Final Report
”Brine convection over the entire sea ice thickness: Laboratory experiments”

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Introduction

Sea ice plays an active and important role in the Earth's climate. Over the last decades the Arctic sea ice is getting thinner and younger which affects not only its interactions with the surrounding layers (e.g. atmosphere, ocean) but also its intrinsic properties. Indeed the thermal properties of the sea ice, for example the heat capacity and the thermal conductivity, are strongly dependent on the sea ice bulk salinity.

First year sea ice presents a distinct salinity profile compared with multiyear sea ice, which has undergone substantial desalination with time (Untersteiner, 1964). The evolution of the salt content of first year sea ice is therefore an important issue. Based on experiments and modelling, Notz and Worster (2009) recently demonstrated that gravity drainage and flushing with snow meltwater are the only two efficient processes to desalinate the sea ice. These desalination processes have been investigated in recent years both from field work (e.g. Freitag and Eicken, 2003; Vancoppenolle et al., 2007; Notz and Worster, 2009), laboratory experiments (e.g. Wettlaufer et al., 1997; Notz and Worster, 2009) and numerical modelling (e.g. Cox and Weeks, 1988; Vancoppenolle et al., 2010; Wells et al., 2011). The general paradigm is that flushing is associated with the summer season, when the heat supplied by the atmosphere is large enough to melt the snow, while gravity drainage is related with the start of the winter season during sea ice formation and consequently restricted to the bottom of the ice. Hence it is generally admitted that sea ice rejects most of its salt during formation and the remainder during the melt season.

However, Jardon et al. (2012) recently showed indirect evidence of gravity drainage through the entire ice thickness after the growth season at the end of the winter (March). This work shows theoretically that a warm enough sea ice is a necessary condition for the onset of a salt convective episode over the full thickness of the ice layer. Until present no direct observations of this salt convection process has been measured neither in fieldwork nor in laboratory. Therefore, there is a real interest in study this process more in details with measurements of sea-ice properties like bulk salinity, temperature, solid fraction and permeability. This would be facilitated by both the fact that a non-destructive method for measuring salinity (based on a ”wire harp” which measures impedance) and hence solid fraction has been recently developed (Notz, 2005) and the possibility to use the sea-ice laboratory from the Max Planck Institute for Meteorology (Hamburg).

Project Objectives

The main objective of the project was to study the temporal evolution of a permeable sea ice in order to assess the theoretical conditions in ice thickness, temperature and salinity to allow full-depth desalination. In fact, as was established by (Jardon et al., 2012), based on a Rayleigh number analysis, a temperature criterion is settled providing a necessary condition for occurrence of convection through the full thickness of the ice. This temperature threshold depends on the thickness and initial salinity of the ice and far exceeds the limit of temperature associated with the permeability threshold.

In the aim to reach the former main objective, several intermediate steps with partial goals have been elaborated during the project development. One of the most relevant objectives was to calibrate and validate the data obtained from the new generation non-destructive instrument that was ready to be tested at the beginning of the project. Therefore, based on this new ”wire harp” we were able to study the properties of the sea ice during its formation under different conditions (air temperature, initial sea water salinity and surface ocean conditions: calm and turbulent). These new dataset can be compared with previous laboratory experiments which were performed with the ancient ”wire harp”.

The second part of the project, was focused in the analysis of the sea ice properties after the growing period. In the aim to study the gravity drainage through the entire ice thickness, the big challenge was to be able to growth a sea ice cold and thick enough, depending in its salt content, to reach impermeable conditions in the upper layers. Finally, once the sea ice has recovered its permeable condition we have assessed the changes in salinity and temperature allowing salt convection.

As was exposed before, this project is in line with the objectives of the Micro-DICE network as i) it focuses on understanding the transport properties of the sea ice that could have implications for large scale sea ice modelling, and ii) contributes to the mobility of a young scientist.

Laboratory Experiments

The experiments were performed in the sea ice laboratory at the Max Planck Institute for Meteorology in Hamburg. This laboratory counts with both a small tank of dimensions 0.8m x 0.4m x 0.4m in which instrument calibration and data validation experiments were carried out; and a cold room with a rectangular tank of dimensions 2m x 1m x 1m (Fig. 1) used for the remaining experiments.

The small tank is built from 12 mm thick perspex and is completely air tight. The bottom plate is a brass cooling plate, through which antifreeze coolant is circulating. To minimise any heat gain from the laboratory, the whole tank was placed in the cold room, the temperature of which was held between -1.5^{o}C and 0^{o}C throughout the whole experiments.

Regarding the cold room, this one was equipped with several atmospheric sensors to measure the air temperature, winds intensity and direction, relative humidity and sea ice surface temperature. Furthermore, the big tank was equipped with two thermistor strings with a spatial resolution between 5, 7.5 and 10 mm and 4 CTDs (Conductive

Temperature Depth sensor) mounted in the tank underneath the ice for temperature and seawater salinity measurements. In addition, we have used the wire harps to measure ice salinity and solid fraction, based on the measurements of the impedance/resistance between two parallel wires (Fig.). In addition, the wire harps were equipped with 8 thermistors located at the same level than each parallel wires. During the experiments we have used 3 wire harps consist of 8 pairs of wires with a vertical spacing between the wire pairs of 10 mm and an extra wire harp with higher spacing (20 mm) which presented a mechanical failure since the beginning and was excluded from the analysis.

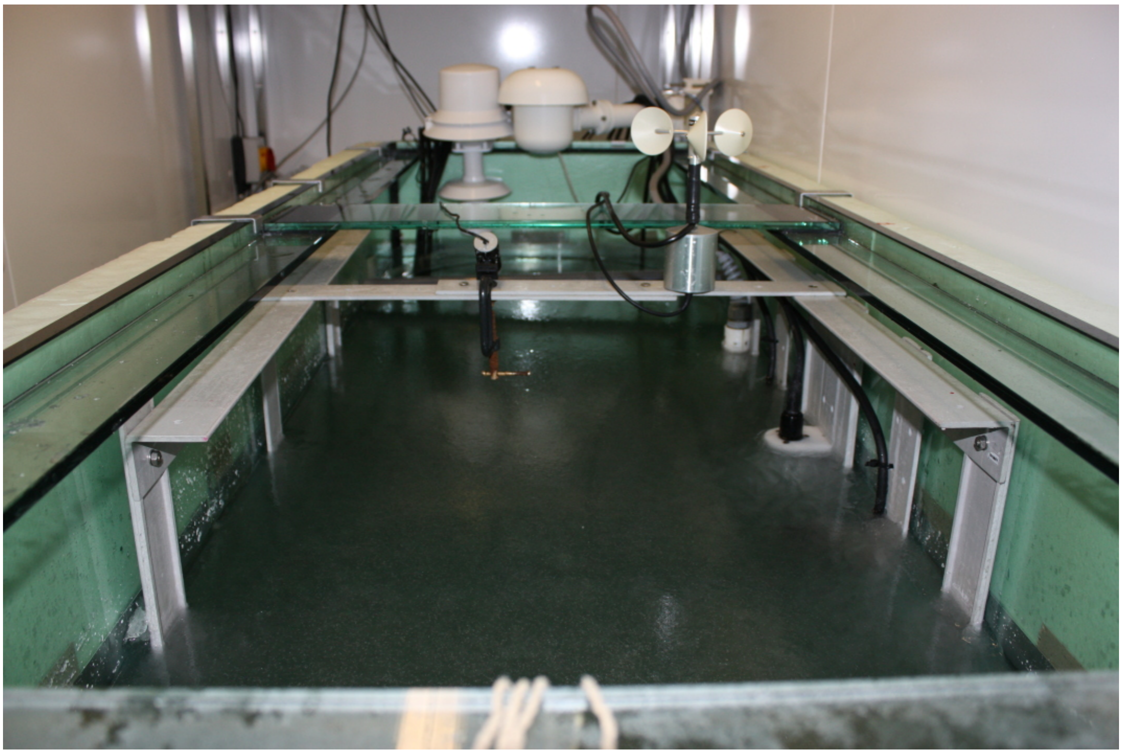

Figure 1: Picture of the cool room with the big tank that was used in the second part of the laboratory experiments.

During the project two distinct types of experiments were conducted. On the one hand, we have carried out a set of experiments so-called: ”Cooling from below”, conducted in the small tank and necessary to assess the performance of the new wire harps. These experiments allow us not only to calibrate the wire harps but also to compare observations with the analytical solution for the ice growth, the ice temperature and the solid fraction. On the other hand, the second part of the project was focused on the experiments so-called: ”Cooling from above”, in which case the big tank in the cold room was used and where we could study the temporal evolution of the ice during its formation, its transition from impermeable to permeable and finally its melting processes. In table 1 the "Cooling from above" experiments are presented, during experiments I and II the 3 wire harps were settled at the same level (see H0, H2 and H3 in Fig.), just below the water surface in order to compare them with each other. On the contrary, for experiments IV and V the harps were settled one below the other to span a greater length. In the particular case of experiment III, the wire harps were overlapped a few centimetres to get both a greater length and several measurements at the same level.

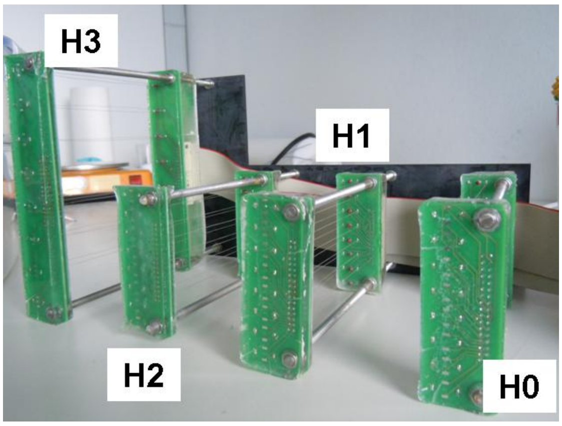

Figure 2: The wire harps (H) set up for experiments I and II (see table 1). Note the different spacing between the parallel wires for wire harps H0, H1 and H2 related with H3.

Table 1: 'Cooling from above" experiments description.

Experiment	**I**	**II**	**III**	**IV**	**V**
Duration	139h (5.8 days)	134h (5.6 days)	305h (12.7 days)	170h (7 days)	636h (26.5 days)
Initial Air Temp.	-20^{o}C	-20^{o}C	-25^{o}C	-25^{o}C	-25^{o}C
Initial seawater Sal.	33.15	33.24	33.18	33.47	33.5
Max. Ice Thickness	11.7 cm	10.8 cm	18.5 cm	18.8 cm	25.5 cm
Water Cond.	calm	calm	calm	turbulent	turbulent
Comments	Flooding event	-	-	Fast melting	Refreezing

In all the experiments that are described in table 1, before the start of an experiment, the temperature of the cold room was held constant between -1^oC and -2^oC for a few hours. Hence, at the beginning of an experiment the whole solution had a temperature very close to its freezing point, and ice formation started within the first minute after the temperature of the room was decreased at the start of an experiment, usually between -20^oC and -25^oC.

Preliminary Results

In this section we present an overview of the preliminary results obtained from the sea ice experiments performed in the frame of this project. We will describe first an experiment in which the seawater is cooled from below, this experiments is useful to establish comparisons between observations and the theoretical solution of the solid fraction. We will show next, some results related with the experiments performed in the cold room in which the seawater is cooled from above. Among these results we will present the solid fraction and bulk salinity evolution during the ice growth as well as some evidence of impermeable conditions and salt convection through the entire sea ice.

Cooling from below: The measured solid fraction for an experiment in which a 28 ppt solution with an initial temperature of -1.7^oC was cooled from below for 12 hours with a constant temperature of -10^oC is shown in Figure 3. The figure shows the solid fraction at each wire as a function of depth, nondimensionalised with the individual wire heights. The theoretical predictions for this setup from the similarity solution derived from the mushy layer theory (see Notz, 2005, for more details) is plotted as the dashed line. The agreement between the theoretical prediction and the measured data is better the farther a wire is to the base of the tank. This is due to some irregularities at the beginning of the experiment which affect the closer wires. For example, the antifreeze coolant should have been circulating through the cooling machine at a constant temperature of around -20^oC during two hours before opening the channels connecting to the cooling plate and set the temperature at the desired value of -10^oC. On the contrary, we have changed the cooling plate temperature from -1^oC to -10^oC suddenly at the beginning of the experiment. Therefore we can observe that the closer wires react slowly due to variations in the cooling plate temperature. A new experiment taken into account these considerations has been performed at the end of the project; unfortunately the data was not analyzed yet.

Cooling from above: As is presented in table 1, we have performed 5 experiments where the seawater solution is cooling from above at initial temperatures of -20^oC and -25^oC. All the experiments, except for experiment IV, were melted warming the cold room by steps, allowing to the ice temperature slowly increases through the entire ice. In the aim to observe how the sea ice reacts to atmospheric rapid changes the sea ice was melted fast during experiment IV. In addition, to be able to describe how the sea ice properties (like solid fraction and salt content) respond to cold-warm-cold atmospheric scenario we have alternatively increased and decreased the air temperature during the melting part in experiment V. The cooling from above experiments present hence several interesting results, following we have briefly exposed some of them.

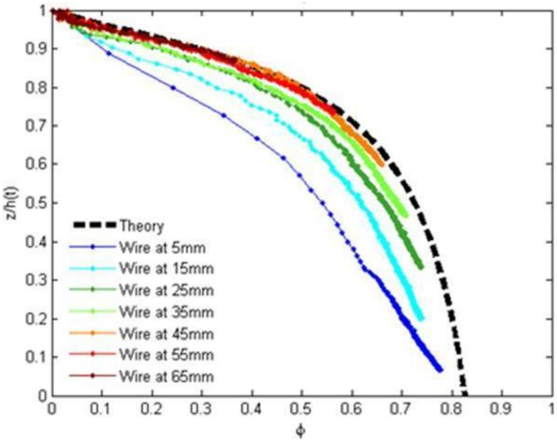

Figure 3: A comparison of the measured solid volume fraction ϕ with the theoretical prediction (dashed line) as a function of non-dimensionalised ice-thickness z/h. The data stem from wires in different heights (color code) from an experiment in which a 28 ppt solution is cooled from below to -10^{o}C for 12 hours. The final ice thickness was 10.8 cm.

- **Ice Growth:** The temporal evolution of the ice thickness for experiment I and IV are plotted in Figure 4. The red, green and blue lines in this figure show the ice thickness deduced from the resistance measurements. Actually, the presence of sea ice around the parallel wires deeply increases its resistance and becomes easy to identify the ice thickness if the initial position of the wire harps is known. The manual measurements of the ice thickness are in good agreement with this measurements for both cases: all the wire harps at the same level (Exp. I, Fig. 4 top panel) or one below the other (Exp. IV, Fig. 4 bottom panel). Since manual measurements were not taken during the night, the experiments present some gaps in the manual measurements that could be completed with the impedance measurements.

  The evolution of the solid-fraction and salinity profile as obtained from the impedance measurements during experiment IV is plotted in Figure 5. The Figure shows the profiles after 10, 15, 20, 25, 45, 55, 75, 100 and 115 hours during the growth period. In this experiment, the salinity maximum at the uppermost wires occurs during the first $\sim$50 hours, at that moment the salinity profile takes a C-shaped whiles during the last 50 hours of the experiment the salinity profile reduces the salinity at the sea ice surface and changes the form to a half of a C-profile.

- **Reaching impermeable conditions:**
  We have assumed that if the bulk salinity (or solid fraction) remains constant with time, the corresponding sea ice layer during that period is under impermeable conditions. In Figure 6 a potential example of impermeable conditions over at least the first 15 mm of the sea ice is presented. This example corresponds to the experiment IV, the impermeable condition ends with the rapid increases in the air temperature that reduces the bulk salinity due to brine convection.

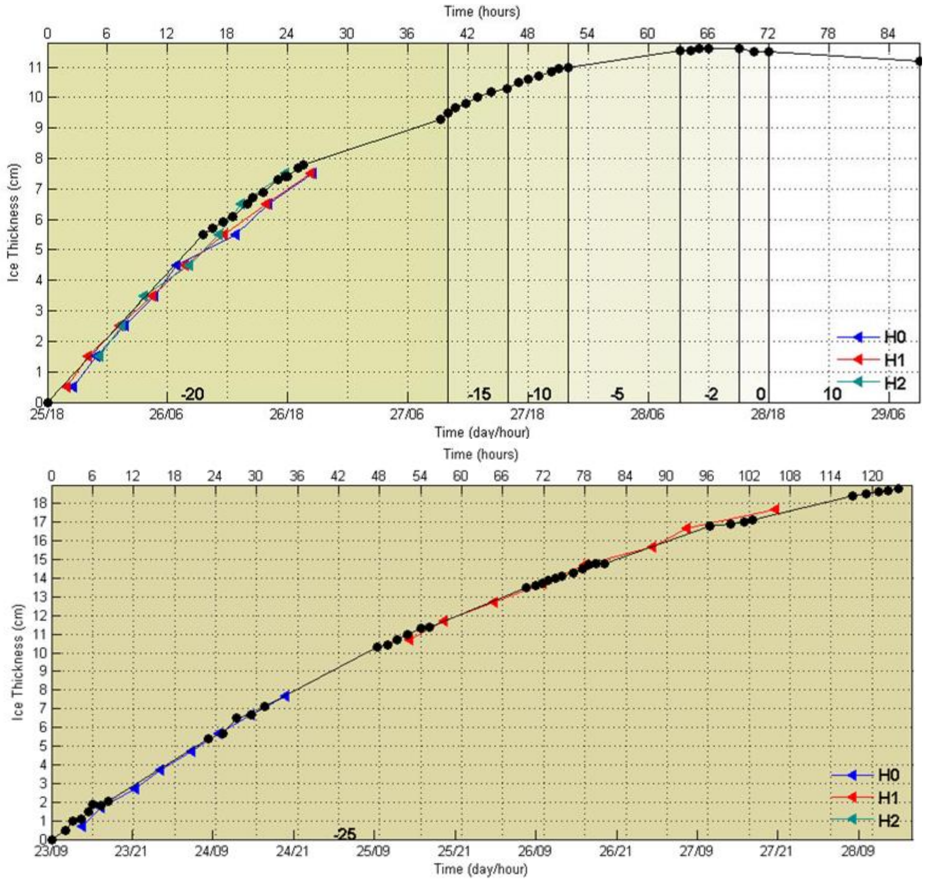

Figure 4: Top panel: The manual measurements of the ice thickness (black circles) are presented as a function of time jointly with the ice thickness obtained from the wire harps (red, blue and green triangles) for experiment I. The surface colour code identifies the changes in air temperature.
Bottom panel: Same as Top panel but for experiment IV.
Note that the vertical and horizontal scales for both panels are different.

- **Full depth convection:**
  The bulk salinity as a function of time and depth for experiment IV is presented in Figure 7. Few hours after the increase in air temperature ($\sim$133h) the salt content decreases in the first 7.5 cm of the sea ice reducing its salinity of around 20%. This preliminary result seems to give some evidence of salt convection from the upper layers of the sea ice. It is necessary to perform more analysis in order to better understand this particular event. He have to quantify, for example, the evolution of the Rayleigh number for this episode.

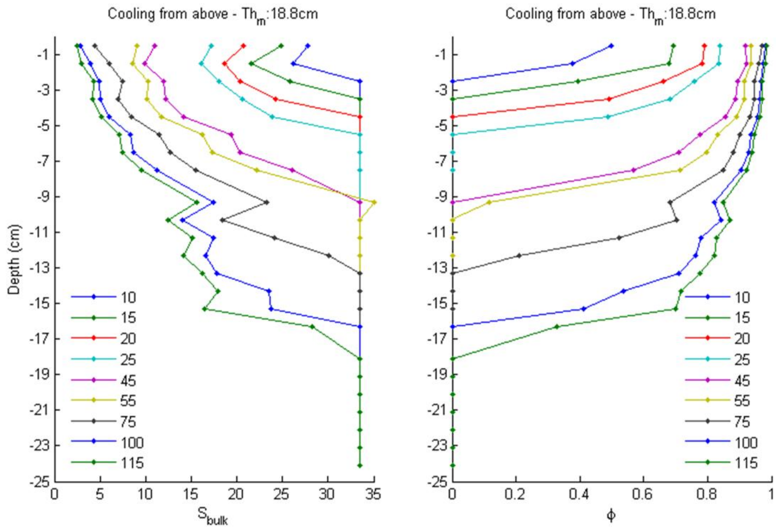

Figure 5: Bulk-salinity (left panel) and Solid-fraction (right panel) profiles at various times (colour code, the time presented in the legend is in hours) for experiment IV where a seawater solution at 33.47 ppt was cooled from above with a temperature of -25^{o}C for 125 hours.

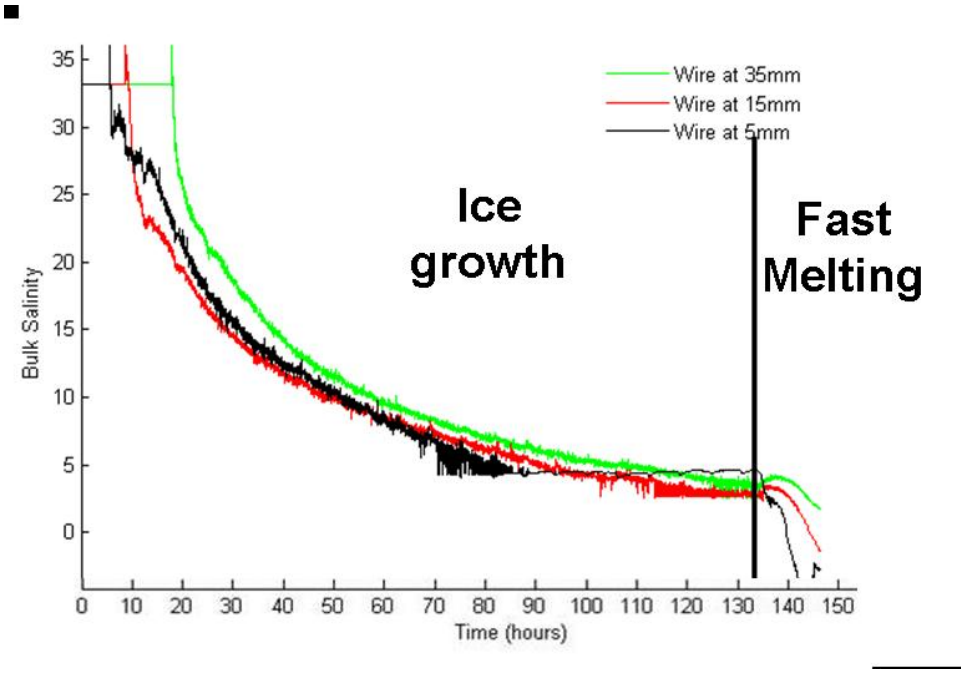

Figure 6: Time evolution of the bulk salinity from three different parallel wires located at 5 mm (black line), 15 mm (red line) and 35 mm (green line) below the sea ice surface. The vertical black line identifies the moment when the air temperature increases from -25^{o}C to 20^{o}C.

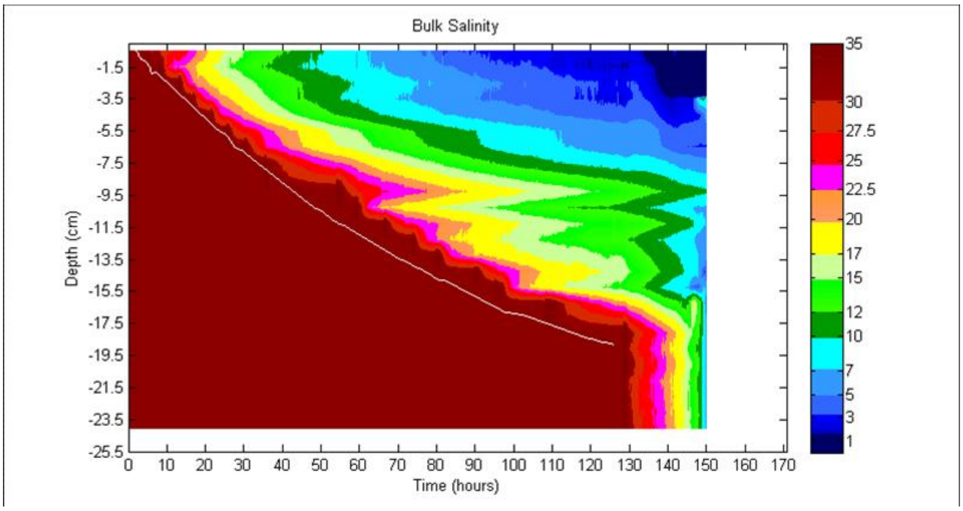

Figure 7: Temporal evolution with depth of bulk salinity for the first 150 hours of experiment IV. The white curve represents the ice thickness from manual measurements and the salinity values below this limit are not valid.

Future collaborations and projected publications

In the beginning, we have started to analyze the variables obtained from the wire harps, nevertheless several other instruments were used during the experiments, like the thermistor chains, the CTDs and the atmospheric variables. I am analyzing in details all these observations jointly with a Master student from the Max Planck Institute for Meteorology (MPI-M) to be able to write an article to be published in a peer-review journal in which a complete study of the sea ice halo-thermodynamic properties during the growth and melt processes will be presented. Simultaneously, I established new collaborations with members of the sea ice group at the MPI-M in Hamburg in order to compare the laboratory observations with sea ice model simulations.

In my humble opinion the project was a complete success even considering some unforeseen. I was able to carried out for the first time several complex laboratory experiments and I was flexible enough to adapt the project according to the daily work. I would like to thank Dr. Dirk Notz who was always willing to help and give his best suggestions and to Micro-DICE without they support nothing would be possible.

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