Growing Artificial Sea Ice and The Importance of Seeding

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KEY STATEMENTS

1. There is a significant relationship between the volume of a tank of water and its extent of supercooling shown in its Meta-Stable Zone Width. The relationship between these two variables is decreasing exponential.
2. Using this relationship, it is thus recommended for any artificial sea ice growth set-up that seeding of the solution is not necessary for large volumes

ABSTRACT

Artificial sea ice growth is an emerging field that aims to assist in understanding the growth conditions and properties of sea ice. The Meta-Stable Zone Width (MSZW) of a supercooled solution is dependent on volume. Larger volumes have a higher probability of having a seed crystal being introduced to the system which halts supercooling and begins nucleation, hence, small extents of supercooling can be found in the ocean before freezing. Small MSZW's are not often reflected in artificial sea ice set-up's, thus many choose to seed to avoid excessive supercooling.

This research focused on determining the MSZW of artificial sea ice grown in four volumes: 5 L, 30 L, 100 L and 370 L. The results showed a decreasing average MSZW as tank volume increased as a decreasing exponential relationship was found between volume and the MSZW.

PLAIN LANGUAGE SUMMARY

Supercooling is a natural phenomenon in which a cooling liquid cools below its natural freezing point yet does not freeze. The extent at which the liquid supercools before it begins freezing is called the Meta-Stable Zone Width (MSZW). This phenomenon happens naturally in the open oceans when they freeze, however at very small extents. There is a correlation that has yet to be determined on how the extent of supercooling changes with the liquid volume, as smaller volumes display larger MSZW. In artificial sea ice growth, it may be beneficial to prevent large extents of supercooling by introducing a seed crystal, thus this research will determine whether that will be necessary for certain tank volumes.

This research grew artificial sea ice in four volumes: 5 L, 30 L, 100 L and 370 L and observed the supercooling within each volume. The results showed a decreasing average MSZW as tank volume increased as a decreasing exponential relationship was found between volume and the MSZW. The largest tank volume also had a MSZW similar to that found in the open ocean.

INDEX TERMS AND KEYWORDS

Sea ice; Analytical modeling and laboratory experiments; Instruments and techniques; Crystallization; Artificial sea ice; Supercooling; Meta-stable zone width;

1. INTRODUCTION

Artificial sea ice production is important in sea ice research due to its ability to study the growth mechanisms of sea ice at different conditions. As the aim of artificial sea ice production is to replicate true sea ice, recreating the conditions of growth is deemed necessary. As there is a relatively small amount of supercooling that occurs in the open ocean, many artificial sea ice set-ups use seeding to limit the effect of supercooling on frazil ice production as well as to create uniform, consistent and repeatable experimental conditions (Golding, et al., 2014; Cottier, et al., 1999). However, the necessity of seeding during artificial sea ice growth may be dependent on the volume of the tank in use since smaller volumes of solution are subject to larger variations in supercooling/undercooling (or the metastable zone width (MSZW) (Nyvlt, 1968). The purpose of this study is to thus determine if seeding is a necessary step in artificial sea ice growth in relation to the volume used in the respective experimental set-up.

Supercooling of liquids is a phenomenon that occurs when a solution remains a liquid below its standard freezing point. This often occurs in conjunction with the supersaturation of a liquid; where the solution holds more dissolved solute than its standard equilibrium amount, rendering the solution less stable or metastable (Wilson, 2012). Crystallization of the solution begins when nucleation occurs. This can be initiated in three ways: 1) the introduction of a seed crystal into the system, 2) the solution reaches a point of maximum supersaturation or 3) the system remains supersaturated for an extended period of time (Myerson & Ginde, 2002).

This extent of supersaturation or maximum supercooling has been considered to be the metastable zone width (MSZW) (Figure 1). The metastable zone is the region between the solubility line, where the solution contains the maximum amount of dissolved solute it can hold, and the point of maximum supersaturation (Randall, et al., 2012).

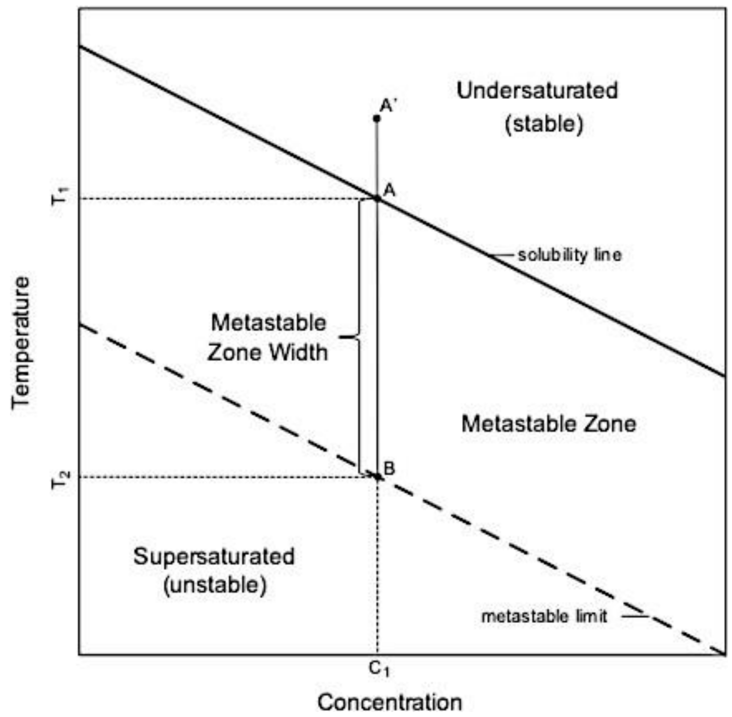

Figure 1: Generic binary phase diagram showing the solubility regions of a solid-liquid system (Randall, et al., 2012)

A typical way to observe the MSZW is by observing the temperature evolution of the freezing solution. If supercooling takes place, the MSZW can be determined by finding the maximum supercooling that took place. Once maximum supercooling has taken place, the solution's temperature jumps back up to the equilibrium freezing point where it plateau's for a short period until further cooling occurs in its solid state (Daly & Axelson, 1986). The detectability of the MSZW is strongly dependent on the accuracy of the measuring instruments used. Detection techniques for identifying the MSZW widely vary but all center around a change in a property of the solution when nucleation begins. This can be a change in the solution visually as crystals form (Mullin & Jancic, 1979), its electrical conductivity (Yuan, et al., 2015; Kubota, 2008), density (Marciniak, 2002; Kubota, 2008), turbidity (Gerson, et al., 1991; Kubota, 2008; Taboada & Graber, 2003), temperature (Randall, et al., 2012) or ultrasonic velocity (Kubota, 2008; Marciniak, 2002; Lyczko, et al., 2002). Some researchers have observed nucleation with the naked eye, such as Mullin and Jancic (1979), which limits detection to a critical nucleus size. Alternatively, detection of particles can be accomplished by the Lasentec Focused Beam Reflectance method (FBRM) or the Lasentec Particle Vision and Measurement method (PVM), which were developed by Barrett and Glennon (2002). FBRM uses laser light beams to determine the number and size of the forming crystals while PVM employs probes to take microscopic video images of the solution's surface.

The volumetric effect on the extent of supercooling has long been considered (Oike, et al., 2018; Mossop, 1954; Knight, 1967) but little published data on the stochastic volume effect on ice crystallization. The stochastic nature of nucleation, causes nucleation to occur randomly at different times, being more pronounced in smaller volumes (Kadam, et al., 2011). It has been found that smaller volumes produce a large distribution of values for the MSZW as well as a greater MSZWs compared to larger volumes (Randall, et al., 2012; Kadam, et al., 2011). For example, Randall and co-workers showed that the temperature variation in a 1.8 mL solution was 9 °C while for a 1 L solution it was 2.5 °C (Randall, et al., 2012). This is consistent with the Single Nucleus Mechanism theory whereby the probability of nucleation increases with the volume of the solution (Kadam, et al., 2011).

Liang and co-workers (2004) showed that stirrer speed affects the MSZW for an investigated volume range of 0.45 to 20 L, where the observed MSZWs were mostly found to decrease with increasing stirring speed. Additionally, van der Elsken and co-workers (1991) also showed that an increase in shear rate (0 to 30 sec^{-1}) within their cold room tank, decreased the extent of maximum supercooling achieved. And similarly, Ye and Doering (2004) reported on an increase in depth water velocity which decreased the MSZW.

Additionally, there is clear evidence to support that the rate of heat loss or cooling rate also strongly affects the maximum supercooling achieved. Oike and co-workers (2018), Ye and Doering (2004) and Liang and co-workers (2004) all reported on this phenomenon. Furthermore the studies that have been conducted thus far have not considered that volume is unimportant, but rather it is of second order in its contribution to nucleation and the extent of supercooling (Hanley, 1978; Daly, 1994).

Seeding of a supercooled solution is a technique used to limit the extent of supercooling. The introduction of a "seed" provides a site for heterogenous nucleation to take place (Wilson, et al., 2003). Homogeneous nucleation is the nucleation of a system that contains no particulate matter previously present or otherwise added. While heterogeneous nucleation, which is most common, is nucleation that occurs where there is a seed crystal present (Randall, et al., 2012; Dirksen & Ring, 1991). Seed crystals, in nature, are usually dust particles, biological matter or any other impurities within the system (Wilson, et al., 2003), and their introduction into a supercooling system reduces the MSZW of the system (Mossop, 1954). Thus, larger volumes, which naturally having a larger probability of having a dust particle or impurity in the solution, are predicted to have a smaller MSZW than smaller volumes of the same solution (Mossop, 1954).

Additionally, agitation of the system has been found to decrease the MSZW (Kubota, 2008; Bogacz & Wójcik, 2014; Liang, et al., 2004). It is theorized that this is due to a ‘washing away’ effect where nuclei first forms on the stirrer and is then ‘washed away’ to the surface where the nucleation of the bulk solution begins (Liang, et al., 2004). In addition, seeding within a MSZW region where two crystals have the potential to nucleate (ice and salt) will only form crystals of the seed. For example, Randall and co-workers showed that seeding with ice in the MSZW of an ice and sodium sulfate system only resulted in ice crystals forming (Randall, et al., 2009).

Supercooling of sea water is a common example of this phenomenon found in nature. Supercooled waters are usually found in coastal polynyas and leads during winter (Shi, et al., 2011; Ushio & Wakatsuchi, 1993; Ito, et al., 2015). However, the extent of supercooling is often minimal, with such water temperatures sometimes reaching only 0.008 °C below freezing point (Lewis & Perkin, 1983). These open waters are subject to often turbulent and windy conditions. The winter conditions together with the lack of insulating ice cover, creates a high latent heat loss off the surface of the water which in turn induces supercooling and associated frazil ice production (Daly & Axelson, 1986; Ushio & Wakatsuchi, 1993; Ito, et al., 2015). Residual supercooling is well documented for frazil ice growth in fresh water streams (Daly, 1984) with the key difference between sea water and fresh water being the much higher salinities in sea water which will ultimately result in greater freezing point depressions. In addition, work by Lewis and Perkin (1983) proposed a “potential” supercooling due to the pressure dependence of the freezing point when rising to the surface. This mechanism is also thought to be the most likely when it comes to supercooling below or near ice shelves as increased pressure increases the freezing point of seawater (McMurdo Sound, work from Leonard et al. (2011) and Lewis and Perkin (1985)).

Supercooled ocean waters result in frazil ice formation, which is a slush-like structure of ice, formed when small ice crystals conglomerate on the sea surface, usually in turbulent and windy conditions (Weeks & Ackley, 1982). Findings on the extent of supercooling in polar waters do vary, however, they do share a common order of magnitude (Table 1).

The varied results are due to the different weather and ocean conditions experienced during measurement as well as the accuracy and precision of the temperature-measurement apparatus used in each study. The relatively small values for the MSZW can be attributed to the high probability of available nuclei on which nucleation can begin. The windy conditions and vast expanse of water creates a high probability of nucleation taking place. Research studies on supercooling and stochastic nucleation in water have traditionally considered volume as an independent property that does not affect the phenomenon in any way (Kubota, 2008; Nyvlt, 1968). Despite this, interrogation and comparison of multiple studies show an emerging relationship: a decreasing exponential relationship between the natural logarithm of volume and extent of supercooling, as seen in Figure 2. Each study referenced in Figure 2 conducted their experiments with artificial or collected sea water with salinities ranging from 34-35 psu. As each set-up ranges significantly in volume, the natural logarithm of volume was taken to display how the MSZW decreases exponentially.

It is evident from Figure 2 that the larger volumes differ in their extent of supercooling far less than smaller volumes. The supercooling temperatures measured by Smith and co-workers in a 280 L tank were reported to be 0.05 °C (Smith, et al., 2002) and Ushio and Wakatsuchi reported an average of 0.15 °C in a 480 L tank (Ushio & Wakatsuchi, 1993) while Smedsrud measured 0.01 °C supercooling temperatures in a 120 000 L tank

(Smedsrud, 2001). Additionally, Schneck et al. (2017) conducted their studies in a 1152 L tank with propeller mixing of 325 rpm, which achieved an average extent of supercooling of 0.093. These values are similar in their order of magnitude when compared to the supercooling temperatures found in nature, as reported in Table 1. In comparison, the 2 L and 10 L tanks used by Katsaros and Liu, reportedly had solutions with larger supercooling temperatures (no mixing) of 1.2 °C and 0.76 °C respectively (Katsaros & Timothy Liu, 1974). All of these studies conducted their experiments using artificial sea water of roughly 35 psu and was used mixing throughout their experiments.

Table 1: Literature findings of the extent of supercooling in Arctic and Antarctic waters

ΔT (°C)	Location	Source
0.02	Laptev Sea Coastal Polynya	Dmitrenko et al. (2010)
0.02-0.03	Chukchi Coastal Polynya	Ito et al. (2015)
0.001-0.015	McMurdo Sound, Antarctica	Leonard et al. (2006)
0.025	McMurdo Ice shelf, Antarctica	Leonard et al. (2011)
0.008	North of Svalbard	Lewis & Perkin (1983)
0.047	McMurdo Sound, Antarctica	Lewis & Perkin (1985)
0.015	Freemansundet, Svalbard	McPhee et al. (2013)
0.065	Prydz Bay, Antarctica	Shi et al. (2011)
0.02	Kapp Lee, Storfjorden polynya	Skogseth et al. (2009)

From these studies, it is clear that there is a foundation upon which a relationship between volume and the MSZW can be investigated. This may be informative for future studies on artificial sea ice set-ups on whether seeding is a necessary step in the growth process.

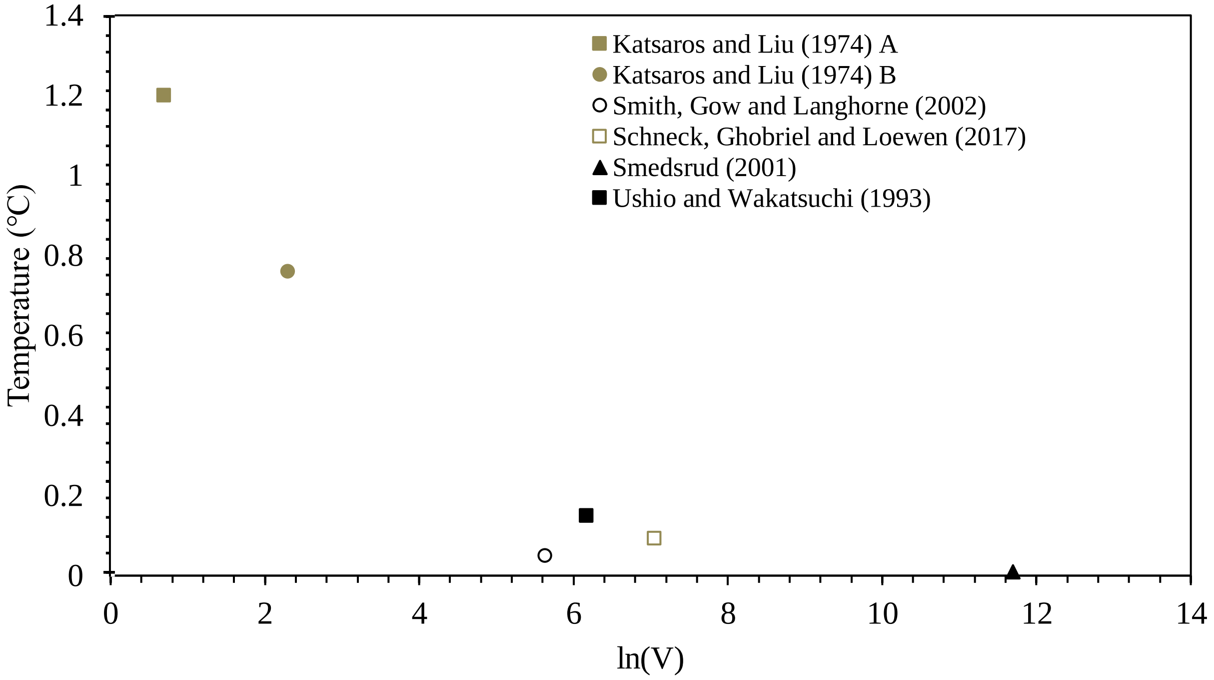

Figure 2: Supercooling results for different volumes (liters) of freezing sea water from other studies. Katsaros and Liu (1974) A and B refer to two of the volumes investigated. Katsaros and Liu (1974) A refers to a 2 L set up while B refers to a 10 L set up.

2. MATERIALS AND METHODS

Experiments were conducted in the cold room laboratory at the University of Cape Town. All experiments were conducted at –20 ± 0.3 °C until freezing occurred. Four volumes of tanks were used: 5 L, 30 L, 100 L and 370 L. Each container was made of plastic and filled its respective volume of deionized water. Aquaforest aquarium sea salt was added to the water to create a 34 psu solution. The salinity of the system was confirmed using a Graigar AZ 8303 conductivity/temperature probe, which is accurate to 1 %. Thermon Class A PT100 three wire temperature probes were used to detect supercooling in the system. These probes are accurate to 0.05 °C after calibration. Temperature was measured and logged every 9 seconds, and recorded onto a Campbell Scientific CR5000 data logger.

Each system was precooled to +1 °C and the solution was mixed so that the entire system was at the same temperature before starting the experiment. This ensured that each repeat experiment began at the same conditions and that variability in the temperature of the water would not affect the extent of supercooling. Fig. 4 illustrates the skeleton of each type of set-up used in this study.

The 5 L cylindrical tank, was mixed using a Lasec magnetic stirrer, as shown by Figure 3A, where the height of the tank was 26 cm and the diameter was 15 cm. The speed of the magnetic bar was set to setting number 4 so that a cyclone within the water was not formed; this ensured gentle yet conformed mixing within the set up. Five consecutive repeats were conducted for the 5 L tank. Entering the container during a repeat was discouraged as this would allow warm air and dust to enter the container which could affect the water temperature. The 5 L solution was allowed to cool and freeze for 4 hours without disturbance. This length of time sufficiently allowed for the solution to supercool and freeze. An ambient temperature probe was situated on top of the 5 L tank set-up to monitor the air temperature for any anomalies, which could affect the freezing profile of the solution.

The 30 L cylindrical tank was also well-mixed using a Lasec magnetic stirrer as shown by Figure 3A, where the height of the tank was 42 cm and the diameter was 30 cm. Six consecutive repeats were carried out in the 30 L tank and was given 8 hours without disturbance to cool and freeze sufficiently.

The 100 L cylindrical tank set-up, unlike the previous two, was mixed using one Grech CW-110 multi-function wave make pump that has a flow capacity range of 500-4000 L/h. The pump was positioned in 30 cm deep to create sufficient mixing throughout, as seen in Figure 3B, where the height of the tank was 60 cm and the diameter was 46 cm. This pump was set to 2 000 L/h pump capacity which corresponded to setting 4 on the controller. A pump was used as a magnetic stirrer, as used in the smaller tank sizes, was too small for the tank size and would not create sufficient mixing throughout the water. A plastic scaffold held the three temperature probes used in this set-up; one probe used for ambient temperature monitoring, one probe located 5 cm below the water surface to ensure the water temperature is consistent and one probe located at the surface to detect nucleation. Other probes were located throughout the tank to ensure consistent mixing throughout the tank before starting the experiments. Three repeats were conducted using this tank set-up, with each repeat being allowed 10 hours to freeze at – 20 °C.

The 370 L cylindrical tank had a height and diameter that was 70 cm and 82 cm respectively. The tank set-up can be shown by Figure 3B, however, it was mixed using two Grech CW-110 multi-function wave maker pumps, positioned at the bottom of the tank and 40 cm deep. This allowed for sufficient mixing throughout the depth of the tank while set to setting 4 which corresponds to roughly 2 000 L/h pump capacity. Additionally, two plastic scaffolds holding two sets of in-water probes were erected to ensure the system is well-mixed and to spot any possible temperature anomalies in the tank. An ambient temperature probe was used to measure the air conditions above the water. Three consecutive repeats were conducted, with each repeat being allowed 15 hours to cool and freeze sufficiently without disturbance.

The polar laboratory was set at -20 °C thus the cooling rate of the air temperature was set to a specific rate according to the laboratory's cooling settings. As a result, the cooling rate of the water for each tank could not be controlled. The cooling rate does affect the nucleation and extent of supercooling (Oike, et al., 2018; Liang, et al., 2004; Ye & Doering, 2004), however, this variable could not be controlled.

The cooling rate of each system was calculated by finding the gradient of the straight-line temperature profile between the start of the repeat to the point where the temperature is at its lowest. The MSZW was calculated by finding the difference between the temperature at which the solution begins to plateau and the lowest temperature the solution experiences.

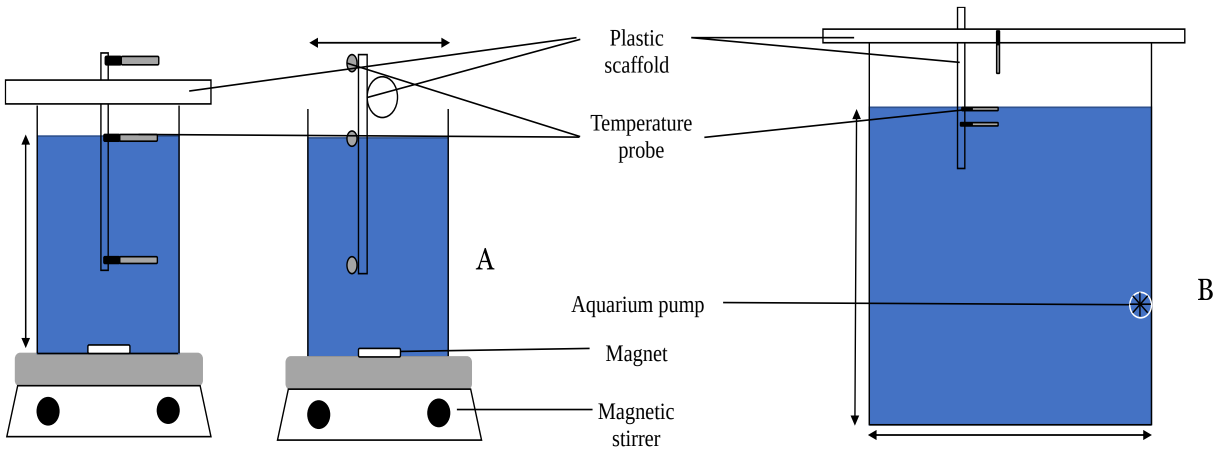

Figure 3: Schematic drawings of the two kind of tank set-ups used in this study. Set-up A used for 5 L and 30 L tanks and set-up B used for 100 L and 370 L tanks.

3. RESULTS AND DISCUSSION

3.1. Results for 5 L, 30 L, 100 L and 370 L tank experiments

Each tank volume was filled with the same solution and was subjected to the same freezing conditions. The resulting freezing profiles of each volume and its repeats can be seen in Figure 4.

The freezing profile of the 5 L solution can be seen in Figure 4A whereby the solution's temperature profile can be matched to a typical supercooling solution's temperature profile, as seen in **Error! Reference source not found.**. The solution cools steadily and with a constant rate as seen in the first part of the profile. The mean cooling rate across all repeats was calculated to be - 3.20 °C/hour. The solution continues to cool past its equilibrium freezing point, which at 34 psu, is -1.87 °C (Fofonoff & Millard Jr, 1983).

Table 2: Summary of results of the 5 L, 30 L, 100 L and 370 L tanks. The expected freezing point temperature for 34 psu sea water is -1.873 ℃ (Weeks & Ackley, 1982)

	Minimum Temperature (°C)	**Plateau Temperature(°C)**	**MSZW (°C)**	**Cooling Rate (°C/h)**
		5 L		
Mean	-2.34	-1.90	0.44	-3.20
Standard Deviation	0.094	0.050	0.10	0.24
		30 L		
Mean	-2.10	-1.88	0.22	-1.88
Standard Deviation	0.050	0.034	0.037	0.22
		100 L		
Mean	-2,00	-1.87	0.13	-2.28
Standard Deviation	0.003	0.014	0.014	0.27
		370 L		

Mean	-	-1.87	-	-2.31
Standard Deviation	-	0.044	-	0.062

Each repeat can be seen to supercool past this temperature and reach a minimum temperature before jumping back to its equilibrium temperature where it plateau’s. This trough is different for each repeat but the mean minimum temperature reached is -2.34 °C. The supercooled water then froze which is signified by the sudden spike in temperature. There is a subsequent temperature plateau for a significant period of time before the solid solution continues to steadily decrease in temperature. The temperature of the solution at this plateau is expected to be the equilibrium freezing point. The mean calculated plateau temperature of the 5 L tank’s repeats is -1.90 °C, with a standard deviation of 0.05 °C. The difference between each repeat’s minimum temperature and its plateau temperature is the calculated MSZW of that repeat. The mean MSZW was found to be 0.44 °C with a standard deviation of 0.10 °C.

The 30 L tank temperature profile is similar to that of the 5 L with the same notable features. The 30 L cooling rate is different to that of the 5 L with an average rate of -1.88 °C/hour. The profiles seen in Figure 4B, have a mean minimum temperature of -2.10 °C and an average plateau temperature of -1.88 °C. The resulting average MSZW is 0.22°C with a standard deviation of 0.037 °C. The 100 L tank temperature profile is similar to that of the 5 L and 30 L with the same notable features. The cooling rate of these repeats in the 100 L are different to that of the 5 L with an average rate of -2.27 °C/hour. The profiles seen in Figure 4C, have a mean minimum temperature of -2.00 °C and an average plateau temperature of -1.87 °C. The resulting average MSZW is 0.13 °C with a standard deviation of 0.013 °C.

The 370 L tank’s profile bears resemblance to the smaller tank’s temperature profile, as seen in Figure 4D, however no significant supercooling was detected. It is thus assumed that any supercooling that took place had an extent less than 0.05 °C, which is the accuracy of the temperature probes used. The average calculated cooling rate was – 2.31 °C/hour until each repeat plateaued at an average of -1.87 °C.

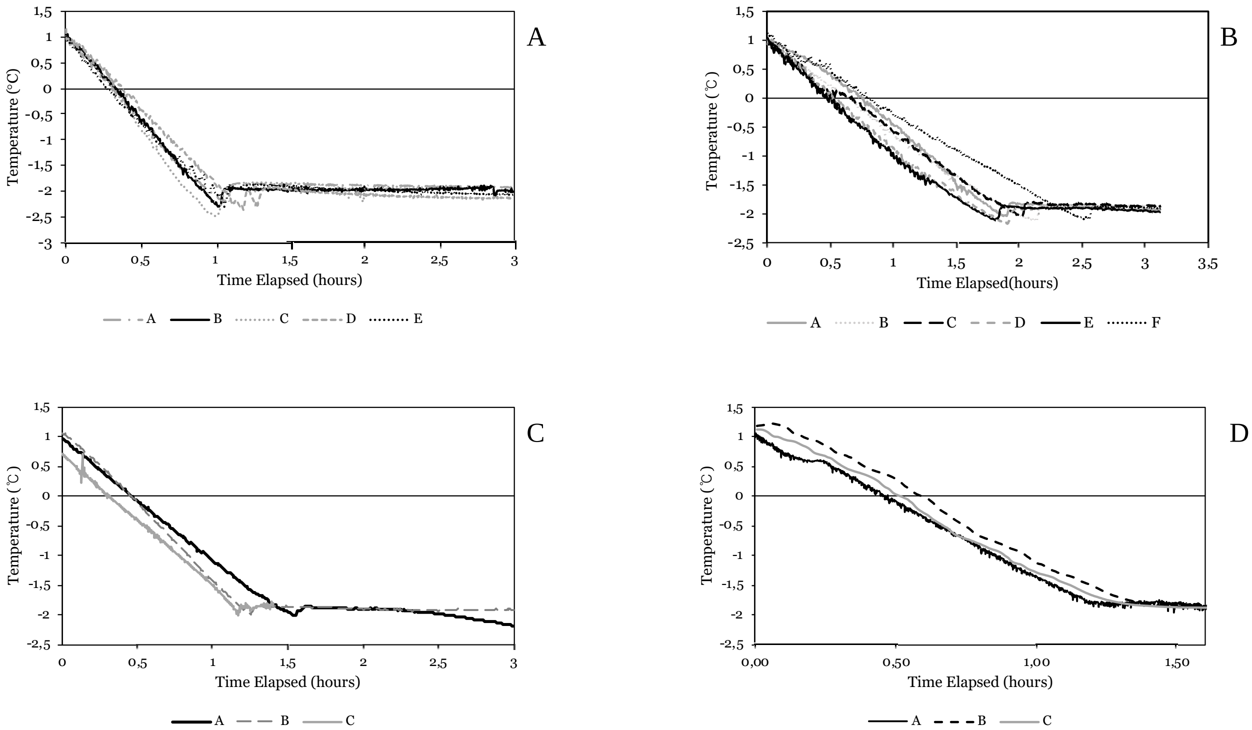

Figure 4: Freezing temperature profiles over time for 5 L (A), 30 L (B), 100 L (C) and 370 L (D) solutions. The average MSZW were calculated to be 0.44, 0.22 and 0.13 for the 5 L, 30 L and 100 L respectively, while there was no measured supercooling for the 370 L.

With the results of all four volumes, comparisons can be made to identify if there is an overarching trend. Comparisons of the notable temperatures, as detailed above, with their standard deviations can be seen in Table 2. It is apparent from Table 2, that the extent of supercooling, the MSZW, decreases with an increasing volume as expected. Additionally, the range of values given for the MSZW for each repeat also decreases with an increasing volume, as seen by the difference in the standard deviation of each volume’s MSZW.

This is further validated by the increase in the minimum temperature reached by the solution as the volume increases. This validates that the solution is being nucleated more quickly in larger volumes. Furthermore, this in conjunction with the Single Nucleus Mechanism theory (Kadam, et al., 2011) which predicts that a larger volume has a higher probability of heterogeneous nucleation. The larger variation in the MSZW for the smaller volumes confirms that the smaller volumes are more stochastic in nature whereby nucleation is more likely to be random and spontaneous and not initiated by freezing nuclei such as dust or other impurities (Kadam, et al., 2011; Kadam, 2012).

3.2. Relating Volume to the MSZW

The results of the 5 L, 30 L, 100 L and 370 L experiments clearly show a decrease in the MSZW as well as in its variance. These results are compared to the findings of other studies on the supercooling of artificial sea water (Figure 5). For the purpose of this Fig., the MSZW of 0.05 °C was used for the 370 L tank. Figure 5 shows that the four volumes investigated in this study, contribute and confirm the proposed relationship between volume and the MSZW. The dotted exponential trendline proposes a relationship between these volumes and their respective supercooling temperatures. The marker representing the 5 L tank is noticeably lower than Katsaros and Liu's 10 L tank experiments. Katsaros and Liu's freezing experiments were non-agitated whereas the experiments conducted in this study were well-mixed. A lower MSZW is thus expected in the system where mixing occurs as in accordance with the 'washing-away' theory proposed by Liang et al. (Liang, et al., 2004).

From the comparisons of this study's results with the results from others, it can thus be concluded that there is an established decreasing exponential relationship between the extent of supercooling experienced and the natural logarithm of volume. In addition, the literature values were taken from studies with different operating conditions and hence any correlation must be taken with caution. Possible errors in these results may occur from the different cooling rates of the water, which could not be controlled in the experiments carried out in this study, together with the extent of mixing of the water. The study also only focused a fixed salinity of artificial sea water but the freezing point depression will change for different salinities. Future work should therefore look at a wider range of operating conditions (salinities, cooling rates, and volumes) as these variables do affect the extent of supercooling.

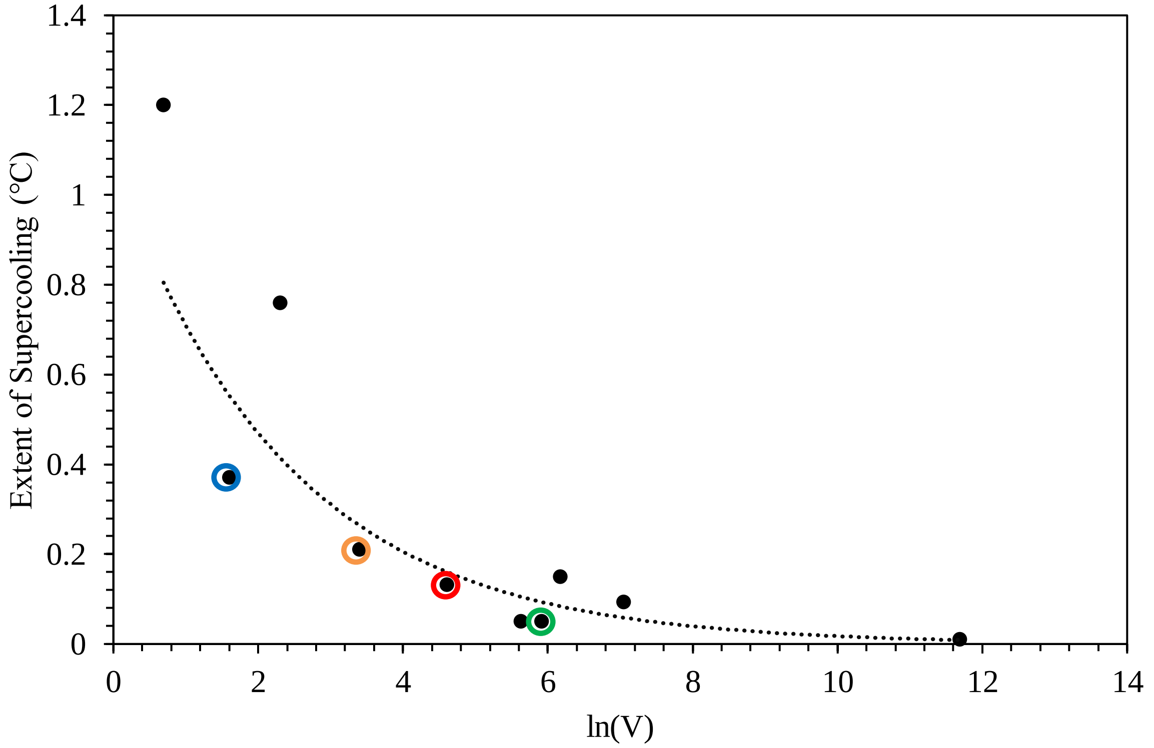

Figure 5: Supercooling results for different volumes of sea water from other studies and the results of the 5 L (blue), 30 L (yellow), 100 L (red) and 370 L (green) tanks conducted in this study. The black dots are representative of the results from other studies as mentioned and referenced in Figure 2.

3.3. Implications for artificial sea ice growth set-ups

One of the main objectives in producing artificial sea ice is recreating the conditions in which sea ice forms. As previously established, very small supercooling temperatures are experienced in nature and recreating this is key to making artificial sea ice. In small volumes, it has been established that there is significant supercooling, while insignificant changes in the extent of supercooling are experienced in larger volumes which is demonstrated by the results of the 370 L tank in this study. This is important to distinguish as the ice morphology, structure and overall mass with a given time will be highly variable with large extents of supercooling. It thus recommended that seeding be considered when growing artificial sea ice in small volumes where significant supercooling is found to be greater than 0.05 °C.

4. CONCLUSIONS

The following conclusions can be drawn from this study:

- There is a decreased measured MSZW with increasing volume as seen in the experiments conducted with artificial sea water using volumes of 5 L, 30 L, 100 L and 370 L.

- There is a tentative relationship between the MSZW and volume using the results from this study together with results from similar studies. This relationship can be described as a decreasing exponential curve between the MSZW and the natural logarithm of volume.

- Owing to the small supercooling temperatures that have been measured in oceans, large volumes used for artificial sea ice growth, that exhibit similar supercooling, do not require seeding as part of their experimental procedure. However, smaller volumes do require seeding in order to lower the extent of supercooling experienced.

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Data Availability Statement

The datasets generated during and/or analysed during the current study are available in the figshare repository. Access to this repository can be found at this link: https://doi.org/10.6084/m9.figshare.13670008.

CRediT author contributions

Siobhan Johnson: Writing-original draft, Methodology, Formal analysis, Investigation, Data curation, Visualization**,** Project management

Dyllon Garth Randall: Conceptualization, Writing-review & editing

Tokoloho Rampai: Supervision, Project management, Funding acquisition, Resources, Writing-review &editing, Validation

Marcello Vichi: Funding acquisition

Sebastian Skatulla: Resources

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REFERENCES

Daly, S. F. & Axelson, K. D., 1986. Estimation of Time to Maximum Supercooling during Dynamic Frazil Ice Formation, Hanover: s.n.

Daly, S. F., 1984. Frazil Ice Dynamics, Hanover: U.S. Army Cold Regions Research and Engineering Laboratory.

Daly, S. F., 1994. Report on Frazil Ice, s.l.: US Army Corps of Engineers.

Dmitrenko, I. A. et al., 2010. Observations of supercooling and frazil ice formation in the Laptev Sea coastal polynya. Journal of Geophysical Research, 115(C05015).

Fofonoff, P. & Millard Jr, R. C., 1983. Algorithms for computation of fundamental properties of seawater. Unesco Technical Papers in Marine Science, Volume 44, p. 53.

Hanley, T. O. D., 1978. Frazil Nucleation Mechanisms. Journal of Glaciology, 21(85), pp. 581-587.

Ito, M. et al., 2015. Observations of supercooled water and frazil ice formation in an Arctic coastal polyna from moorings and satellite imagery. Annals of Glaciology, pp. 307-314.

Kadam, S. S., 2012. Monitoring and Characterization of Crystal Nucleation and Growth during Batch Crystallization, s.l.: Delft Technical University.

Kadam, S. S., Kramer, H. J. & ter Horst, J. H., 2011. Combination of a Single Primary Nucleation Event and Single Nucleation in Crystallization Processes. Crystal Growth and Design, 11(4), pp. 1271-1277.

Katsaros, K. B. & Timothy Liu, W., 1974. Supercooling at a Free Salt Water Surface in the Laboratory. Journal of Physical Oceanography, October.pp. 654-658.

Knight, C. A., 1967. The freezing of supercooled liquids. London: Moderm Book Company.

Kubota, N., 2008. A new intrepretation of metastabe zone widths measured for unseeded solutions. Journal of Crystal Growth, Volume 310, pp. 629-634.

Leonard, G. H. et al., 2006. Observations of platelet ice growth and oceanographic conditions during the winter of 2003 in McMurdo Sound, Antarctica. Journal of Geophyscial Research, 111(C04012).

Leonard, G. H. et al., 2011. Evolution of supercooling under coastal Antarctic sea ice during winter. Antarctic Science, 4(23), pp. 399-409.

Lewis, E. & Perkin, R., 1983. Supercooling and Energy Exchange Near the Arctic Ocean Surface. Journal of Geophysical Research, 88(C12), pp. 7681-7685.

Lewis, E. L. & Perkin, R. G., 1985. The Winter Oceanography of McMurdo Sound, Antarctica. In: S. S. Jacobs, ed. Oceanology of the Antarctic continental shelf. s.l.:American Geophysical Union, pp. 145-165.

Liang, K. et al., 2004. Examination of the Process Scale Dependence of L-Glutamic Acid Batch Crystallized from Supersaturated Aqueous Solutions in Relation to Reactor Hydrodynamics. Industrial & Engineering Chemistry Research, Volume 43, pp. 1227-1234.

McPhee, M. G., Skogseth, R., Nilsen, F. & Smedsrud, L. h., 2013. Creation and tidal advection of a cold salinity front in Storfjorden: 2. Supercooling induced by turbulent mixing of cold water. Journal of Geophysical Research, Volume 118, pp. 3737-3751.

Mossop, S. C., 1954. The Freezing of Supercooled Water. Proceedings of the Physical Society, pp. 193-208.

Nyvlt, J., 1968. Kinetics of Nucleation in Solutions. Journal of Crystal Growth, 3(4), pp. 377-383.

Oike, H. et al., 2018. Size effects on supercooling phenomena in strongly correlated electron systems: IrTe2 and □-(BEDT-TTF)2RbZn(SCN)4. Physical Review, 085102(95), pp. 1-7.

Randall, D., Nathoo, J. & Lewis, A., 2009. Seeding for Selective Salt Recovery During Eutectic Freeze Crystallization. Pretoria, s.n.

Schneck, C., McFarlane, V. & Loewen, M., 2017. Laboratory measurements of frazil ice properties in saline water. Whitehorse, CGU HS Committee on River Ice Processes and the Environment.

Shi, J., Cheng, Y., Jiao, Y. & Hou, J., 2011. Supercooled water in austral summer in Prydz Bay, Antarctica. Chinese Journal of Oceanology and Limnology, 29(2), pp. 427-437.

Skogseth, R., Nilsen, F. & Smedsrud, L. H., 2009. Supercooled waters in an Arctic polynya: observations and modelling. Journal of Glaciology, 55(189), pp. 43-52.

Smedsrud, L. H., 2001. Frazil-ice entrainment of sediment: large-tank laboratory experiments. Journal of Glaciology, 47(158), pp. 461-471.

Smith, I. J., Gow, A. J. & Langhorne, P. J., 2002. Laboratory Investigations into Platelet Ice Formation. Dunedin, s.n.

Ushio, S. & Wakatsuchi, M., 1993. A Laboratory Study on Supercooling and Frazil Ice Production Processes in Winter Coastal Polynyas. Journal of Geophysical Research, 98(C11), pp. 20,321-20,328.

van der Elsken, J., Dings, J. & Michielsen, J. C. F., 1991. The freezing of supercooled water. Journal of Molecular Structure, Issue 250, pp. 245-251.

Weeks, W. F. & Ackley, S. F., 1982. The growth, structure and properties of sea ice, Hanover: US Army Cold Regions Research and Engineering Laboratory.

Ye, S. Q. & Doering, J., 2004. Simulation of the supercooling process and frazil evolution in turbulent flows. Canadian Journal of Civil Engineering, Issue 31, pp. 915-926.

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