

Interactive comment on “Inorganic carbon dynamics of melt pond-covered first year sea ice in the Canadian Arctic” by N.-X. Geilfus et al.

Anonymous Referee #1

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General comments:

The author investigated the carbonate system in sea ice in first year landfast sea ice and CO₂ fluxes between the atmosphere and sea ice/melt ponds in the Resolute Passage, Nunavut (74.726°N, 95.576°W,) in June 2012.

P.7493, L.1 “ To discard concentration – dilution effect, we normalized TA_{ice} and TCO_{2ice} to a salinity of 5 ...”

COMMENT/QUESTION: Normalization is useful, however, I’m not convinced that a salinity of 5 is the most appropriate choice. I suggest using a value close to sea-water salinity to facilitate comparison with under ice conditions. If taking the sea-water salinity value $S = 33.2$ (P.7496, L.6) for normalization one obtains the follow-

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ing NTA_{ice} and NTCO_{2ice} values (capital 'N' for S = 33.2 normalization; all values in $\mu\text{mol kg}^{-1}$): upper 20 cm: S = 33.2 S = 5 NTA_{ice,June4} = 3107 (nTA_{ice,June4} = 468) NTCO_{2ice,June4} = 2291 (nTCO_{2ice,June4} = 345) NTA_{ice,June17} = 11700 (nTA_{ice,June4} = 1762) NTCO_{2ice,June17} = 6912 (nTCO_{2ice,June4} = 1041)

The resulting values are higher (4 June) or much higher (17 June) than typical seawater values and thus need explanation. Which processes can explain these large changes over a time span of about two weeks? The discussion about the normalized values of TA and TCO₂ values (p.7498) is not adequate. How to explain the high TA and TCO₂ values in melt ponds?

P.7499 “nTA_{br} and nTCO_{2br} remained relatively constant, until at least a period of melt water percolation, which corresponded to a significant rise in both nTA_{br} and nTCO_{2br}. This increase suggests that despite the low salinity promoting the low TA and TCO₂, melt ponds and surface brine absorb CO₂ from the atmosphere.”

COMMENT/QUESTION: Uptake of CO₂ from the atmosphere by melt ponds leads to an increase of TCO₂ (however: is this a quantitative explanation?), however, it has no impact on TA! Remark: The authors know that pCO₂ uptake has no impact on TA (“An exchange of CO₂(gas) will affect TCO₂ while TA will remain constant.” P.7501, L.16)

P.7499 “From 4 to 10 June, the decrease of the in situ brine pCO₂ is mainly due to the drop in brine salinity associated with rising temperature and the dissolution of ikaite.”

COMMENT/QUESTION: The contribution of dissolution of ikaite to decrease in pCO₂ is not supported by measurements (ikaite has not been quantified).

COMMENT/QUESTION: The manuscript contains interesting new measurements. It is, however, mainly descriptive. I'm missing a detailed analysis of the data. The results shown in Fig. 9 are most interesting, however, the discussion remains on the qualitative level. How much ikaite precipitation/dissolution is required to explain the observed changes in TA and TCO₂? How does this compare with recent observations of ikaite

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in sea ice? Another example: one could ask whether the large change of salinity (from 33.2 to 31.4) in the water layer directly underneath sea ice can be explained by local melting or if advection of a different water mass is required. Another example is the dissolution of ikaite: “As previously suggested, the dissolution of ikaite crystals during sea ice melt likely contributed to a lowering of in situ brine $p\text{CO}_2$ according to Reaction (R1).” (P.7498) How much ikaite dissolution is necessary to explain observed changes in $p\text{CO}_2$? How does this amount of ikaite compare to the quantities of ikaite found so far?

Specific comments:

- I suggest dropping ‘in situ’ in front of $p\text{CO}_2$

- Abstract: “The low in situ $p\text{CO}_2$ observed in brine and melt ponds results in CO_2 fluxes of -0.04 to $-5.4 \text{ mmol m}^{-2} \text{ d}^{-1}$.” -> “The low in situ $p\text{CO}_2$ observed in brine and melt ponds results in air-ice CO_2 fluxes of -0.04 to $-5.4 \text{ mmol m}^{-2} \text{ d}^{-1}$ (negative sign for fluxes out of the atmosphere).”

- Abstract: “As melt ponds reach equilibrium with the atmosphere, the uptake becomes less significant. However, since melt ponds are continuously supplied by melt water their in situ $p\text{CO}_2$ still remains low, promoting a continuous but moderate uptake of CO_2 ($-1 \text{ mmol m}^{-2} \text{ d}^{-1}$).”

COMMENT/QUESTION: I found this a bit confusing. From the first sentence I got the impression that equilibrium is reached, whereas this is actually not the case according to second sentence (compare Fig.4). Please rewrite.

- Abstract: “The potential uptake of atmospheric CO_2 by melting sea ice during the Arctic summer has been estimated from 7 to 16 Tg of C ignoring the role of melt ponds. This additional uptake of CO_2 associated to Arctic sea ice needs to be further explored and considered in the estimation of the Arctic Ocean’s overall CO_2 budget.”

COMMENT/QUESTION: What is meant by ‘potential uptake’? Who estimated the

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range of 7 to 16 Tg of C (I guess per year)? How to relate the local fluxes in units of mmol m⁻² d⁻¹ to the regional (Arctic) fluxes in units of Tg C yr⁻¹?

- P.7489, L.3 "... pCO₂ between 0 to 188 μatm ..."

COMMENT/QUESTION: What is the detection limit of pCO₂?

- P. 7489, L.25 "During our survey, the air temperature increased from 0.6 to 3.2°C, with a maximum temperature of 4.3°C observed on 19 June (Fig. 2)." COMMENT/QUESTION: Maximum (4.3°C) is larger than the range (0.6 to 3.2°C). Please rewrite.

- P.7491, L.19 "were bring back" -> were brought back - P.7491, L.1 "TCO₂ was determined by CO₂ equilibration chamber coupled to an infrared CO₂ analyzer with a precision of ±2 μmol kg⁻¹."

COMMENT/QUESTION: Please explain. I guess: infrared analyzer -> mixing ratio of CO₂ -> pCO₂ -> [CO₂] & finally calculate TCO₂ from [CO₂] and alkalinity (?). Does the precision of ±2 μmol kg⁻¹ refer to TCO₂ or [CO₂]?

- P. 7494, L.9 "We assumed a conservative behaviour of dissociation constants for the range of temperature and salinity encountered in the ice cover."

COMMENT/QUESTION: It is not clear to me what you exactly mean by 'conservative behaviour of dissociation constants'.

- COMMENT/QUESTION: Fig.4: For sea ice you give 3 different pCO₂ values: (1) brine in situ pCO₂, (2) [bulk?] sea ice pCO₂, and (3) sea ice calculated pCO₂. If (1) & (2) are measured quantities: what are the differences in method & meaning? Which of the pCO₂ values is 'responsible' for air-ice gas exchange?

- P.7494, L. 15 "We observed few ikaite crystals in the ice ..."

âĖŠ "We observed few crystals in the ice ..."

- P.7494, L.25 "at the 40 cm depth" -> "at 40 cm depth"

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- P.7495, L.13 “with concentrations ranging from 20 μatm to . . .” -> “with values ranging from 20 μatm to . . .”

- P.7496, L.18 “The in situ pCO₂ at the seawater surface . . .”

COMMENT/QUESTION: I’m not sure what the authors mean by ‘in situ pCO₂’: I guess they mean the surface seawater equilibrium partial pressure (often denoted by PCO₂, i.e. using capital P).

- P.7496, L.19 “(negative flux denoting uptake of CO₂)” -> “(negative values denoting flux of CO₂ out of the atmosphere)”

- P.7500 “On 19 and 21 June, the bulk ice pCO₂insitu slightly increased while the in situ melt ponds pCO₂ slightly decreased to reach the same range of concentration.”

COMMENT/QUESTION: I have no idea what that means.

- P.7500, L.26 “To test the sackhole technique’s ability to sample uncontaminated brine, we compared T_{abr} and TCO_{2br} with a TA and TCO₂ estimated from the calculated brine volume (Cox and Weeks, 1983; Leppäranta and Manninen, 1988) and T_{oice} and TCO_{2ice} (Fig. 8). Both methods yield similar TA and TCO₂ concentrations (from 102 to 4425 $\mu\text{mol kg}^{-1}$), with a similar relationship between TA and TCO₂ with a R₂ of 0.96. The scatter between the two methods could be due to the impossibility of determining the exact original depth from which the brine seeped, especially if melt ponds are present at the surface of the ice cover.”

COMMENT/QUESTION: I suggest to slightly reorder the first sentence: To test the sackhole technique’s ability to sample uncontaminated brine, we compared (Fig. 8) T_{abr} and TCO_{2br} with a TA and TCO₂ estimated from T_{oice} and TCO_{2ice} and the calculated brine volume (Cox and Weeks, 1983; Leppäranta and Manninen, 1988).

- COMMENT/QUESTION: From Fig.8 one cannot see how good TCO_{2br} and TCO₂ estimated from T_{oice} and brine volume fit to each other: Which data correspond to each other?. I suggest splitting Fig. 8 into 2 panels: one for TCO₂ over TCO₂, the

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other for TA over TA.

- P.7501, L.9 “The only noticeable impact of sea ice melt on the underlying seawater was observed on 20 June where the decrease of TAsw and TCO2sw was associated with the low isotopic ratio of $\delta^{18}\text{O}$ and δD occurring over a very short period (Fig. 6).”

COMMENT/QUESTION: The decrease of TAsw and TCO2sw is probably related to the decrease of salinity (mentioned earlier, right?). I’m missing information about sea ice thickness and its development over time.

- P.7501, L.20 ‘To calculate these theoretical effects we assumed that seawater sampled at 50m was not influenced by the overlying melting sea ice.’

COMMENT/QUESTION: Please give the seawater values at 50 m depth: TCO2, TA, T, S. Let me suggest again to scale (normalize) all TCO2 & TA values to seawater salinity (S50 m).

- P.7501, L.26 “The concentration of algal biomass (Chl a) has been measured at the bottom of the ice and decreased from $11.1 \mu\text{g L}^{-1}$ in 4 June to $0.05 \mu\text{g L}^{-1}$ on 21 June (unpublished data, C. Mundy).”

COMMENT/QUESTION: What’s the reason for the decrease (actually vanishing) of chlorophyll at the bottom of sea ice? Is it related to melting (compare, for example, Zeebe et al., 1996)? Zeebe, R. E., Eicken, H., Robinson, D. H., Wolf-Årøgladrow, D., & Dieckmann, G. S. (1996). Modeling the heating and melting of sea ice through light absorption by microalgae. *Journal of Geophysical Research: Oceans* (1978–2012), 101(C1), 1163-1181.

- P.7502, L.29 “... pond coverage (x) ...”-> “... pond coverage (fraction $0 \leq x \leq 1$) ...”

- P.7503, L.3 “The pond coverage (Fig. 2) was obtained six times between the date of pond onset (10 June) and the final sampling date, with a terrestrial laser scanner. In short, the scanner 5 was used to measure the surface topography of an untouched $80 \times 160\text{m}$ area of sea ice and could also differentiate between ice cover and melt ponds

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at the surface, thereby providing the pond fraction (Landy et al., 2014)."

COMMENT/QUESTION: This paragraph could go under 'Methods/Results'. - - P.7503, L.8 "... then return to previous values ($-1 \text{ mmol m}^{-2} \text{ d}^{-1}$) when melt ponds are dominating. pCO_2 conditions in melt ponds are determined by a balance between equilibration with atmospheric CO_2 the continuous supply of melt water from the snow and sea ice." -> "... then returned to previous values ($-1 \text{ mmol m}^{-2} \text{ d}^{-1}$) when melt ponds are dominating. pCO_2 conditions in melt ponds are determined by a balance between equilibration with atmospheric CO_2 and the continuous supply of low- pCO_2 melt water from snow and sea ice." ' - P.7504, L.8 "Early in the melt period, increased ice temperatures and subsequent decreased bulk ice salinity dissolution of ikaite crystals promoted a strong decrease of TA, TCO_2 and pCO_2 observed in bulk sea ice and brines (Fig. 10). The decrease of pCO_2 causes sea ice to act as a sink for the atmospheric CO_2 ($\approx -1 \text{ mmol m}^{-2} \text{ d}^{-1}$). This sink increases (up to $-5.4 \text{ mmol m}^{-2} \text{ d}^{-1}$) during the initial formation of melt pond due to its very low pCO_2 levels. The percolation of melt pond water into the ice matrix will intensify the brine dilution and the decrease of the brine TA, TCO_2 and pCO_2 (Fig. 10). " -> "Early in the melt period, increased ice temperatures and subsequent decreased bulk ice salinity and dissolution of ikaite crystals promoted a strong decrease of TA, TCO_2 and pCO_2 observed in bulk sea ice and brines (Fig. 10). The decrease of pCO_2 causes sea ice to act as a sink for atmospheric CO_2 ($\approx -1 \text{ mmol m}^{-2} \text{ d}^{-1}$). This sink increases (up to $-5.4 \text{ mmol m}^{-2} \text{ d}^{-1}$) during the initial formation of melt ponds due to its very low pCO_2 levels. The percolation of melt pond water into the ice matrix will intensify the brine dilution and the decrease of the brine TA, TCO_2 and pCO_2 (Fig. 10). "

COMMENT/QUESTION: (1) In Fig. 9 normalized values of TCO_2 and TA ($n\text{TCO}_2$ and $n\text{TA}$) are shown whereas you talk about TCO_2 and TA, (2) no information about pCO_2 is provided by Figs. P or 10, (3) decrease of salinity and dissolution of ikaite have opposite effects on both TCO_2 & TA (dissolution of ikaite leads to increase of both TCO_2 & TA in the molar ratio of 1:2). The sign of change (decrease or increase) of

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TCO₂ & TA depends on the strength of dilution versus dissolution of ikaite.

- P.7504, L.17 "As melt ponds forms from melted snow and melted ice surface the in situ melt pond pCO₂ is low (36 μatm). The percolation of this low pCO₂ melt water into the sea ice matrix dilutes the brine causing the in situ brine pCO₂ to decrease (20 μatm)."

COMMENT/QUESTION: In contrast to TCO₂ or TA, pCO₂ is not a conservative quantity and thus it does obey a linear mixing equation. You might argue for a lowering of pCO₂ by considering changes in TCO₂ and TA by dilution.

- P.7504, L.24 "in situ pCO₂ remains undersaturated"

COMMENT/QUESTION: In my opinion a pCO₂ cannot be 'undersaturated'; a water mass can be undersaturated.

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