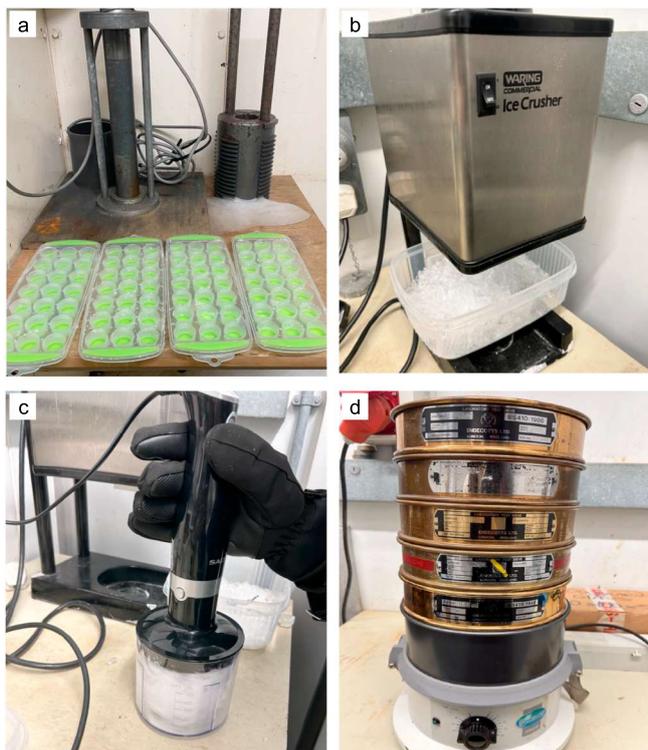


Figure 3. The process of making artificial snow. (a) freezing fresh ice, (b) using an ice crusher to initially crush the ice, (c) using a blender for finer crushing, (d) using sieves and a vibrating machine to separate snow in different grain sizes, with sieves sizes of 4.00 mm, 2.00 mm, 1.00 mm, 0.71 mm and 0.355 mm.

Massom 2016) and less porous. In nature, depending on the temperature and humidity during the snow formation, snow can form complex hexagonal crystals in a wide variety of shapes (Fierz *et al* 2009, Sturm and Massom 2016). Artificial snow grains, on the other hand, do not have the complex crystal structure found in real snow, and are relatively uniformly round and smooth (Fierz *et al* 2009). Although both natural and artificial snow can compact and metamorphose into much larger grains of diameter via vapour diffusion within the snowpack, forming rounded grains, faceted crystals and depth hoar up to 4.5 mm in diameter (Colbeck 1983, Fierz *et al* 2009), the absence of natural crystal structure in artificial snow likely affects permeability, and salt transport dynamics in the experiments. The smoother, denser artificial grains are expected to reduce capillary pathways, potentially limiting brine migration compared to natural snowpacks. The small change in snowpack height observed after snow placement suggests that the measurement method may not capture subtle compaction or settlement during the experiment. In addition, the irregular shape and size distribution of crushed ice particles are different from natural snow, which may affect the true porosity and packing structure. These may lead to uncertainties in the calculation of snowpack density. These differences in snow grain size, shape, and packing structure mean that the artificial snow used here does not fully replicate the microstructure, porosity, or thermal properties of natural snowpacks. As a result, subtle variations in compaction and settlement during the experiment may not have been fully captured. The small change in snowpack height observed after placement suggests that the measurement method may underestimate minor densification processes. Furthermore, the irregular shape and broad size distribution of crushed ice particles differ from natural snow, affecting porosity and packing arrangement and introducing slight uncertainty in calculated bulk density. Despite these limitations, the advantage of the laboratory environment is that homogeneous snowpacks can be produced to isolate the effects of the independent variables such as grain size, salinity, and structural layering.

2.2. Experiments

Experiments were conducted to test how sea ice and snow properties affect brine transfer into overlying snow, as well as the timescales over which snow salinity evolves (figure 4). Figure 5 shows an example of this experimental setup. The sea ice disc (yellow) was wrapped in a plastic sheet and a cable tie used to keep this in a cylindrical shape around the ice. Snow (white) was then added above the sea ice.

Experiment 1 investigated the effect of varying sea ice disc salinities (4, 9, 14, 19 ppt; all 30 ml) on snow salinity in a uniform snowpack (<0.355 mm grains), with sampling at multiple time points. Experiment 2 examined the influence of sea ice disc volume; 2.1 used volumes of 25–40 ml (all 9 ppt, <0.355 mm snow) and multi-timepoint sampling, while 2.2 included a wider volume range (20–70 ml) and measured vertical salinity

Experiment	Sea ice discs salinity (ppt)	Sea ice discs volume (ml)	Snow grain size (mm)	Sampling time elapsed (h)	Sampling method
Control	9	30	0.355-0.710	2	Bulk snowpacks
1	4, 9, 14, 19	30	<0.355	1, 2, 3, 4, 5, 24	Bulk snowpacks
2.1	9	25, 30, 35, 40	<0.355	1, 2, 3, 4, 5, 24	Bulk snowpacks
2.2	9	20,30,40, 50,60,70	<0.355	24	Sampling at every 1cm
3	9	70	<0.355, 0.355-0.710, 0.710-1	24	Sampling different snow grains

Figure 4. Experimental design matrix summarizing all separate experiment, showing control group and variables. Those highlighted in blue at the top represent the control group, while the four lines below correspond to the experimental groups with controlled variables. The orange boxes indicate the independent variables.



profiles after 24 hours. Experiment 3 explored the impact of snowpack grain size and structure, using homogeneous and layered packs of three different grain sizes on 70 ml, 9 ppt ice discs and sampling after 24 hours.

Two control experiments were also conducted to determine the repeatability and uncertainty of salinity measurements. The first used nine zero-salinity sea ice discs to confirm whether the source of salinity in the snow was the sea ice disc. The discs were topped with snow with a grain size of <0.355 mm, 0.355–0.710 mm and 0.710–1.00 mm, and left for an elapsed times of 2, 4, and 24 hours (with the smallest grain size tested only at 24 hours due to availability). Across all conditions, these zero-salinity controls consistently resulted in

Table 1. Results from the control experiment, performed 9 replicate experiments using sea ice discs (9 ppt salinity, 30 ml volume) and 3 cm medium-grained snow (0.355–0.710 mm). Salinity values after 2 hours are shown for internal reproducibility under the same conditions.

Post-expt. snow salinity (ppt)	Sea ice disc salinity (ppt)
0.2	7.9
0.3	8.1
0.2	7.8
0.4	7.9
0.6	8.0
0.3	7.8
0.2	7.8
0.4	7.8
0.6	7.6

undetectable snow salinity (0 ppt), providing critical evidence that observed increases in snow salinity during experiments were driven solely by brine migration from saline sea ice.

The second set of control experiments addressed measurement repeatability and uncertainty. Nine replicate sea ice discs (9 ppt initial salinity, 30 ml volume), each covered with 3 cm of medium-grained snow (0.355–0.710 mm), were left for 2 hours before sampling. After brine migration, the measured snow salinity averaged 0.36 ppt ($\sigma = 0.16$ ppt), and the corresponding sea ice disc salinity averaged 7.86 ppt ($\sigma = 0.14$ ppt; table 1). These results demonstrate the reproducibility of salinity transfer and enable robust assessment of experimental uncertainty under standardized conditions.

After the specified elapsed times, samples of snow or ice were collected via destructive sampling, stored in labeled Whirlpak sample bags, and melted at room temperature. The salinity of the liquid was then measured using the salinity meter. These values were recorded for further analysis in subsequent data processing and interpretation. In this paper we use bulk salinity to indicate the overall salinity of the melted sample. Unless stated otherwise, this is a column-averaged value i.e. the entire snow pack atop the sea ice disc.

2.3. Data analysis

Relationships between measured snow salinity and the control variables after the elapsed times were then examined using scatter plots and visual representations of the snow stratigraphy, allowing for an initial assessment of any potential relationships. Spearman's Rank correlation coefficient was then calculated in R studio.

3. Results

3.1. Impacts of sea ice properties (experiments 1 and 2)

Panels a and b of figure 6 show bulk snowpack salinity values versus sea ice disc salinities and volumes, at each elapsed time. Error bars represent the ± 0.16 ppt measurement uncertainty discussed in the Methods section. It is clear that at all elapsed times there are strong relationships between snow salinity and both sea ice disc salinity and volume.

Spearman's correlation analyses (table 2) revealed positive correlations between bulk snowpack salinity and sea ice disc salinity at all times, indicating a strong connection between higher sea ice disc salinities and increased bulk snowpack salinities. This positive correlation persisted throughout the experiment, underscoring the consistent link between snowpack and sea ice disc salinities as time progressed. Even after 24 hours, this correlation remained robust. These highly positive correlation coefficients indicate a direct relationship whereby higher sea ice salinity caused an increase in bulk snowpack salinity.

Regarding the impact of sea ice disc volume on snowpack salinity, consistent trends of increased salinity with larger disc volumes were measured across all time intervals. The highly positive Spearman's correlation coefficients of the bulk snowpack salinity versus sea ice disc volume at all time elapsed confirm the robustness of the observed significant positive relationship between snow salinity and sea ice disc volume (table 2).

We note that sea ice disc salinity values reported in the manuscript are slightly lower than the water salinity used to make sea ice discs, as mentioned in the Methods section. An examination of how much salt was lost in the brine left in the moulds is reported in the Supplement section 'Salinity Loss During Freezing Process'. We found a strong linear relationship between the water salinity prior to, and after, freezing and melting, with the Spearman's Rank correlation coefficient value of 1.00.

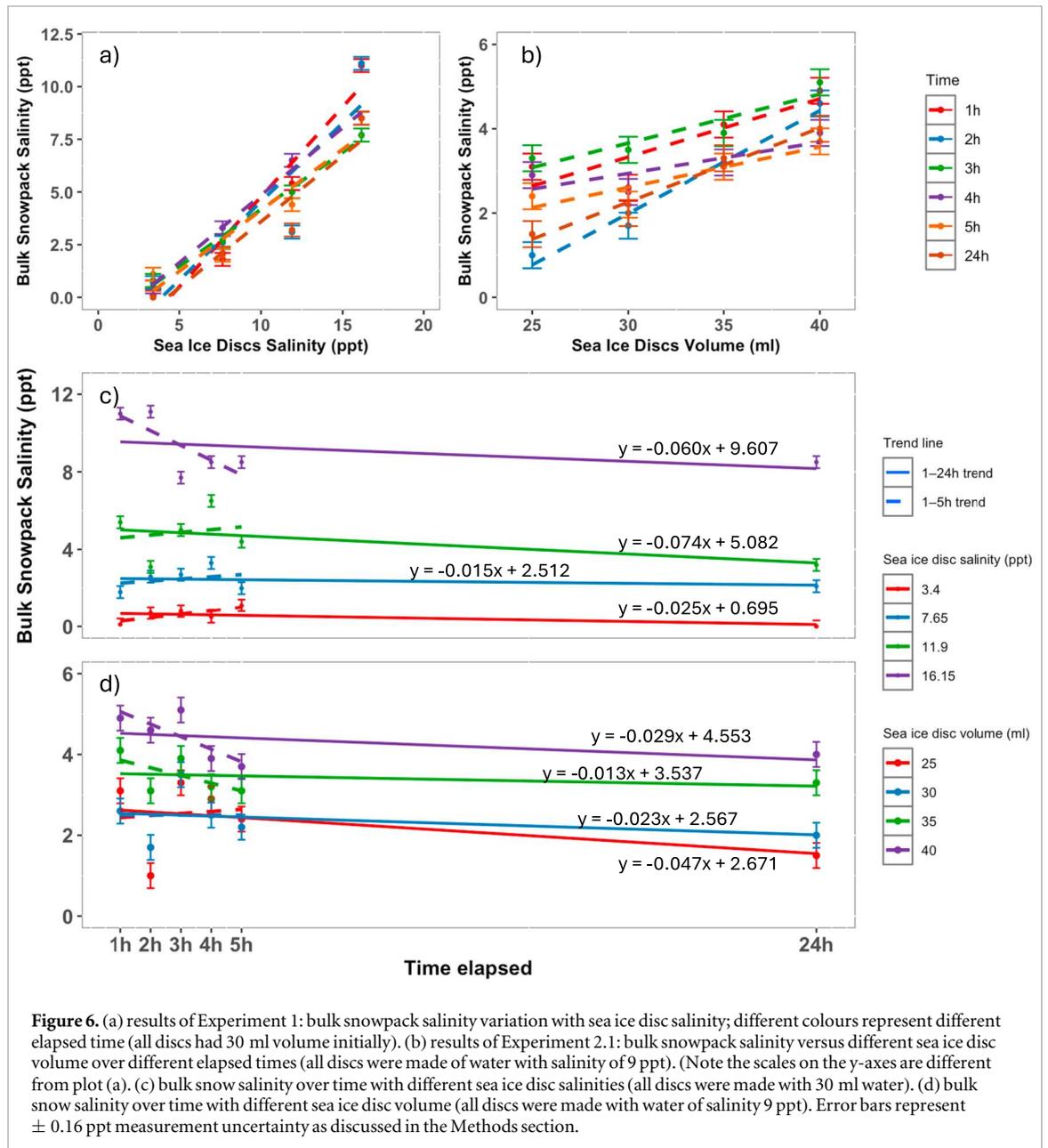


Table 2. Results from Experiment 1 and 2. Spearman’s Rank correlation coefficient (ρ) between bulk snowpack salinity and sea ice disc salinity (left column) and sea ice disc volume (right column) at different time intervals setup.

Time Elapsed (h)	Spearman’s ρ (with sea ice disc salinity)	Spearman’s ρ (with sea ice disc volume)
1	1.0	0.8
2	1.0	1.0
3	1.0	1.0
4	1.0	0.8
5	1.0	0.8
24	1.0	1.0

We now look at how bulk snowpack salinity changed over time, for the different sea ice disc salinities and volumes (figure 6 panels (c) and (d)). Differences between treatments of less than ± 0.16 ppt fall within measurement uncertainty and should be interpreted with caution. In the experimental sets with higher initial sea ice disc salinity of 16.2 ppt or volume of 40 ml, salinity decreased over 24 hours, with the steepest negative slopes. For lower initial salinities (3.4 ppt, 7.7 ppt, and 11.9 ppt), the trend lines vary, with no consistent changes over time. Regarding the sea ice disc volumes, all experiments exhibit a decline in snowpack salinity over time. However, the slopes do not show a similar decrease trend. Compare to the clear time-dependent salinity changes observed among sea ice discs with different initial salinities, salinity remained relatively stable over time across sea ice discs of varying volumes.

Error bars with an uncertainty of ± 0.16 ppt are present at each data point. Nonetheless, the trends point to a consistent decrease in snowpack salinity over time, influenced by both the salinity and volume of the underlying sea ice.

3.2. Impact of snowpack properties (experiments 3.1 and 3.2)

We now examine the impact of snow grain size on snow salinity. The medium-over-small and small-over-medium configurations were designed to replicate naturally occurring snow stratification patterns (figure 7) with the medium-over-small setup simulating conditions where surface snow undergoes grain growth over a fine basal layer, and the small-over-medium representing fresh snowfall over aged, coarsened snow. This design allowed for assessment of whether grain size gradients enhance or impede upward brine transport compared to uniform grain size distributions. The highest salinities for each grain size were found within the basal layer and the lowest salinities were found in the upper range of the snowpack (figure 7). A linear trendline was fitted to the salinity results for the layer 0 to 1 cm above the snow/ice interface. This indicated that salinity decreases at a steady rate within the basal layer with increasing grain size. Analysis of snowpacks with different grain size structures on sea ice discs made with 70 ml water of 9 ppt salinity (figure 7, table 3) revealed distinct salinity patterns. Within the basal layers, setups with smaller grains (< 0.355 mm) showed higher salinity (3.1 and 4 ppt), followed by medium (0.355–0.710 mm) with salinity of 1.2 ppt and large grains (0.710–1 mm) at 0.8 ppt. Notably, when medium-grained snow overlay small-grained snow, upward brine migration was observed, whereas reverse configurations impeded this migration. The uppermost snow layers (3.0–4.5 cm) consistently showed no salinity, irrespective of the grain size.

Incorporating a fresh ice layer within the snowpacks resulted in salinity confined to the bottom layer adjacent to the sea ice discs (figure 8, table 4). Staining patterns indicated extensive brine transfer into small grains, while minimal transfer occurred in medium and large grains.

4. Discussion

This study investigated salt transfer from sea ice into overlying snow in a laboratory environment. The study did not aim to precisely replicate environmental conditions, but rather to permit investigation of the influence of some key sea ice and snow properties on the salinity of snow on sea ice. Artificial sea ice properties (salinity and volume) and artificial snow properties (snow grain size and presence of an ice layer) were varied to investigate their effect on the snow salinity. The progression of snow salinity was also studied via measurements at various elapsed times between 1 and 24 hours. In all experiments, salinity was detected in the snow directly above the sea ice discs, confirming that salt had moved from the sea ice into the snow.

Results from Hudson Bay in 2024 (Mallett *et al* 2024) suggested the positive impact of ice salinity on basal snow salinity, so this was investigated in the lab and established a quantitative relationship. Strong positive correlations between snow salinity and sea ice disc salinity (Experiment 1) and volume (Experiments 2.1 and 2.2) were found at elapsed times between 1 and 24 hours, with Spearman's Rank correlation coefficient between 0.8 and 1.0. We attribute this to several factors, with brine volume and drainage channels playing a crucial role. Firstly, higher sea ice salinity indicates a greater brine volume within the ice structure (Cox and Weeks 1973). As sea ice forms, some brine is trapped within the ice matrix, creating brine pockets. Larger brine volumes provide more drainage channel for brine release and migration (Petrich and Eicken 2010). Therefore, the higher the sea ice salinity, the greater the potential for brine release into the snow above. In the field experiments of Mallett *et al* (2024), higher salinity sea ice (15.1 ppt versus 4.9 ppt) increased the salinity of basal snow by an order of magnitude (5.9 ppt versus 0.7 ppt). Another study conducted in late winter in Canadian Arctic shows that the basal snow salinity increases significantly with rising sea ice surface scraping salinity (Nandan *et al* 2017). Other previous studies in polar regions have observed that snow salinity tends to be greater on the saltier FYI compared to MYI (Schwarzacher 1959, Untersteiner 1968, Nakawo and Sinha 1981).

The plot of sea ice disc salinity against snowpack salinity at various time intervals shows positive linear trends across the measurement range (figure 6, panel a). If the linear trendlines were extrapolated they would

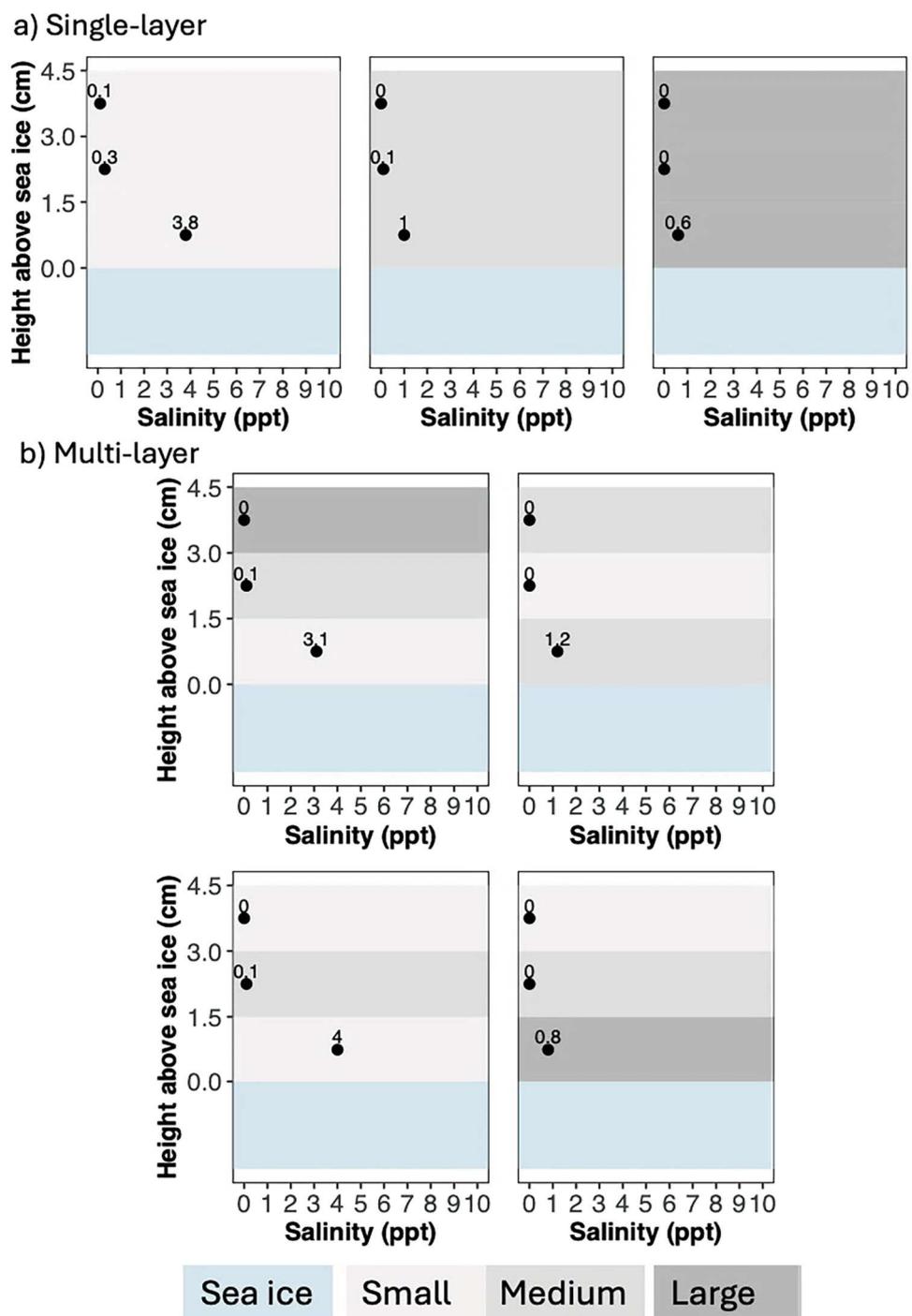


Figure 7. Salinity variations with different snowpack layering, (a) single layer (i.e. consistent initial grain size at all vertical levels), (b) varied initial grain sizes in three layers. Medium-over-small and small-over-medium configurations were chosen to represent realistic asymmetric snow stratification scenarios commonly observed in natural sea ice environments. The black points indicate the salinity levels for each snowpack grain size and the values are provided in table 3. All sea ice discs were made with water 70 ml volume with 11 ppt salinity. Small grain size is less than 0.355 mm, medium grain size is 0.355–0.710 mm, and the large grain size is 0.710–1 mm.

reach negative y-intercepts, which are not physical, suggesting the existence of a sea ice salinity threshold to start measurable brine transfer to the snowpack or that the observed linear trends do not continue to lower sea ice salinity values. Extrapolation beyond the measurement range requires caution, and though our data suggest that this minimum sea ice salinity threshold could be at ~ 2 – 3 ppt for our setup, this would require additional experiments with lower sea ice salinities for verification. Our zero-salinity control experiment consistently shows undetectable snow salinity throughout the entire observation period, again demonstrating the presence of the sea ice salinity required for the upward transfer of salt into the snowpack.

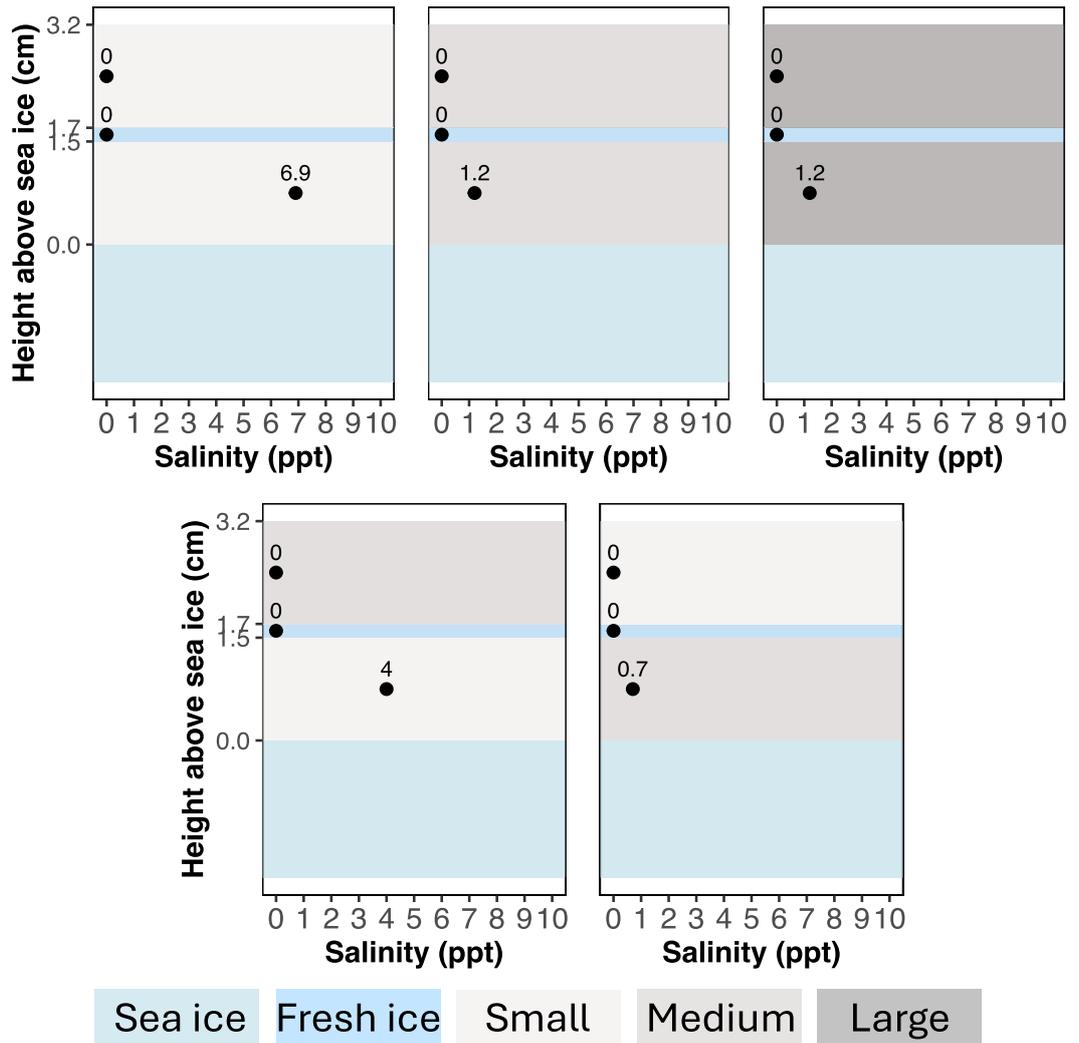


Figure 8. Salinity variations in different snowpack layering including an ice layer. Medium-over-small and small-over-medium configurations were chosen to represent realistic asymmetric snow stratification scenarios commonly observed in natural sea ice environments. The black points indicating the salinity levels for each snowpack grain size and ice layer. All sea ice discs were made with 70 ml water of 11 ppt salinity. Small grain size is less than 0.355 mm, medium grain size is 0.355–0.710 mm, and the large grain size is 0.710–1 mm.

Table 3. Initial snow grain size for bottom, middle and upper snow layers and measured snow salinity for seven configurations in different snowpack structures.

Configuration		Bottom (0–1.5 cm)	Middle (1.5–3.0 cm)	Upper (3.0–4.5 cm)
1	Snow Size (mm)	< 0.355	< 0.355	< 0.355
	Salinity (ppt)	3.8	0.3	0.1
2	Snow Size (mm)	0.355–0.710	0.355–0.710	0.355–0.710
	Salinity (ppt)	1	0.1	0
3	Snow Size (mm)	0.710–1	0.710–1	0.710–1
	Salinity (ppt)	0.6	0	0
4	Snow Size (mm)	< 0.355	0.355–0.710	0.710–1
	Salinity (ppt)	3.1	0.1	0
5	Snow Size (mm)	0.355–0.710	< 0.355	0.355–0.710
	Salinity (ppt)	1.2	0	0
6	Snow Size (mm)	< 0.355	0.355–0.710	< 0.355
	Salinity (ppt)	4	0.1	0
7	Snow Size (mm)	0.710–1	0.355–0.710	< 0.355
	Salinity (ppt)	0.8	0	0

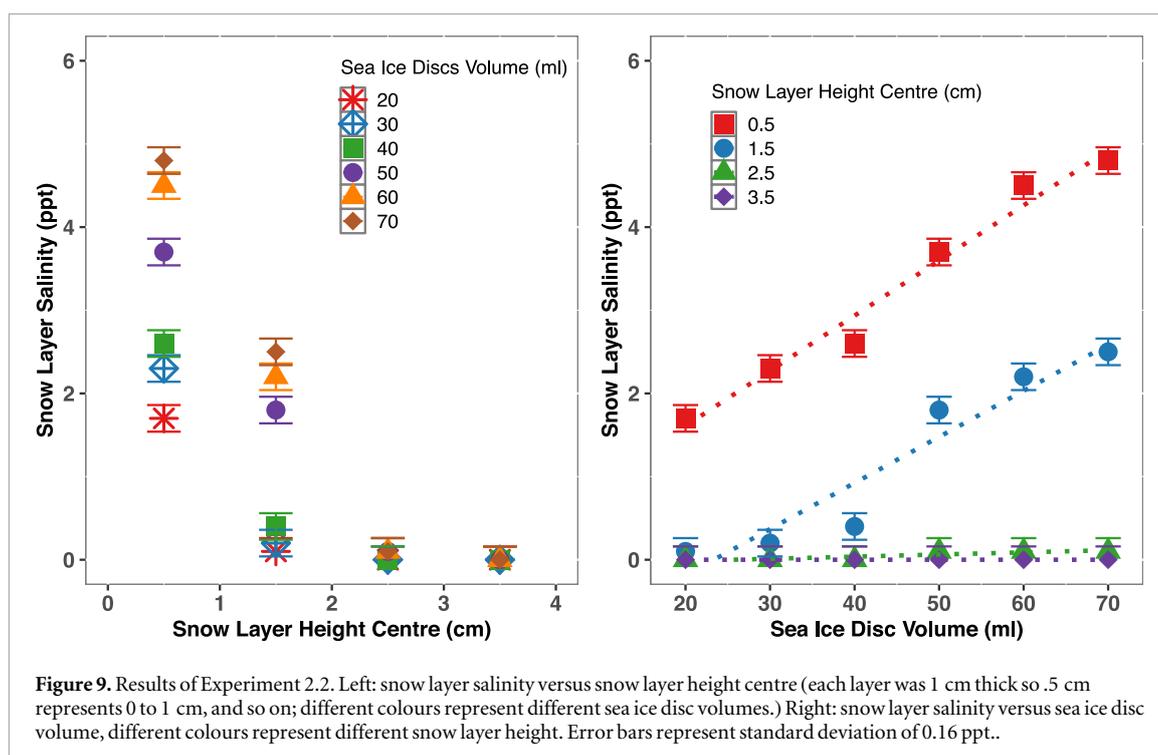


Figure 9. Results of Experiment 2.2. Left: snow layer salinity versus snow layer height centre (each layer was 1 cm thick so .5 cm represents 0 to 1 cm, and so on; different colours represent different sea ice disc volumes.) Right: snow layer salinity versus sea ice disc volume, different colours represent different snow layer height. Error bars represent standard deviation of 0.16 ppt.

Table 4. Snow grain size and salinity configurations in different snowpack structures.

Configuration		Bottom (0–1.5 cm)	Ice (1.5–1.7 cm)	Upper (1.7–3.2 cm)
8	Snow Size (mm)	< 0.355	/	< 0.355
	Salinity (ppt)	6.9	0	0
9	Snow Size (mm)	0.355–0.710	/	0.355–0.710
	Salinity (ppt)	1.2	0	0
10	Snow Size (mm)	0.710–1	/	0.710–1
	Salinity (ppt)	1.2	0	0
11	Snow Size (mm)	< 0.355	/	0.355–0.710
	Salinity (ppt)	4	0	0
12	Snow Size (mm)	0.355–0.710	/	< 0.355
	Salinity (ppt)	0.7	0	0

The increase of bulk snowpack salinity with sea ice disc volume suggests that larger ice samples made more brine available at the ice surface for subsequent wicking. This in turn reinforces our analysis above: that a saltier ice surface results in more salt being delivered into the snow. While post-experiment measurements of whole sea ice disc salinity revealed an average 1.2 ± 0.3 ppt decrease compared to initial values of 9 ppt, the absence of vertical salinity profiling of the sea ice discs prevents a deeper analysis of from what depth in the ice the salt was sourced.

We found that salinity was consistently detected in the snowpack directly above the sea ice discs and decreased with height in the snowpack (Experiment 2.2). No salinity was detected in the top snow layer (3–4 cm). The relationships between layer height and salinity do not appear to be linear, but rather show curves with salinity quickly reducing with height; perhaps exponentially, but we do not have sufficient data points to determine this (figure 9, table 5). Dye added to the sea ice discs visually confirmed this limited brine transfer, with the bottom snow stained and the upper snow remaining unstained. This observation suggests that brine transfer was limited by height above the sea ice discs in these experiments. This is qualitatively consistent with previous field studies finding higher salinities towards the base of the snowpack (Nandan *et al* 2017, 2020, Frey *et al* 2020, Petrich and Eicken 2010, Mallett *et al* 2024, Komarov *et al* 2025).

We investigated 9 layering configurations of snow grain size and inclusion of a non-saline ice layer to investigate the impact of snow grain size and layering on brine transfer. Snowpacks with small snow grains (< 0.355 mm) consistently exhibited higher salinity compared to medium (0.355–0.710 mm) and large (0.710–1 mm) snow grains (the specific discussion of the effects of snow grain size on brine transfer is provided

Table 5. Spearman's correlation analysis of snow layer salinity and snow layer height above sea ice disc. No salinity was detected in the 3–4 cm layer hence a result of N.A. is reported.

Snow Layer Height Centre (cm)	Spearman's ρ
0.5	1.0
1.5	1.0
2.5	0.9
3.5	N.A.

in supplement). Despite variations in the structure of the upper snow layer, consistent salinity levels were observed in the bottom snow layer with the same grain sizes. This suggests that the transfer of brine from the sea ice to the snow cover may be primarily influenced by the characteristics of the lowermost snow layer. The lower snow layer serves as a crucial interface for brine transfer, with its permeability and porosity affecting the rate and extent of brine migration within the snowpack. Small snow grains in the basal layer resulted in higher basal layer salinities (3.1 to 4.0 ppt) than medium (1.2 ppt) or larger grains (0.8 ppt). When the basal snow layer contained small grains, the medium-sized snow grains above had a salinity of 0.1 ppt. However, when the basal snow layer contained large grains the small- or medium-sized snow grains above had zero salinity. The upward migration of salt can therefore be interrupted when larger grains are present between the sea ice and smaller grains above. This outcome resonates with previous observations regarding the transportation of freshwater within various snowpack grain size structures where water was capable of migrating from fine-grained snow to coarse-grained snow but was constrained or even interrupted when moving from coarse-grained snow to fine-grained snow (Avanzi *et al* 2016). This phenomenon can be attributed to the different porosity and capillary forces inherent to snow of different grain sizes. These results also align with field studies on snow sample permeability and capillary absorption (Colbeck 1974, Coléou and Lesaffre 1998). In our experiments, however, the post-experiment salinity profiles do not allow us to unambiguously distinguish whether the enhanced salinity of the basal snow arose primarily from surface brine skim expulsion at the ice-snow interface or from sustained upward migration of brine from deeper within the ice through capillary rise. While both processes are likely to contribute, their relative dominance is unresolved, and this uncertainty must be borne in mind when extrapolating to natural sea ice conditions. Finer-grained snow tends to exhibit a larger specific surface area (SSA) and more interconnected pores, which favors capillary-driven brine movement upward into the overlying layers. In contrast, larger snow grains contain fewer and wider pores, and may additionally form ice bridges that obstruct liquid connectivity, both of which could hinder effective brine transport (Avanzi *et al* 2016). Moreover, it should be noted that the particle size range we employed in the laboratory (0.355–1 mm) does not cover the finer particles (<0.3 mm) commonly produced by wind-driven sublimation and deposition in natural polar snow (Dai and Huang 2014, Huang *et al* 2016), and this limitation may also influence the representativeness of our observed transport mechanisms.

We found that introduction of a fresh ice layer into the snowpack impeded transfer of salt, restricting salt to the snowpack below. When comparing the salinity of the middle snow layer (at 3–4 cm) from Experiment 3.1 to that of the snow above the fresh ice layer (at 3.2–4.2 cm) from Experiment 3.2, with the same set up of snow particle sizes: medium over small (configurations 1 and 8), notable differences were observed. The salinity of the snow layer without fresh ice layer was 0.1 ppt, where there was no salinity present in the layer with fresh ice layer. These salinity differences, observed under the same snow grain size set up and height, demonstrate the limiting of the fresh ice layer on the upward transfer of brine in the snowpacks.

In addition to snow grain size, the effect of snow grain morphology on capillary action is an important consideration. Irregularly shaped particles may produce more complex paths of capillary motion than round particles, which can affect the rate and extent of liquid movement through capillary action (Colbeck 1974). Theoretically, smaller grain sizes should lead to higher snow salinities due to increased capillary rise under the same conditions.

Preliminary experiments, not reported here, employed a hammer to chisel ice, yielding uneven and irregularly shaped snow particles (figure 10(a)). However, this took considerable time and it was not feasible to produce the quantities of snow of different grain sizes required for the study presented. This experiment employed an ice crusher and blender, producing relatively smoother and rounder snow particles (figure 10(b)) than that in the preliminary experiments. Smoother particles tend to exhibit reduced capillary forces due to higher contact angles on smooth surfaces, which reduce the strength of capillary forces (Calonne *et al* 2012, Colbeck 1974). Moreover, smoother particles may possess less interconnected pore space, limiting capillary movement. (Calonne *et al* 2012, Colbeck 1974). The sphericity and surface roughness differences between our artificial snow and natural snow crystals have important implications for upward brine transport mechanisms. Natural

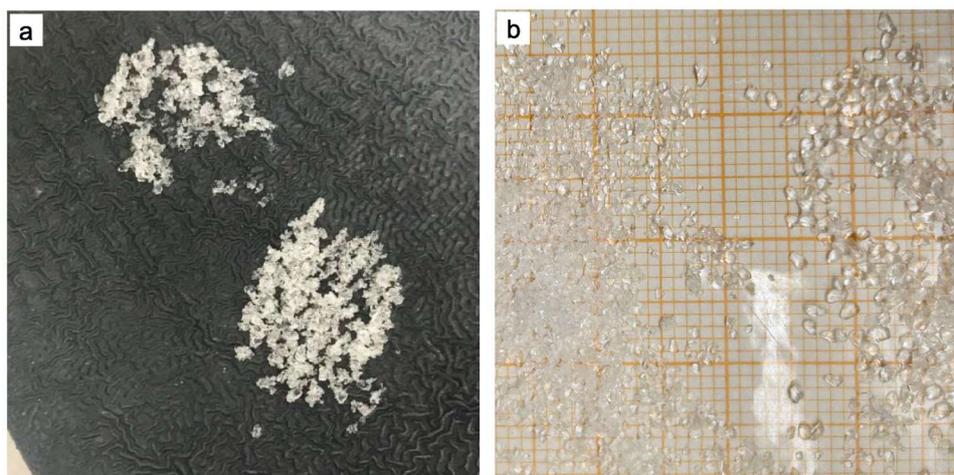


Figure 10. Comparison of the shapes of snow made by (a) chiselling ice with a hammer and (b) grinding ice with a blender.

snow exhibits highly irregular, dendritic structures with complex surface textures that maximize specific surface area and create numerous micro-capillary pathways, facilitating efficient liquid transport through enhanced wetting and reduced contact angles (Calonne *et al* 2012). In contrast, our rounded, smooth artificial snow grains likely underestimate the capillary transport efficiency observed in natural snowpacks, as the greater surface roughness and lower sphericity of natural snow would be expected to enhance upward salt migration through stronger capillary action and more extensive pore connectivity.

The results of Experiments 1 and 2.1 indicate that snowpack salinity typically decreased over 24 hours. In the experiments involving higher initial salinities of 14 ppt and 19 ppt, the overall trend indicated decreasing snowpack salinity over 24 hours. This suggests a decrease of snow salinity over time, perhaps due to melting taking place at the outer edges of snow grains leading to more rounded shapes and smaller SSA. In contrast, snowpacks over sea ice discs made with water of 4 ppt and 9 ppt salinity displayed a relatively stable salinity level, indicating that the system may be reaching a state of equilibrium after the initial rapid transfer of brine (within the first hour). This equilibrium state is crucial for understanding long-term processes (such as seasonal changes) of the salinity distribution and transport within snow-covered sea ice. However, it must be acknowledged that the small-scale experiments used in this study are limited in their interpretation of brine transport dynamics. In natural environments, brine transport occurs across vertical gradients that may extend for several meters. In contrast, our laboratory experiments used sea ice discs with diameters of only 5 to 5.5 cm and snow columns of only 3 centimeters in height, which represent only a small fraction of the spatial dimensions found in the field. This scale mismatch may constrain the development of complex brine channels in height and may enhance brine retention in the basal snow layer, while the smaller lateral dimensions restrict lateral variations and the formation of interconnected brine channel networks. Therefore, the brine transport dynamics observed in our laboratory may be simplified relative to those in natural environments, and future controlled experiments should be extrapolated to larger-scale or more heterogeneous field conditions to better replicate the vertical and lateral dimensions unique to natural sea ice and snow environments.

In the early stages of growth of FYI it can have a range of salinities from 6 to 15 ppt (Nakawo and Sinha 1981). The salinity of the basal 4 cm snow on FYI observed in the field were as high as 35 ppt (Confer *et al* 2023). In our experiments, snow salinity was never observed to exceed the salinity of the sea ice. Differences in salinity between snow and sea ice observed in the field compared to laboratory settings can be attributed to several factors. Natural environmental conditions, such as temperature fluctuations, can lead to changes in the migration and redistribution of brine in the snowpack, and processes such as melting, refreezing, and compaction over time, can lead to brine enrichment in specific layers of the snowpack (Sturm and Massom 2016). However, our laboratory experiments were conducted under controlled temperature conditions without co-located temperature measurements within the snowpack, which limits our ability to directly assess how temperature variability may have influenced brine migration patterns across different snow grain sizes. This absence of temperature monitoring represents a significant limitation when interpreting our salt transport results, as even small temperature gradients can alter capillary forces, brine viscosity, and localized melting-refreezing cycles that drive salt redistribution in natural snowpacks (Colbeck 1974, Domine *et al* 2004). Additionally, field environments may contain additional sources of salts or minerals, such as aerosol particles and seawater spray, which may contribute to elevated salinity in snow on sea ice (Domine *et al* 2004). Very low salinity (0.01–0.12 ppt) has been measured in the uppermost layers of snow in the field (Domine *et al* 2004). The lower

values within this range would not be measurable in our laboratory experiments due to limitations of our salinity meter (0.1 ppt). We believe the most likely reason for our lower salinity values to be the smooth grains from our artificial snow production method, with reduced SSA relative to more irregular shapes.

5. Conclusion and future work

We have demonstrated the value of laboratory experiments using artificial snow and sea ice to investigate the controls on the movement of salt from sea ice into overlying snow. This study is motivated by the need to understand controls on salt transfer, especially in light of the transition from an Arctic sea ice pack predominantly comprising SYI and MYI to primarily FYI which has a higher salinity.

The artificial snow microstructure employed in our experiments does not capture the complexity of real-world snow on sea ice, which falls as precipitation and undergoes continual metamorphosis driven by temperature fluctuations, wind, and other environmental factors. Our experiments were conducted under controlled temperature conditions that do not fully simulate the temperature variability experienced in natural polar environments, for instance diurnal cycles, or the much colder temperatures during Arctic winter of -20 to -68°C (Serreze and Barry 2011). Repeating the experiments at different temperatures could help to reveal the effect of temperature on salt movement for a range of sea ice and snow properties.

The blender and sieves produced grains in rounded shapes of varying sizes. However, real snow is typically less smooth and future experiments should endeavour to create more realistic snow grain shapes. Snowpack layering is often much more complex and includes snow metamorphosis as well as the influence of many external factors, such as wind, temperature changes, precipitation, etc (Colbeck 1983, Sturm and Massom 2016). By producing uniform snow packs with controlled grain sizes we were able to isolate the effect of grain size and show its impact on salt transfer.

The results indicated that the most rapid brine transfer occurs within the initial hour of snowfall onto sea ice. This hypothesis suggests an exploration of changes in snowpack salinity on shorter time scales is needed. Subsequent experiments and field observations should prioritize the initial hour after snow deposition on sea ice, potentially uncovering more details of the process through finer temporal resolutions. In addition, examination of snow grains at various elapsed times (e.g., using a microscope, or ideally, Micro-CT) would indicate whether our assertion that snow salinity appears to decrease due to a further rounding of the grains caused by melting at the edges due to the salt on the surface of grains.

We found that snow salinity (both whole-snowpack and basal layer) increased with sea ice disc volume, but we did not investigate whether larger sea ice discs had higher salinity at their upper surface (in a brine skim or uppermost layer) at the start of the experiment or whether salinity reduced throughout the sea ice disc during the experiments. We therefore suggest that future experiments should examine layerwise salinities of sea ice discs both before and after salt transfer into overlying snow. In addition, measurements of the volume and salinity of brine skim atop frozen sea ice discs would help to indicate how sea ice disc volume affects salt availability to the overlying snow.

Salinity has implications for snow and ice physical properties, remote sensing, and more broadly for climate. The presence of salt in the snow and ice reduces the freezing point, causing melting at lower temperatures. Our experimental results provide quantitative relationships between snow salinity, particle size, and sea ice properties, which may inform improved parameterization of remote sensing algorithms via understanding of salinity transfer into the snow cover, and therefore potential effects on physical and dielectric properties. Additionally, sea salt from blowing snow can cause surface warming by increasing the concentration of cloud condensing nuclei, enhancing longwave emissivity (Gong *et al* 2023).

This study highlights the importance of sea ice and snow properties in salt transport from the saline upper sea ice layers into the snow pack, and therefore in the resulting salinities of sea ice and its snow cover. In the context of a warming climate and younger Arctic sea ice pack, understanding the processes and controls on salt transfer from sea ice into overlying snow is crucial for monitoring and predicting physical changes to the snow and ice, developing accurate remote sensing techniques and in modelling climate-relevant feedbacks via aerosols.

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Author contribution statement

SH conducted the majority of the experiments and led writing and review of the manuscript. RW conceived the experimental setup based on initial ideas by RM and VN, led supervision of Masters projects by SH, EM and WL and contributed to writing and review of the manuscript. AF performed additional experiments to determine the uncertainty and repeatability, and contributed to writing and review of the manuscript. EM conducted preliminary experiments and contributed to writing and review of the manuscript. WL conducted the concurrent experiments used to investigate uncertainties and reviewed the manuscript. RM contributed to writing and review of the manuscript. VN advised on experimental equipment and reviewed the manuscript. TM advised on planning and running experiments. JS contributed to writing and review of the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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