1 Estimates of ikaite export from sea ice to the underlying seawater in a sea

2 ice-seawater mesocosm

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11 1. Abstract

12 The precipitation of ikaite and its fate within sea ice is still poorly understood. We quantify temporal 13 inorganic carbon dynamics in sea ice from initial formation to its melt in a sea ice-seawater mesocosm 14 pool from 11 to 29 January 2013. Based on measurements of total alkalinity (TA) and total dissolved 15 inorganic carbon (TCO_2) , the main processes affecting inorganic carbon dynamics within sea ice were 16 ikaite precipitation and CO₂ exchange with the atmosphere. In the underlying seawater, the dissolution of 17 ikaite was the main process affecting inorganic carbon dynamics. Sea ice acted as an active layer, 18 releasing CO_2 to the atmosphere during the growth phase, taking up CO_2 as it melted and exporting both 19 ikaite and TCO_2 into the underlying seawater during the whole experiment. Ikaite precipitation of up to 167 µmol kg⁻¹ within sea ice was estimated while its export and dissolution into the underlying seawater 20 was responsible for a TA increase of 64 to 66 µmol kg⁻¹ in the water column. The export of TCO₂ from 21 sea ice to the water column increased the underlying seawater TCO₂ by 43.5 µmol kg⁻¹, suggesting that 22 23 almost all of the TCO_2 that left the sea ice was exported to the underlying seawater. The export of ikaite 24 from the ice to the underlying seawater was associated with brine rejection during sea ice growth, 25 increased vertical connectivity in sea ice due to the upward percolation of seawater, and meltwater 26 flushing during sea ice melt. Based on the change in TA in the water column around the onset of sea ice 27 melt, more than half of the total ikaite precipitated in the ice during sea ice growth was still contained in 28 the ice when the sea ice began to melt. Ikaite crystal dissolution in the water column kept the seawater 29 pCO_2 undersaturated with respect to the atmosphere in spite of increased salinity, TA, and TCO_2 30 associated with sea ice growth. Results indicate that ikaite export from sea ice and its dissolution in the

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underlying seawater can potentially hamper the effect of oceanic acidification on the aragonite saturation state ($\Omega_{aragonite}$) in fall and winter in ice-covered areas, at the time when $\Omega_{aragonite}$ is smallest.

2. Introduction

34 Currently, each year, 7 Pg of anthropogenic carbon are released to the atmosphere, 29% of which is 35 estimated to be taken up by the Oceans through physical, chemical and biological processes (Sabine et al., 2004). The Arctic Ocean are taking up -66 to -199 Tg C year⁻¹, (where a negative value indicates an 36 37 uptake of atmospheric CO_2) contributing 5-14% to the global ocean CO_2 uptake (Bates and Mathis, 38 2009), primarily through primary production and surface cooling (MacGilchrist et al., 2014). However, 39 polar ocean CO_2 uptake estimates consider sea ice as an impermeable barrier, ignoring the potential role 40 of ice-covered areas on gas exchange between the ocean and atmosphere. Recent studies have shown that 41 sea ice covered areas participate in the variable sequestration of atmospheric CO_2 into the mixed layer 42 below the ice (e.g. Papakyriakou and Miller 2011; Geilfus et al., 2012; Nomura et al., 2013; Delille et al., 43 2014; Geilfus et al., 2014; 2015). Studies are required to elucidate the processes responsible as well as 44 their magnitudes both temporally and spatially.

45 The carbonate chemistry in sea ice and brine is spatially and temporally variable, which leads to 46 complex CO₂ dynamics with the potential to affect the air-sea CO₂ flux (Parmentier et al., 2013). Release 47 of CO₂ from sea ice to the atmosphere has been reported during sea ice formation from open water 48 (Geilfus et al., 2013a) and in winter (Miller et al., 2011; Fransson et al., 2013) while uptake of CO₂ by sea 49 ice from the atmosphere has been reported after sea ice melt onset (e.g. Semiletov et al., 2004; Nomura et 50 al., 2010; Geilfus et al., 2012; Nomura et al., 2013; Fransson et al., 2013; Geilfus et al., 2014; 2015). In 51 combination, these works suggest that the temporal cycle of sea ice formation and melt affects 52 atmospheric CO_2 uptake by the ocean in variable ways. Sea ice may also act as an important control on 53 the partial pressure of CO_2 (pCO_2) in the sea surface through a sea ice pump (Rysgaard et al., 2007). 54 During the earliest stages of sea ice formation, a small fraction of CO₂-supersaturated brine is expelled 55 upward onto the ice surface promoting a release of CO_2 to the atmosphere (Geilfus et al., 2013a). As sea 56 ice forms and grows thicker, salts are partly rejected from the sea ice to the underlying seawater and 57 partly trapped within the sea ice structure, concentrated in brine pockets, tubes and channels. As a result, 58 the concentration of dissolved salts, including inorganic carbon, increase within the brine and promote the 59 precipitation of calcium carbonate crystals such as ikaite (CaCO₃•6H₂O) (Marion 2001). These crystals 60 have been reported in both natural (Dieckmann et al., 2008; Nomura et al., 2013, Søgaard et al., 2013)

- and experimental sea ice (Geilfus et al., 2013b; Rysgaard et al., 2014) and have been suggested to be a
 key component of the carbonate system (Rysgaard et al., 2007; Fransson et al., 2013; Delille et al., 2014).
- 63 During ikaite precipitation within sea ice, TA in brine is reduced by 2 moles due to the reduction of 64 bicarbonate (HCO_3^{-}) while TCO_2 in brine is only reduced by 1 mole (equation 1 to 3).

65
$$Ca^{2+} + 2HCO_3^- + 5H_20 \Rightarrow CaCO_3 \cdot 6H_20 + CO_2$$
 (1)

66
$$TCO_2 = [HCO_3^-] + [CO_3^{--}] + [CO_2^{--}]$$
 (2)

67
$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+]$$
(3)

68 The specific conditions leading to ikaite precipitation as well as the fate of these precipitates in sea ice are 69 still not fully understood. Ikaite crystals may remain within the ice structure while the CO_2 formed during 70 their precipitation is likely rejected with dense brine to the underlying seawater and sequestered below the 71 mixed layer. During sea ice melt, the dissolution of these crystals triggered by increased ice temperatures 72 and decreased bulk ice salinity will consume CO_2 and drive a CO_2 uptake from the atmosphere to the ice. 73 Such mechanism could be an effective sea ice pump of atmospheric CO_2 (Delille et al., 2014). In 74 addition, ikaite stored in the ice matrix could become a source of TA to the near-surface ocean upon its 75 subsequent dissolution during sea ice melt (Rysgaard et al., 2007; 2009).

76 The main air-sea fluxes of CO_2 and TCO_2 are driven by brine rejection to the underlying seawater and 77 its contribution to intermediate and deep-water formation (Semiletov et al., 2004; Rysgaard et al., 2007, 78 2009; Fransson et al., 2013) or below sea ice in ice tank studies (e.g. Killawee et al., 1998 and 79 Papadimitriou et al., 2004). As sea ice thickens, reduced near-surface ice temperatures result in reduced 80 brine volume content, increased brine salinity and increased solute concentration in the brine. In the 81 spring-summer, as the ice temperature increases, sea ice brine volume increases and sea ice becomes 82 vertically permeable to liquid (Golden et al., 2007), enhancing the potential CO_2 exchange between the 83 atmosphere, sea ice and ocean. Eventually internal ice melt promotes brine dilution, which decreases 84 brine salinity, TA, TCO_2 , and leads to lower pCO_2 in the brine. In addition, the dissolution of ikaite 85 decreases brine pCO₂ (Eq. 1) (Geilfus et al., 2012; 2015). These conditions all favour sea ice as a sink for 86 atmospheric CO₂ (Nomura et al., 2010; Geilfus et al., 2012; Nomura et al., 2013; Geilfus et al., 2015). 87 Melting sea ice stratifies surface seawater leading to decreased TA, TCO_2 and pCO_2 , in the sea surface, 88 enhancing air-sea CO₂ fluxes (Rysgaard et al., 2007; 2009).

89 Although we now have a basic understanding of the key mechanisms of carbon cycling in sea ice, 90 significant unknowns remain. One of the major unknowns is the fate of ikaite, TCO₂ and CO₂ released 91 from sea ice during winter. It is unclear what proportion of precipitated ikaite crystals in sea ice remain in 92 the matrix to be released upon melt or what proportion are expelled with brine drainage during ice 93 formation and growth. Examining the chemical signatures of the water column beneath sea ice may 94 provide an indication of the importance of the different processes. However, the signal of carbon 95 components released from 1-2 meters of sea ice growth is difficult to detect in a water column several 96 hundred meters deep.

97 In this study, we followed the evolution of the inorganic carbon dynamics within experimental sea ice 98 from sea ice formation to melt in a sea ice-seawater mesocosm pool (\sim 435 m³). The benefits of this type 99 of environment are multiple. An artificial pool equipped with a movable bridge makes it possible to 100 collect undisturbed samples from thin growing sea ice. We gain the ability to carefully track carbonate 101 parameters in the ice, in the atmosphere, and in the underlying seawater, while growing sea ice in a large 102 volume of seawater, so that conditions closely mimic the natural system. During this experiment, we 103 examined physical and chemical processes, in the absence of biology, responsible for changes in the 104 inorganic carbon system of sea ice and the underlying seawater and quantify fluxes of inorganic carbon 105 between the atmosphere, sea ice and the water column. We also discuss that dissolution of ikaite crystals 106 exported from sea ice in the underlying seawater can potentially hamper the effect of oceanic 107 acidification on $\Omega_{aragonite}$.

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3. Site description, sampling and analysis

109 The Sea-ice Environmental Research Facility (SERF) is an in-ground outdoor concrete pool of 18.3 m 110 by 9.1 m in surface area and 2.6 m deep exposed to ambient temperatures, winds and solar radiation (by 111 retracting its roof, Fig. 1). The weather conditions in the region are conducive to sea ice growth for 112 several months every winter. Prior to the experiment, the pool is filled with artificial seawater (ASW) 113 made by dissolving large quantities of various rock salts into local groundwater to mimic the major 114 composition of natural seawater (see Rysgaard et al., (2014) for exact composition of the ASW). Sea ice 115 is melted in the pool by circulating heated ethylene glycol through a closed-loop hose located at the 116 bottom of the pool, allowing successive ice growth/melt experiments to be carried out during one winter. 117 The experimental sea ice and brine exhibit similar physical and chemical properties to those observed in 118 natural Arctic sea ice (Geilfus et al., 2013; Hare et al., 2013). The experiment described herein was initiated from open water conditions on 11 January 2013 when the heater was turned off. Sea ice grew
until 26 January when the heat was turned back on. The experiment ended on 30 January when the pool
was 20% ice-free.

Four 375 W pumps were installed on the bottom of the pool near each of the corners to induce a consistent current. The pumps were configured to draw water from their base and then propel it outward parallel to the bottom of the pool. The pumps were oriented successively at right angles to one another, which created a counterclockwise circulation of 2-3 cm s⁻¹ (Else et al., 2015).

Bulk ice and seawater temperatures were recorded by an automated type-T thermocouple array fixed vertically in the pool. Seawater salinity was measured continuously using Aanderaa CT sensors (model 4319) located at 30, 100, 175 and 245 cm depth. The in situ seawater pCO_2 was measured every 5 sec using a Contros HydroC (resolution < 1 µatm, accuracy ± 1% of the upper range value) located at 1.3 m depth.

Air temperature and relative humidity were measured using a Vaisala HMP45C probe at a meteorological station located 2 m above the sea ice surface. Solar irradiance was continuously recorded by an Eppley Precision Spectral Pyranometer (range=0.285–2.8 μ m) mounted 10 m above the sea ice surface. In addition, estimated photosynthetically active radiation (PAR) values at the ice bottom were recorded with Alec mkv-L PAR sensors throughout the study and ranged from 0 to 892 μ mol photons m⁻² s⁻¹.

137 Sea ice and seawater samples were obtained from a confined area located on the North side of the 138 pool to minimize effects on other experiments (e.g. Else et al., 2015). Ice samples were collected using 139 ceramic knives or a Kovacs Mark II coring system depending on the ice thickness. Sampling was 140 performed from a movable bridge to avoid walking on the ice surface and to ensure only undisturbed sites 141 were sampled. Ice cores were collected from one end of the pool (half meter away from the edge of the 142 pool) and at least 20 cm away from previous cored sites. Ice cores were packed in clean plastic bags and 143 kept frozen during the 20 minutes transport to a cold laboratory and processed within a few hours. 144 Seawater was sampled for total alkalinity (TA) and total dissolved inorganic carbon (TCO_2) with a 145 peristaltic pump (Cole Palmer, Masterflex-Environment sampler, equipped with PTFE tubing) through an 146 ice core hole the ice-water interface, at 1.25 m, and 2.5 m depth. Samples were stored in 12 ml gas-tight

vials (Exetainer, Labco High Wycombe, UK) and poisoned with 12 μl of saturated HgCl₂ solution and
stored in the dark at 4°C until analysed.

149Air-ice CO_2 fluxes were measured using a Li-Cor 8100-103 chamber associated with a LI-8100A soil150 CO_2 flux systems. The chamber was connected in a closed loop to the IRGA with an air pump rate of 3 L151 min^{-1} . The measurement of pCO_2 in the chamber was recorded every sec over a 15 minute period. The152flux was computed from the slope of the linear regression of pCO_2 against time ($r^2>0.99$) according to153Frankignoulle (1988), taking into account the volume of ice or snow enclosed within the chamber. The154uncertainty of the flux computation due to the standard error on the regression slope was on average ±3%.

155 In the cold laboratory, sea ice cores were cut into 2 cm sections using a pre-cleaned stainless steel 156 band saw. Each section was placed in a gas-tight laminated (Nylon, ethylene vinyl alcohol and 157 polyethylene) plastic bag (Hansen et al., 2000) fitted with a gastight Tygon tube and a valve for sampling. 158 The plastic bag was sealed immediately and excess air was gently removed through the valve using a 159 vacuum pump. The bagged sea ice samples were then melted in the dark at 4°C to minimize the 160 dissolution of calcium carbonate precipitates (meltwater temperature never rose significantly above 0°C). 161 Once melted, the meltwater mixture and bubbles were transferred to gas-tight vials (12 ml Exetainer, 162 Labco High Wycombe, UK), poisoned with 12 µl solution of saturated HgCl₂ and stored in the dark at 163 4°C until analysed.

164 Bulk ice and seawater salinities were measured using a Thermo Orion 3-star with an Orion 165 013610MD conductivity cell and values were converted to bulk salinity (Grasshoff et al., 1983). TA was 166 determined by potentiometric titration (Haraldsson et al., 1997) while TCO₂ was measured on a 167 coulometer (Johnson et al., 1987). Routine analysis of Certified Reference Materials provided by A. G. 168 Dickson, Scripps Institution of Oceanography, verified that TA and TCO_2 were analyzed within ± 3 and 169 $\pm 2 \mu$ mol kg⁻¹, respectively. Brine volume was estimated from measurements of bulk salinity, temperature 170 and density according to Cox and Weeks (1983) for temperatures below -2°C and according to 171 Leppäranta and Manninen (1988) for ice temperatures within the range -2 to 0°C.

172Bulk ice samples for biological measurements were collected between 14 and 21 January. Filtered173(0.2 μm) SERF seawater (FSW) was added at a ratio of 3 parts FSW to 1 part ice and the samples were174left to melt in the dark. Chlorophyll *a* was determined on three occasions by filtering two aliquots of the175melted ice sample onto GF/F filters (Whatmann brand) and extracting pigments in 10 ml of 90% acetone

176 for 24 h. Fluorescence was measured before and after the addition of 5% HCl (Turner Designs 177 Fluorometer) and Chl a concentration was calculated following Parsons et al. (1984). Measurements of 178 bacterial production were done four times during the biological sampling period by incubating 6-10 ml 179 subsamples of the ice-FSW solution with ³H-leucine (final concentration of 10 nM) for 3h at 0°C in 180 darkness (Kirchmann, 2001). Half of the samples were spiked with trichloroacetic acid (TCA, final 181 concentration 5%) as controls prior to the incubation, while the remaining active subsamples were fixed 182 with TCA (final concentration 5%) after incubation. Following the incubation, vials were placed in 80°C 183 water for 15 minutes (Garneau et al., 2006) before filtration through 0.2 µm cellulose acetate membranes 184 (Whatmann brand) and rinsing with 5% TCA and 95% ethanol. Filters were dried and dissolved in 185 scintillation vials by adding 1 ml ethyl acetate, and radioactivity was measured on a liquid scintillation 186 counter after an extraction period of 24 h. Bacterial production was calculated using the equations of 187 Kirchman (1993) and a conversion factor of 1.5 kg C mol⁻¹ (Ducklow et al., 2003).

188 **4.** Results

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4.1. Sea ice and seawater physical conditions

190 Sea ice was grown in the pool from open water on 13 January 2013 and reached a maximum thickness 191 of 24 cm on 26 January at which point the heat at the base of the pool was turned on. On 30 January the 192 experiment ended with the pool 20% ice-free. Three main snowfall events occurred during the 193 experiment. The first, from 14 to 15 January, covered the sea ice surface with 1 cm of snow. The second, 194 from 18 to 23 January, deposited 6-9 cm of snow over the entire pool. On the morning of 23 January, the 195 snow was manually cleared off the ice surface to investigate the insulating effect of the snow on the ice 196 temperature and ikaite precipitation (Rysgaard et al., 2014). Finally, from noon on 24 January to 27 197 January, 8 cm of snow covered the entire pool until the end of the experiment on 30 January.

The air temperature at the beginning of the experiment ranged from -2°C to -26°C, which initiated rapid sea ice growth to 15 cm until 18 January (Fig. 2). During this initial sea ice growth, the sea ice was attached to the side of the pool resulting in the development of a hydrostatic pressure head that caused percolation of seawater at the freezing point upwards through the sea ice volume as the sea ice grew downwards. This resulted in repeated events of increased sea ice temperature from the bottom to the surface observed between 15 and 18 January (Fig. 2). Subsequently, the ice was cut using an ice saw around the perimeter, allowing the ice to float and a pressure release valve was installed to prevent such

205 events (Rysgaard et al., 2014). During this period, the ice temperature oscillated between relatively warm 206 $(\sim -3^{\circ}C)$ and cold $(\sim -7^{\circ}C)$ phases. Brine volume content (0.047) was low in the middle part of the ice 207 cover, close to the permeability threshold of 0.05 as suggested by Golden et al., (2007). The bulk ice 208 salinity profiles were typically C-shaped with values ranging from 6 to 23 (Fig. 2). The underlying 209 seawater salinity increased rapidly due to sea ice growth. From 18 to 23 January, the 9 cm snow cover 210 insulated the ice cover from the cold atmosphere (Rysgaard et al., 2014), resulting in a fairly constant ice 211 thickness, nearly no change in ice temperature and salinity, a brine volume content above the 212 permeability threshold and a small increase in the underlying seawater salinity. Once the ice surface was 213 cleared of snow on the morning of 23 January, the ice temperature decreased throughout the entire ice 214 thickness and the ice surface salinity increased. The sea ice volume cooled from the top downwards, and 215 the brine volume content decreased below the permeability threshold on 23 January and rapid sea ice 216 growth rapidly increased the seawater salinity. Shortly after the snow clearing, the last snowfall event 217 covered the ice surface with 8 cm of snow, reducing the effect of the cold atmosphere on the ice cover. 218 On 26 January, the heater was activated to initiate sea ice melt. Sea ice temperatures increased and 219 became isothermal around -2°C while the bulk ice salinity decreased and the brine volume content 220 increased up to 0.13. The sea ice melt decreased the seawater salinity. The pool was well mixed during 221 the whole growth phase with similar salinity and temperature observed at the four depths. However, once 222 the heat was turned on, the pool become stratified with respect to salinity changes, as the salinity at 30 cm 223 depth started to diverge from the deeper depths (Fig. 2).

4.2. Carbonate system

225 TA and TCO_2 in seawater, noted as $TA_{(sw)}$ and $TCO_{2(sw)}$, were sampled at the sea ice-seawater 226 interface, 1.25 and 2.5 m depth. An ANOVA test over the 3 depths revealed that the means are not 227 statistically different (p < 0.01) so we consider the average concentration of the three depths in the 228 following analysis. During sea ice growth, TA_(sw) increased from 2449 to 2644 µmol kg⁻¹ (black line, Fig. 229 3a) while $TCO_{2(sw)}$ increased from 2347 to 2516 µmol kg⁻¹ (black line, Fig. 3b). Once the ice started to 230 melt, $TA_{(sw)}$ decreased to 2607 µmol kg⁻¹ and $TCO_{2(sw)}$ decreased to 2461 µmol kg⁻¹. As the experiment 231 stopped before the ice was completely melted in the tank, both the seawater salinity and TA_(sw) do not 232 reach their initial values at the end of the experiment (Table 1, Fig 2 and 3). To discard the effect of 233 salinity changes, we normalized $TA_{(sw)}$ and $TCO_{2(sw)}$ to a salinity of 33 (noted as $nTA_{(sw)}$ and $nTCO_{2(sw)}$) 234 according to the equations 4 and 5:

235
$$nTA_{(sample) t} = \frac{TA_{(sample) t}}{S_{(sample) t}} \times 33$$
(4)

236
$$nTCO_{2 (sample) t} = \frac{TCO_{2 (sample) t}}{S_{(sample) t}} \times 33$$
(5)

where *t* is the time of the sampling and S the salinity of the sample (seawater or sea ice). During ice growth, $nTA_{(sw)}$ and $nTCO_{2(sw)}$ increased slightly to 2446 and 2328 µmol kg⁻¹, respectively (Fig. 3c). However, once the ice started to melt, $nTA_{(sw)}$ increased to 2546 µmol kg⁻¹ and $nTCO_{2(sw)}$ increased to 240 2404 µmol kg⁻¹.

The in situ pCO_2 of the underlying seawater ($pCO_{2(sw)}$) decreased from 377 to 360 µatm as the seawater temperature in the pool decreased to the freezing point. The $pCO_{2(sw)}$ then oscillated from 360 to 365 µatm during sea ice growth. One day after the heater was turned on, the $pCO_{2(sw)}$ increased to a similar concentration as at the beginning of the experiment before decreasing to 373 µatm by the end of the experiment (Fig. 3d).

Within bulk sea ice, TA_(ice) ranged from 300 to 1907 µmol kg⁻¹ while TCO_{2(ice)} ranged from 237 to 246 247 1685 µmol kg⁻¹. Both TA_(ice) and TCO_{2(ice)} exhibited C-shaped profiles with higher concentrations at the 248 surface and bottom layers of the ice cover (Fig. 4). The concentration of $TA_{(ice)}$ (average = 476 µmol kg⁻¹) and $TCO_{2(ice)}$ (average = 408 µmol kg⁻¹) did not show significant variability during our survey, except at 249 250 the surface of the ice. A first maximum was observed on 17 January with concentration of 1907 μ mol kg⁻¹ 251 for TA and 1685 µmol kg⁻¹ for TCO₂. A second maximum was observed on 23 January with 252 concentration of 1433 µmol kg⁻¹ for TA and 861 µmol kg⁻¹ for TCO₂. These maxima matched the high 253 bulk ice salinity (Fig. 2), so we also normalized $TA_{(ice)}$ and $TCO_{2(ice)}$ (noted as $nTA_{(ice)}$ and $nTCO_{2(ice)}$, Fig. 254 4) to a salinity of 33 (according to the equations 4 and 5) to discard the effect of salinity changes and 255 facilitate comparison with the underlying seawater. During initial sea ice formation (up to 17 January), the concentration of both $nTA_{(ice)}$ (from 1083 to 2741, average = 1939 µmol kg⁻¹) and $nTCO_{2(ice)}$ (from 256 257 853 to 2440, average = 1596 μ mol kg⁻¹) were at their minima in the experimental time series. From 17 to 258 21 January, both $nTA_{(ice)}$ and $nTCO_{2(ice)}$ increased throughout the ice column (average $nTA_{(ice)} = 2375$ 259 μ mol kg⁻¹ and *nT*CO_{2(ice)} = 2117 μ mol kg⁻¹). However, from 21 January until the initial sea ice melt, 260 $nTA_{(ice)}$ and $nTCO_{2(ice)}$ decreased in the top 5 cm of the ice cover (average $nTA_{(ice)} = 2125 \ \mu mol \ kg^{-1}$ and 261 $nTCO_{2(ice)} = 1635 \ \mu mol \ kg^{-1}$).

262 4.3. Air-ice CO_2 fluxes

263 The CO_2 fluxes measured at the variably snow-covered sea ice surface (Fig. 2b), ranged from 0.29 to 4.43 mmol m⁻² d⁻¹ show that growing sea ice released CO₂ to the atmosphere (Fig. 5). However, as soon 264 265 as the ice started to warm up and then melt, the sea ice switched from source to sink for atmospheric CO₂ with downward fluxes from -1.3 to -2.8 mmol $m^{-2} d^{-1}$. These ranges of air-ice CO₂ exchanges are of the 266 267 same order of magnitude as fluxes reported on natural sea ice using the same chamber technique in the Arctic during the initial sea ice growth (from 4.2 to 9.9 mmol $m^{-2} d^{-1}$ in Geilfus et al., 2013) and during 268 the spring-summer transition (from -1.4 to -5.4 mmol m⁻² d⁻¹ in Geilfus et al., 2015). In Antarctica air-ice 269 270 CO_2 fluxes were reported during the spring-summer transition from 1.9 to -5.2 mmol m⁻² d⁻¹ by Delille et al (2014), from 0.3 to -2.9 mmol $m^{-2} d^{-1}$ (Geilfus et al., 2014) and from 0.5 to -4 mmol $m^{-2} d^{-1}$ (Nomura et 271 272 al., 2013).

273 5. Discussion

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5.1. Key processes affecting the carbonate system

275 The dynamics of inorganic carbon in the ocean and sea ice are mainly affected by temperature and 276 salinity changes, precipitation and dissolution of calcium carbonate, and biological activities (Zeebe and 277 Wolf-Gladrow, 2001). During this experiment, neither organic matter nor biota were purposely introduced into the pool; the observed range of bulk ice microbial activity $(5.7 \times 10^{-9} \text{ on } 14 \text{ January to } 7.5 \text{ m})$ 278 x 10^{-7} g C L⁻¹ h⁻¹ on 21 January) and algal Chl a (0.008 on 14 January to 0.002 µg L⁻¹ on 21 January) were 279 280 too low to support any biological activity (Rysgaard et al., 2014). Therefore biological activity is unlikely 281 to have played a role. During the same 2013 time series at SERF, Rysgaard et al. (2014) discussed the 282 precipitation of ikaite within the ice cover in detail, reporting high concentrations of ikaite (> 2000 µmol kg⁻¹) at the surface of the ice in brine skim and frost flowers and ikaite precipitation up to 350 μ mol kg⁻¹ 283 284 within bulk sea ice. Within sea ice, ikaite precipitation is associated with low ice temperatures, high bulk 285 salinity and high TA_(ice) and TCO_{2(ice)} concentrations (Fig. 2 and 3).

The main processes affecting the carbonate system can be described by changes in TA and TCO_2 (Zeebe and Wolf-Gladrow, 2001). An exchange of $CO_{2(gas)}$ affects TCO_2 while TA remains constant and the precipitation-dissolution of calcium carbonate affects both TA and TCO_2 in a ratio of 2:1 (see equation 1 to 3, Fig. 6). To calculate the theoretical changes in TA and TCO_2 during the course of the experiment, we used seawater samples from 11 January prior to sea ice formation (t=0, Table 1) as the origin point (blue circle on Fig. 6). Sea ice data are located between the theoretical calcium carbonate precipitation line and the CO₂ release line (Fig. 6a) while seawater data mainly fall on the calcium 293 carbonate dissolution line (Fig. 6b), suggesting that the carbonate system within sea ice is affected by 294 both the precipitation of ikaite and a release of $CO_{2(gas)}$ while the underlying seawater is mainly affected 295 by the dissolution of calcium carbonate.

296 5.2. Estimation of the precipitation-dissolution of ikaite

During the experiment, Rysgaard et al., (2014) observed ikaite within sea ice using direct microscopic observations. The precipitation-dissolution of ikaite and gas exchange are the only two processes taking place during the experiment. As illustrated in Fig. 6, an exchange of CO₂ does not affect TA while the precipitation-dissolution of ikaite affects TA and *T*CO₂ in a ratio 2:1. Therefore, we use TA to estimate how much ikaite is precipitated or dissolved within the ice cover and the underlying seawater.

302 Assuming no biological effect, ikaite precipitation/dissolution and gas exchange, TA and TCO_2 are 303 considered conservative with salinity. Therefore, we can calculate the expected TA and TCO_2 (noted as 304 $TA_{(ice)}^*$ and $TCO_{2(ice)}^*$ in the ice cover and $TA_{(sw)}^*$, $TCO_{2(sw)}^*$ for the water column) based on the initial 305 seawater conditions ($TA_{(sw)}$, $TCO_{2(sw)}$ and $S_{(sw)}$ at t=0, Table 1) and the sample salinity (bulk sea ice or 306 seawater) measured during the experiment:

307
$$TA^*_{(sample)t} = \frac{TA_{(sw)t=0}}{S_{(sw)t=0}} \times S_{(sample)t}$$
(6)

308
$$TCO_{2\,(sample)\,t}^{*} = \frac{TCO_{2\,(sw)\,t=0}}{S_{(sw)\,t=0}} \times S_{(sample)\,t}$$
(7)

309 where t is the time of the sampling. Within the ice cover, $TA_{(ice)}$, $TCO_{2(ice)}$, and the bulk ice salinity are 310 averaged throughout the ice column at each sampling day (Fig. 7a, b, black line) while for the underlying 311 seawater, we used the averaged $TA_{(sw)}$, $TCO_{2(sw)}$ and salinity for all the measured depths (Fig. 2a, b, black line). The difference between TA_(sample)* and the observed TA is only due to the precipitation or 312 dissolution of ikaite crystals. In case of ikaite precipitation (*i.e.* $TA_{(sample)}^* > TA_{(sample)}$), half of this 313 314 positive difference corresponds to the amount of ikaite precipitated within the ice. This ikaite may either 315 remain or may be exported out of the ice. A negative difference (*i.e.* $TA_{(sample)}^* < TA_{(sample)}$), indicates 316 ikaite dissolution.

317 5.2.1. Sea ice

318 Greater $TA_{(ice)}^*$ and $TCO_{2(ice)}^*$ compared to the averaged observed $TA_{(ice)}$ and $TCO_{2(ice)}$ (Fig. 7a, b) are 319 expected as ikaite is precipitated and CO₂ released from the ice to the atmosphere (Fig. 5, 6). Half the 320 difference between $TA_{(ice)}^*$ and $TA_{(ice)}$ is a result of ikaite precipitation (Fig. 7c, black diamonds). Highly

321 variable ikaite precipitation was observed (Fig. 7c). Ikaite precipitation was up to 167 µmol kg⁻¹ (e.g. first 322 days of the experiment) and as low as 1 µmol kg⁻¹ (e.g. 19 January). A negative difference between 323 TA_(ice)^{*} and TA_(ice) (*i.e.* ikaite dissolution) occurred on three occasions: 14, 20 and after the 26 January 324 (beginning of the sea ice melt). On these occasions, the ice cover was relatively warm due to warmer 325 atmospheric temperatures (14 January), thicker snow cover insulating the ice cover from the cold 326 atmosphere (20 January) or when heat was turned back on (after 26 January, Fig. 2). Relatively high sea 327 ice temperatures likely promote ikaite dissolution in agreement with Rysgaard et al., (2014) who linked 328 ikaite precipitation/dissolution to ice temperature. The upward percolation of seawater observed from 15 329 to 18 January might complicate the effect of sea ice temperature on ikaite formation because it was in part 330 responsible for increased ice temperatures (Fig. 2b) and therefore increased the sea ice brine volumes 331 (Fig. 2c). Increased vertical connectivity (permeability) of the network of liquid inclusions throughout the 332 sea ice (Golden et al., 2007; Galley et al., 2015) would have allowed the export of ikaite crystals from the 333 ice cover to the underlying seawater. However, while we calculated a negative difference between TA_(ice)* 334 and TA(ice), ikaite crystals were observed by Rysgaard et al., (2014). We compared the direct microscopy 335 observations by averaging the amount of ikaite precipitated throughout the ice thickness for each 336 sampling day from Rysgaard et al., (2014) (Fig. 7c, white dots) with our estimation of the amount of 337 ikaite based on the difference between $TA_{(ice)}^{*}$ and $TA_{(ice)}$ (Fig. 7c, black diamonds). Both ikaite 338 measurements are of the same order of magnitude however the average (22 µmol kg⁻¹) and maximum 339 (100 µmol kg⁻¹) of direct observations presented by Rysgaard et al. (2014) were lower than our estimated 340 average (40 µmol kg⁻¹) and maximum of up to 167 µmol kg⁻¹ over this whole experiment. Deviations are 341 likely due to methodological differences. Here, sea ice samples were melted to subsample for TA and 342 TCO₂, Ikaite crystals may have dissolved during melting, leading to an underestimation of the total 343 amount of ikaite precipitated in the ice. However, the difference between TA_(ice)^{*} and TA_(ice) provides an 344 estimation of how much ikaite is precipitated in the ice cover, including those crystals potentially already 345 exported to the underlying seawater. The method used by Rysgaard et al., (2014) avoid the bias of ikaite 346 dissolution during sea ice melt with the caveat that crystals need to be large enough to be optically 347 detected. If no crystals were observed, Rysgaard et al., (2014) assumed that no crystals were precipitated 348 in the ice, though ikaite crystals could have been formed and then exported into the underlying seawater 349 prior to microscopic observation of the sample, which may explain the difference observed between both 350 methods during initial sea ice formation (15-18 January) when the ice was still very thin. In addition, the

351 succession of upward percolation events could have facilitated the ikaite export from the ice cover to the 352 underlying seawater. Estimations from both methods show similar concentrations when the ice (i) 353 warmed due to snowfall (18-23 January) and (ii) cooled once the snow was removed (on 23 January). 354 Once the ice started to melt (26 January), Rysgaard et al., (2014) reported a decrease in the ikaite 355 precipitation while in this study we reported a negative difference between $TA_{(ice)}^*$ and $TA_{(ice)}$, possibly 356 indicating that ikaite dissolved in the ice.

357 5.2.2. Water column

358 The main process affecting the carbonate system in the underlying seawater in this study is the export 359 of ikaite from the ice and its dissolution in the water column (Fig. 6). While a few studies of ikaite 360 precipitation within sea ice carried out over open ocean hypothesized that ikaite remained trapped within 361 the sea ice matrix (Rysgaard et al., 2007; 2013; Delille et al., 2014), the observed increase of *n*TA_(sw) (Fig. 362 3) suggests that ikaite precipitated within the ice cover was exported to the underlying seawater where the 363 crystals were dissolved as suggested by Fransson et al., (2013). Lower $TA_{(sw)}^*$ and $TCO_{2(sw)}^*$ compared to 364 $TA_{(sw)}$ and $TCO_{2(sw)}$ (Fig. 3) confirm the dissolution of ikaite in the underlying seawater as the dissolution 365 of ikaite crystals will decrease both TA and TCO_2 (equations 1 to 3). Therefore, half the difference 366 between TA_(sw)^{*} and TA_(sw) corresponds to the concentration of ikaite exported from the ice and dissolved 367 in the underlying seawater (Fig. 8a). This concentration increased over time to a maximum of 66 µmol 368 kg⁻¹.

During this experiment, nTA_(sw) increased by 128 µmol kg⁻¹ while nTCO_{2(sw)} increased by 82 µmol kg⁻¹ 369 370 (Fig. 3c). This suggests that 64 μ mol kg⁻¹ of ikaite are dissolved compared to the 66 μ mol kg⁻¹ estimated 371 from the difference between $TA_{(sw)}^{*}$ and $TA_{(sw)}$. As a result of the effect of ikaite dissolution on the 2:1 372 ratio of TA: TCO_2 , the dissolution of ikaite accounts for the entire increase of $nTA_{(sw)}$ but only accounts for 64-66 μ mol kg⁻¹ of the 82 μ mol kg⁻¹ increase in $nTCO_{2(sw)}$. So, 16-18 μ mol kg⁻¹ (about 25%) of the 373 374 increase of $nTCO_{2(sw)}$ cannot be explained by the dissolution of ikaite. The increase of both $nTA_{(sw)}$ and 375 $nTCO_{2(sw)}$ is more significant once the ice starts to melt (26 January). During sea ice melt, increased 376 vertical permeability resulting in increased liquid communication through the sea ice volume from below 377 likely in part dissolved ikaite crystals still residing in the ice at that time, and also will have created a 378 downward crystal export mechanism. As the ice melt advanced, patches of open water occurred at the 379 surface of the pool. Therefore, uptake of atmospheric CO₂ by the undersaturated seawater likely occurred, 380 increasing the $TCO_{2(sw)}$.

381 The dissolution of ikaite crystals could also have a strong impact on the $pCO_{2(sw)}$. The water column 382 was undersaturated compared to the atmosphere during the whole experiment (Fig. 3d). A release of CO₂, 383 from the ice to the atmosphere was measured during sea ice growth (Fig. 5) in spite of the undersaturated 384 $pCO_{2(sw)}$. This suggests that air-ice CO₂ fluxes are only due to the concentration gradient between the ice 385 and the atmosphere (Geilfus et al., 2012; Nomura et al., 2013) but that sea ice exchanges CO₂ with the 386 atmosphere independently of the seawater concentration (Geilfus et al., 2014). The $pCO_{2(sw)}$ is highly 387 correlated with the seawater temperature (Fig. 2) with a rapid decrease of $pCO_{2(sw)}$ during the first days of 388 the experiment (13 to 15 January) and a relative constant $pCO_{2(sw)}$ until 27 January. However, on 26 389 January, the heat was turned back on affecting the seawater temperature on the same day (Fig. 2) while 390 the impact of increasing temperature on the $pCO_{2(sw)}$ appeared one day later (Fig. 3d). We normalized the 391 pCO_{2(sw)} to a temperature of -1°C (after Copin-Montegut (1988), noted as npCO_{2(sw)}, blue line on Fig. 3d). 392 The npCO_{2(sw)}, does not show major variations during sea ice growth with values around 380 µatm. 393 However, once the heat is turned on and the seawater temperature increased (on 26 January), npCO_{2(sw)} 394 decreased from 383 μ atm to 365 μ atm, while pCO_{2(sw)} did not change in response to increased seawater 395 temperatures until 27 January, suggesting that a process other than temperature change affected the 396 $pCO_{2(sw)}$. According to equation 1, the dissolution of calcium carbonate has the potential to reduce 397 pCO_{2(sw)}. Therefore, during sea ice growth and the associated release of salt, TA, TCO₂ and ikaite crystals 398 to the underlying seawater, ikaite dissolution within the seawater could be responsible for maintaining 399 stable $pCO_{2(sw)}$ values while seawater salinity, $TA_{(sw)}$ and $TCO_{2(sw)}$ are increasing. Once the seawater 400 temperature increased (26 January), sea ice melt likely released ikaite crystals to the underlying seawater 401 (Fig. 2, 8a) along with brine and meltwater, a process that would continuously export ikaite from the sea 402 ice as the volume interacting with the seawater via percolation or convection increased. The dissolution of 403 these crystals likely contributed to keeping the $pCO_{2(sw)}$ low and counterbalancing the effect of increased 404 temperature. We argued that once all the ikaite crystals are dissolved, the increase seawater temperature 405 increased the $pCO_{2(sw)}$ simultaneously with the $npCO_{2(sw)}$ (27 January, Fig. 3).

406

5.3. Ikaite export from the ice cover to the water column

We estimated the amount of ikaite precipitated and dissolved within sea ice and seawater based on the sea ice (and seawater) volume (in m³), the sea ice and seawater density, the concentration of ikaite precipitated and dissolved within the ice cover (Fig. 7c), and the concentration of ikaite dissolved in the water column (Fig. 8a). Within the ice cover, the amount of ikaite precipitated-dissolved ranged from -0.7 411 to 1.97 mol (Fig 8b, Table 2), with a maximum just after the snow was cleared on 23 January. In the 412 underlying seawater, the amount of ikaite dissolved in the pool increased from 0.47 mol on the first day 413 of the experiment to 11.5 mol on 25 January when sea ice growth ceased. Once the ice started to melt the 414 amount of dissolved ikaite increased up to 20.9 (28 Jan) and 26.7 mol (29 January, Table 2). The 415 estimation of ikaite dissolution in the pool is significantly higher than the estimated amount of ikaite 416 precipitated (and potentially exported) within the ice cover, especially during sea ice melt. Within the ice 417 cover, the ikaite values presented here represent a snapshot of the ikaite content in the ice at the time of 418 sampling. In the underlying seawater, ikaite dissolution increased TA_(sw) cumulatively over time.

419 The difference between $TA_{(ice)}^{*}$ and $TA_{(ice)}$ provides an estimation of ikaite precipitated within the ice, 420 including potential ikaite export to the underlying seawater, so it cannot be used to determine how much 421 ikaite remained in the ice versus how much dissolved in the water column. However, Rysgaard et al., 422 (2014) indicate ikaite precipitated within the ice based on direct observations. Using the ikaite 423 concentration reported in Rysgaard et al (2014) (and shown in Fig. 7c), the sea ice volume (in m³) and 424 density, we calculate that 0 to 3.05 mol of ikaite precipitated within the ice cover during sea ice growth 425 (Fig. 8b and Table 2). This amount decreased to 0.46 and 0.55 mol during the sea ice melt (28 and 29 426 January, respectively). Increased ikaite dissolution in the water column when the ice began to melt (from 427 11.5 to 20.9 mol) indicates that 9.4 mol of ikaite were stored in the ice and rejected upon the sea ice melt. 428 This amount is about three times the amount of ikaite precipitated in the ice estimated by Rysgaard et al., 429 (2014) at the end of the growth phase (3.05 mol, Table 2), suggesting more work is needed best estimate 430 ikaite precipitation within sea ice.

Once the ice started to melt, the increased ikaite dissolution from 11.5 mol to 20.9 mol (28 January) and to 26.7 mol (29 January) suggests that about the same amount of ikaite is dissolved during the sea ice growth as during the first two days of the sea ice melt. The amount of ikaite dissolved in the water column after melt commenced continued to increase cumulatively, suggesting that ikaite is continuously exported to the underlying seawater as increased sea ice temperatures permit more of the volume to communicate with the underlying seawater. Therefore, we can assume that more than half of the amount of ikaite precipitated within the ice remained in the ice cover before ice melt began.

438 5.4. Air-ice-seawater exchange of inorganic carbon

SERF is a semi-closed system where the only way for the surface (water or sea ice) to gain or lose CO₂ is through exchange with the atmosphere, making it reasonable to track the exchange of TCO_2 in the atmosphere-sea ice-seawater system. The ice cover always had lower $TCO_{2(ice)}$ during the experiment $(TCO_{2(ice)}^* > TCO_{2(ice)})$ compared to what would be expected if the CO₂ simply followed brine rejection in a conservative process (i.e. $TCO_{2(ice)}^*$) (Fig. 7b). This could be due to: (i) CO₂ released to the atmosphere from sea ice, (ii) decreased $TCO_{2(ice)}$ due to the precipitation of ikaite within sea ice and/or (iii) sea ice exchanging TCO_2 with the underlying seawater.

446 The number of moles of TCO_2 exchanged during this experiment was calculated using the sea ice (and seawater) volume (in m³) and density (in kg/m³). The total amount of TCO_{2(ice)} lost from the ice cover (the 447 448 difference between TCO_{2(ice)}^{*} and TCO_{2(ice)}) ranged from 0.11 to 6.02 mol (average 2.38 mol, Fig. 9, black 449 dots). The greatest sea ice TCO_2 losses occurred on 15-16 January during initial sea ice growth and from 450 23 to 25 January, during ice cooling due to snow removal. The exchange of CO_2 between the ice and the 451 atmosphere is known (Fig. 5). The number of mole of CO_2 exchanges between the ice and the atmosphere 452 were calculated (noted as $CO_{2(air-ice)}$ in Table 2) using the time step between each flux measurement, the 453 ice thickness and density. During sea ice growth 0.01 to 0.42 mol of CO_2 were released from the ice-454 covered pool to the atmosphere. During sea ice melt uptake of atmospheric CO_2 by the ice-covered pool 455 ranged from -0.15 to -0.93 (Fig. 9, white triangles). On average, over the duration of the experiment, the 456 ice cover released 0.08 mol of CO₂ to the atmosphere. Assuming we know how much ikaite is contained 457 within the ice cover (Fig. 8b), we can estimate how much TCO_2 is exported from the ice to the underlying 458 seawater (Fig. 9, blue triangles) by subtracting the air-ice CO₂ exchange and the ikaite precipitation from 459 the total reduction of $TCO_{2(icc)}$ observed within the ice cover (Fig. 9, black dots). The sea ice-to-seawater 460 TCO_2 export ranged from 0.2 to 3.98 mol (average = 1.7 mol), confirming that sea ice primarily exports 461 TCO_2 to the underlying seawater. TCO_2 export from the ice to the water column ranged from 23% of the 462 total sea ice TCO_2 early in the ice growth (14 January) to 100% after the onset of melt. These estimations 463 are comparable to the study of Sejr et al., (2011) who suggested that sea ice exports 99% of its total TCO_2 464 to the seawater below it. On average over the whole experiment, sea ice exported 1.7 mol of TCO_2 to the 465 underlying seawater (Fig. 9), which corresponds to a TCO_{2(sw)} increase of 43.5 µmol kg⁻¹ considering the 466 average sea ice thickness and density during the experiment and the volume of the pool. However, 467 $TCO_{2(sw)}$ increased by 115 µmol kg⁻¹ over the whole experiment (Fig. 3b), leaving an increase of 71.5 468 μ mol kg⁻¹ in the TCO_{2(sw)} that cannot be explained by the sea ice-seawater exchange of TCO₂. We

469 postulate that as the ice melt advanced, patches of open water that opened at the surface of the pool which 470 were undersaturated compared to the atmosphere (Fig. 3d) imported the additional TCO_2 directly from the 471 atmosphere in the form of $CO_{2(g)}$. Considering the pool volume, the 71.5 µmol kg⁻¹ increase of $TCO_{2(sw)}$ 472 could be explained by an air-sea water CO_2 uptake of 8.5 mmol m⁻² d⁻¹ over 3 days of sea ice melt in a 473 20% ice free pool. High air-sea gas exchanges rates have been observed over partially ice-covered seas 474 (Else et al., 2011; 2013). This mechanism is also corroborated by models that account for additional 475 sources of turbulence generated by the presence of sea ice (Loose et al., 2014).

476 The design of the experiment allowed for constrained measurements of inorganic carbon fluxes 477 between sea ice and the water column not possible in a natural environment where large volume, mixing 478 processes alter the underlying seawater making it more complicated to identify changes. We build a CO₂ 479 budget based only on the sea ice growth phase because only two days of data for the melt phase are 480 available and the experiment stopped while the pool was 20% ice-free (Rysgaard et al., 2014; Else et al., 481 2015). The initial seawater (origin point, t=0) contained 1040.9 mol of $TCO_{2(sw)}$ on 11 January while on 482 the last day of sea ice growth (25 January) the seawater contained 1017.3 mol of $TCO_{2(sw)}$ (Table 2) with 483 the difference, $(23.6 \text{ mol of } TCO_2)$ in all likelihood transferred from the water column to the ice cover or 484 the atmosphere. However, the TCO_2 content within the ice cover at the end of the growing phase was 15.6 485 mol and the ice cover released 3.1 mol of CO_2 to the atmosphere (Table 2). Therefore, 4.9 mol of the 23.6 486 mol of TCO_2 exchanged from the water column are unaccounted for, but may be explained by air-ice CO_2 487 fluxes. The chamber measurement technique for air-ice CO₂ flux may underestimate the exchange of 488 CO₂, and the air-seawater CO₂ fluxes are unknown until the ice started to grow (13 January). These 489 missing moles of TCO_2 may also be explained by our assumption of uniform sea ice thickness in the 490 SERF. Using the seawater conditions at the end of the experiment, 1-cm of seawater in the pool contains 491 4.21 mol of TCO₂, making it difficult to close our budget.

492 5.5. Potential impact of sea ice growth and ikaite export on aragonite saturation state of the 493 underlying seawater.

The Arctic Ocean is a region where calcifying organisms are particularly vulnerable to ocean acidification since low temperatures and low salinity lower the carbonate saturation state. As a result several areas of the Arctic Ocean are already undersaturated with respect to aragonite (Chierici and Fransson 2009; Yamamoto-Kawai et al., 2009; Bates et al., 2011). This undersaturation is enhanced in winter as the temperature decreases and pCO_2 increases as a result of respiration. Calcifying organisms might therefore be most susceptible to the effects of acidification in the winter, corresponding to the annual minimum in aragonite saturation state ($\Omega_{aragonite}$). Sea ice retreat is thought to enhance the impact of ocean acidification by freshening and ventilating the surface water (Yamamoto-Kawai et al., 2008; Yamamoto et al., 2012; Popova et al., 2014). However, any understanding of the effect of ikaite precipitation in sea ice on ocean acidification is still in its infancy (e.g. Fransson et al., 2013).

504 Since the discovery of ikaite precipitation in sea ice (Dieckmann et al., 2008), research on its impact on 505 the carbonate system of the underlying seawater has been ongoing. Depending on the timing and location 506 of this precipitation within sea ice, the impact for the atmosphere and the water column in terms of CO_2 507 transport can be significantly different (Delille et al., 2014). Dissolution of ikaite within melting sea ice in 508 the spring and export of this related high TA:TCO₂ ratio meltwater from the ice to the water column will 509 decrease the pCO_2 , increase pH and $\Omega_{aragonite}$ of the surface layer seawater. Accordingly, during sea ice 510 melt, an increase of $\Omega_{\text{aragonite}}$ in the surface water in the Arctic was observed (Chierici et al., 2011, 511 Fransson et al., 2013, Bates et al., 2014). However, it was difficult to ascribe this increase to the legacy of 512 excess TA in sea ice, ikaite dissolution or primary production.

513 The impact of ikaite precipitation on the surface seawater during sea ice growth is less clear. Fransson 514 et al., (2013) suggested in winter in the Amundsen Gulf that the release of brine decreased $\Omega_{aragonite}$ by 0.8 515 at the sea ice-seawater interface as a result of ikaite precipitation within sea ice and the related CO_2 516 enrichment of brine. Conversely, during ice melt, $\Omega_{aragonite}$ increased by 1.4 between March and May, 517 likely due to both calcium carbonate dissolution and primary production. This contrasts with the present 518 experiment. Figure 10 shows the evolution of $\Omega_{aragonite}$ and pH in the water column derived from TA_(sw) 519 and $TCO_{2(sw)}$ and the evolution of $\Omega_{aragonite}$ and pH predicted solely from salinity changes (i.e. using 520 $TA_{(sw)}^*$ and $TCO_{2(sw)}^*$, noted as $\Omega_{aragonite}^*$ and pH^{*}). We used the CO2sys_v2.1.xls spreadsheet (Pierrot et 521 al., 2006) with the dissociation constants from Goyet and Dickson (1989) and all other constants from 522 DOE (1994). This shows the complexity of ikaite and its impact on the carbonate system and Ω in the 523 underlying water.

524 During ice growth, sea ice brine rejection appears to increase both pH (from 8.00 to 8.06) and $\Omega_{aragonite}$ 525 (from 1.28 to 1.65) of the underlying seawater, offsetting the effect of decreased temperature. A slight 526 increase of $\Omega_{aragonite}$ was predicted due to increased salinity and a proportional increase of TA and TCO_2 527 as depicted in $\Omega_{aragonite}^*$. However, the effect of ikaite rejection and subsequent changes in TA strongly 528 enhance the increase of $\Omega_{aragonite}$. Therefore, ikaite rejection from sea ice has a much stronger potential to

529 increase $\Omega_{\text{aragonite}}$ than brine rejection during fall and winter sea ice growth, suggesting ikaite exported to 530 seawater from sea ice may hamper the effect of oceanic acidification on $\Omega_{aragonite}$ in fall and winter in at 531 the time when $\Omega_{aragonite}$ is at its minimum (Chierici and Fransson 2009, Yamamoto-Kawai et al., 2009, 532 Chierici et al., 2011). Ice formation may therefore delay harmful effects of ocean acidification on 533 calcifying organisms by increasing $\Omega_{aragonite}$ in the critical winter period when $\Omega_{aragonite}$ reaches its minimal 534 values. As a corollary, ice removal acts to alleviate the effect of ikaite rejection and may therefore lowers 535 $\Omega_{aragonite}$. This calls for an accounting of under-ice ikaite rejection in modeling predictions on the 536 consequences of Arctic Ocean acidification in the context of northern hemispheric annual multi-year sea 537 ice loss, as increased summer open water will lead to more first year sea ice formation in fall and winter 538 in the future.

539 6. Conclusion

We quantified the evolution of inorganic carbon dynamics from initial sea ice formation to its melt in a sea ice-seawater mesocosm pool from 11 to 29 January 2013. Based on our analysis of TA and TCO_2 in sea ice and seawater, the main processes affecting inorganic carbon within sea ice are ikaite precipitation and CO_2 exchange with the atmosphere, while in the underlying seawater dissolution of ikaite was the main process affecting the inorganic carbon system.

545 During this experiment, sea ice exchanged inorganic carbon components (e.g. CO₂, ikaite, TCO₂) with 546 both the atmosphere and the underlying seawater. During sea ice growth, CO₂ was released to the atmosphere while during ice melt an uptake of atmospheric CO2 was observed. We report ikaite 547 548 precipitation up to 167 µmol kg⁻¹ of sea ice, similar to previous estimates from Rysgaard et al., (2014) 549 based on microscopically observed values. In the underlying seawater, a net increase of $nTA_{(sw)}$ over the whole experiment was observed (up to 128 µmol kg⁻¹), suggesting that a portion of the ikaite crystals 550 551 precipitated within sea ice were exported to the underlying seawater and then dissolved as the ice cover 552 evolved in time. Ikaite export from ice to the underlying seawater was associated with brine rejection 553 during sea ice growth, increased sea ice vertical connectivity due to the upward percolation of seawater, 554 and meltwater flushing during sea ice melt. Rysgaard et al., (2007) suggested that ikaite precipitation 555 within sea ice could act as a significant sink for atmospheric CO₂, however to act as a sink for 556 atmospheric CO2, ikaite crystals must remain in the ice structure while the CO2 produced by their 557 precipitation is expelled with dense brine rejection and entrained in deep seawater (Delille et al., 2014). 558 TA changes observed in the water column once the sea ice started to melt indicate that more than half of the total amount of ikaite precipitated in the ice during the sea ice growth remained in the ice until the sea ice began to melt. Derivation of air-sea CO_2 fluxes related to the sea ice carbon pump should take into account ikaite export to the underlying ocean during sea ice growth, which might reduce the efficiency of oceanic CO_2 uptake upon sea ice melt. As sea ice melts, ikaite is flushed downward out of the ice along with the meltwater.

Ikaite export from sea ice and its dissolution had a strong impact on the underlying seawater. In this semi-closed system, sea ice growth increased the seawater salinity, $TA_{(sw)}$, and $TCO_{2(sw)}$. In spite of those increases, the pCO_2 of the underlying seawater remained undersaturated compared to the atmosphere. We conclude that ikaite dissolution within the water column is responsible for the seawaters' continual pCO_2 undersaturation. In addition, we discuss that dissolution of ikaite crystals exported from sea ice in the underlying seawater can potentially hamper the effect of oceanic acidification on $\Omega_{aragonite}$ in fall and winter in ice-covered areas at the time when $\Omega_{aragonite}$ is smallest.

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723 9. Table

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Table 1: Seawater conditions on 11 January, before any sea ice formation (t=0), on 25 January, just before the heat was turned back on and on 29 January, at the end of the experiment. Note that seawater salinity and TA_(sw) do not reach the initial seawater values as sea ice was still present at the end of the experiment.

Date	Temperature (°C)	Salinity	TA (μmol kg ⁻¹)	nTA (μmol kg ⁻¹)	TCO_2 (µmol kg ⁻¹)	$nTCO_2$ (µmol kg ⁻¹)
11 Jan.	-1.4	33.5	2453	2416	2341	2306
25 Jan.	-1.9	35.5	2659	2471	2524	2346
29 Jan.	-0.6	34.4	2607	2500	2461	2361

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730	Table 2: Masses of TCO_2 in the water column ($TCO_{2(sw)}$) and in the ice cover ($TCO_{2(ice)}$), masses of
731	ikaite within the ice cover estimated from this study and from Rysgaard et al., (2014), masses
732	of ikaite dissolved in the water column (Ikaite $_{(sw)}$) and masses of CO ₂ exchanged between the
733	ice and the atmosphere over the whole pool (estimation based on the air-ice CO ₂ fluxes). All
734	units are in mole.

January (DOY)	TCO _{2(sw)}	TCO _{2(ice)}	Ikaite _(ice) from this study	Ikaite _(ice) from Rysgaard et al. (2014)	Ikaite _(sw)	CO _{2(air-ice)}
t=0	1041					
13.75	1040	2.38	0.17	0.00	0.47	
13.88	1044	2.09	0.00	0.00	0.87	
14	1043	2.90	0.25	0.00	0.83	0.03
14.13	1043	3.29	0.62	0.00	2.57	0.02
14.25	1038	4.91	-0.05	0.00	1.06	0.01
14.5	1037	4.77	0.18	0.00	3.75	0.12
14.75	1039	4.36	0.12	0.05	2.73	0.07
15	1037				1.80	0.08
15.25	1032	4.67	0.98	0.68	1.28	0.01
15.5	1034	3.89	1.58	0.00	-1.57	0.07
15.92	1034	4.47	0.69	0.00	1.63	0.12
16.38	1024	7.36	1.45	0.08	3.60	0.19
16.67	1028	8.17	1.87	0.00	6.00	0.10
17.38	1023	15.48	0.29	0.65	3.90	0.22
17.67	1026	13.26	0.04	0.46	4.50	0.13
18.38	1030	11.39	0.74	2.14	5.61	0.38
18.67	1027	12.06	0.21	0.21	7.16	0.10
19.38	1029	11.13	0.01	0.84	6.96	0.23
19.67	1030	10.75	0.03	0.09	1.97	0.11
20.38	1028	10.25	-0.12	0.23	1.47	0.42
20.67	1022	10.36	-0.70	0.71	3.48	0.12
21.38	1025	10.50	0.88	0.35	7.42	0.35
23.63	1034	12.60	1.34	2.14	11.18	
24.38	1026	14.84	1.30	1.94	9.75	0.21
25.38	1017	15.67	1.09	3.05	6.62	
25.5	1029				11.51	0.02
28.67	1022	13.46	-0.57	0.46	20.91	-0.93
29.38	987.3	15.82	-0.56	0.55	26.72	-0.15

10. Figure Captions



Figure 1: The Sea Ice Environmental Research Facility with thin sea ice covering the pond during the

2013 experiment. Photo: J. Sievers.

Figure 2: Evolution of (a) Air temperature (°C) at 2 m height, (b) snow thickness (black shaded areas) and sea ice/seawater temperature (°C), (c) bulk ice salinity, (d) brine volume content within sea ice, (e) seawater temperature (blue) and salinity (green). Measurements were performed at 30, 100, 175 and 245 cm water depths. The darker the color is, the closer to the surface. In panels (b), (c), (d) sea ice thickness is illustrated by black dots. Stars on panel (b) represent the depth at which the temperature profiles are derived from. Open squares in the lower part of (d) mark the sampling times. The dashed line on panel (e) indicates when the heat at the bottom of the pool was turned back on.



Figure 3: Evolution of (**a**) $TA_{(sw)}$ and $TA_{(sw)}^{*}(\mu mol kg^{-1})$, (**b**) $TCO_{2(sw)}$ and $TCO_{2(sw)}^{*}(\mu mol kg^{-1})$, (**c**) $nTA_{(sw)}$ (black) and $nTCO_{2(sw)}$ (green) (μ mol kg^{-1}) and (**d**) the seawater pCO_2 (μ atm) measured in situ (black) and corrected to a constant temperature of -1°C (blue). In panels (**a**) and (**b**) the black line is the average over the three depths while the dotted red line is the expected concentrations according to the variation of salinity observed and calculated from the mean values of the three depths ($TA_{(sw)}^{*}$ and $TCO_{2(sw)}^{*}$, respectively). The vertical black dotted line on 26 January mark when the heat was turned back ON.



Figure 4: Evolution of (a) TA_(ice) (μmol kg⁻¹), (b) TCO_{2(ice)} (μmol kg⁻¹), (c) nTA_(ice) (μmol kg⁻¹) and (d) nTCO_{2(sw)} (μmol kg⁻¹). Sea ice thickness is illustrated by black dots. Open squares in the lower part of (d) mark the sampling times.



Figure 5: Air-ice CO₂ fluxes (mmol m⁻² d⁻¹). Positive air-ice CO₂ flux means outgassing from the ice and negative CO₂ flux means uptake of atmospheric CO₂. The vertical black dotted line on 26 January mark when the heat was turned back ON.



Figure 6: (a) Relationship between $nTCO_2$ and nTA (µmol kg⁻¹) in bulk sea ice (white hexagons) and seawater (black dots), (b) Zoom on seawater data. The different dotted lines represent the theoretical evolution of nTA and $nTCO_2$ ratio following the precipitation/dissolution of calcium carbonate and release/uptake of $CO_{2(g)}$. A linear regression is shown in green for the ice samples (a) and blue for seawater samples (b).



Figure 7: Evolution of (a) TA_(ice) averaged throughout the ice thickness at each sampling day (black dots) and TA_(ice)* (dashed red line) (µmol kg⁻¹) and (b) *T*CO_{2(ice)} averaged throughout the ice thickness at each sampling day (black diamonds) and *T*CO_{2(ice)}* (dashed red line) (µmol kg⁻¹),
(c) Estimation of the ikaite precipitation/dissolution from half of the difference between TA_(ice)* and TA_(ice) (µmol kg⁻¹) (black diamonds) compared to the average amount of ikaite precipitated throughout the ice thickness for each sampling day from Rysgaard et al., (2014) (white dots). The vertical black dotted line on 26 January mark when the heat was turned back ON.



Figure 8: Evolution of (a) ikaite dissolution within the water column (in μmol kg⁻¹), (b) mass of ikaite dissolved in the underlying seawater (blue), mass of ikaite precipitated in sea ice (black) estimated from this study and estimated from Rysgaard et al., (2014) (white). The vertical black dotted line on 26 January mark when the heat was turned back on.



Figure 9: Total amount of TCO_2 lost from the ice cover (black dots), amount of CO_2 exchanges between the atmosphere and the ice cover ($CO_{2air-ice}$, white triangle) and sea ice-seawater TCO_2 exchanges (blue triangle). In mole for each day, integrated over the whole tank. The dotted line on 26 January mark when the heat was turned back ON.



Figure 10: Evolution of (**a**) $\Omega_{aragonite}$ in the water column, calculated based on $TA_{(sw)}$ and $TCO_{2(sw)}$ (black dots) and calculated based on $TA_{(sw)}^*$ and $TCO_{2(sw)}^*$ (dashed red line) and (**b**) pH in the water column calculated based on $TA_{(sw)}$ and $TCO_{2(sw)}$ (black dots) and calculated based on $TA_{(sw)}^*$ and $TCO_{2(sw)}^*$ (dashed red line).

