

Interactive comment on “Ikaite crystal distribution in Arctic winter sea ice and implications for CO₂ system dynamics” by S. Rysgaard et al.

M. Vancoppenolle (Referee)

mvlod@locean-ipsl.upmc.fr

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This paper by Rysgaard et al presents novel measurements of CaCO₃ crystal concentrations in sea ice in what constitutes a very stylish, minimalist paper.

There are many positive aspects in this study: the measurements seem to have been made very carefully, the crystal abundance and concentration quantification method is rigorous and seems to significantly improve previous ones, the paper is concise and accurate, and the discussion encompasses all the interesting aspects.

The minimalist approach renders the paper concise, easy to read and pleasant to review, but the drawback is that in several instances, information is missing.

The best example is the too concise description of the sampling strategy (how many

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cores, which parameters come from which core, etc...). The authors claim later that $TA \approx CaCO_3$ in the surface layers. But careful examination of the figure indicates that this is not true ($CaCO_3 > TA$ near the top). In this context, more info on sampling and observational errors would have been useful. The surplus of $CaCO_3$ is not enormous. Therefore, this is probably fine. But me, reader, was left with the vague impression that something was wrong there.

Another weakness of the paper was the discussion of physical drivers, which can be improved.

I do not want to destroy the readability of the paper, which is otherwise of excellent quality, hence I suggest to modify it very carefully. I suggest to publish this paper after the revisions I suggest are incorporated or properly rejected.

You can contact me directly (mvlod@locean-ipsl.upmc.fr) if some points are unclear.

Best regards,

Martin Vancoppenolle

Major comments

- Describe your sampling strategy in more details. Support this with a table, with the actual numbers, for TA, TCO₂, CaCO₃, T and S. Also mention from which core they are from. Just to cut down any ambiguity.
- The thermodynamic regime of your sea ice cover seems not typical at all of Arctic sea ice, but rather looks like Antarctic sea ice, with a deep snow cover and high salinities. The ice proves to be both quite cold and saline, which arguably may favour CaCO₃ formation. As your site is very peculiar, you must acknowledge this early on (in the abstract?)
- The X-ray table is abstruse. There are no titles in the columns. You nowhere explain

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what the numbers mean. I'm not a crystallographist at all. But the standard reader of that journal neither is. Explain more, both in the table and in the text, or remove.

- The modelling exercise has the same problem. You say, I use that model, but you don't even explain what are the basic principles, and how temperature determines your computations. Hence, this part is at this stage unhelpful. Explain in one or two sentences: i) basic principle of the model; ii) what are your controlling factors (including T); iii) what is the ice fraction and brine salinity in your equilibrium state

- The discussion of the physical drivers of ikaite formation is unconvincing. Extensive invocation of downwards brine expulsion is made, while this is typically a minor process (Notz and Worster 2009). In addition, more important mechanisms (e.g. full depth brine convection) are likely at work.

Detailed comments

page 5039

* Abstract: I didn't like the term "bottom layer" here and throughout the paper. Be more precise. The last sentence does not help. Instead of vaguely telling what you do, you should rather explain what comes out of what you've done.

* line 12 surfaceice typo

page 5040

* I'm more familiar with the Assur 1958 reference, but this might be the same paper.

page 5041

line 8

* I don't understand why this sentence is here.

* What is the difference between brine drainage and brine expulsion ? Base on Notz and Worster JGR 2009.

* If you to use brine motion to elaborate on how your reaction works in the sea ice environment, you must be more precise. I would tend to describe this reaction as being driven by brine concentrations. But in this context, the reasoning could be the opposite: in brines, concentrations of all salts are much higher than in seawater, but the stocks are very low. Besides, if brine concentrations are the relevant values, speaking of brine motion could be meaningless. Desalination has no impact at all on brine values. Desalination changes brine volume and bulk salinity, but not brine salinity, which solely depends on temperature, if one assumes equilibrium.

line 9 "within sea ice interstices". If you mean that they lose contact with brine then use "between pure ice crystals with no contact with brine?". What do you mean by "pushed to the right" ? Do you mean that there is a CaCO₃ deficit in the brine solution ?

Methods

* The ice conditions seem very peculiar. You must say slightly more. Did you choose that site on purpose? Given the very deep snow, it is very likely that negative freeboard was widespread. Did you measure freeboard ? Or, do you have indirect indications of negative freeboard, e.g., did you see slush on the base of the snow layer? A quick computation suggests that you could easily have highly negative freeboard if the snow was dense enough. Then, the question is, was the snow old (high density) or fresh (low density)?

* Was there ice algae on the site? Was the site chosen to avoid ice algae? Ice algae would reduce nutrients and nitrates could affect TA. I understand that the authors don't want to elaborate on biological aspects, but this information could be useful for future use of your study.

* You must be more precise in acknowledging the potential sources of errors. The key issue is the temperature cycle you impose to your samples before observation. Add a paragraph to describe the different source of errors. Keeping your ice cores at -20°C may produce CaCO₃. If the time they are kept at this temperature is very short, that

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should be fine. But what if the (unknown) ikaite production rate is very high?

* You must precisely say whether you measured S, TA, CaCO₃ from the same ice core or not.

page 5042

* Period missing line 29

* Line 29. Why 1.07mm² ? This numbers falls from outer space at present.

page 5043

* "The area of the melt sea ice sample was determined..." how can one measure the area of a liquid?

* Lines 13-15 "Its volume". Say that you sum over all crystals.

* Paragraph starting line 16. Say in two words which quantity you measure with X-rays. It is not obvious at the moment.

page 5045

* line 15 less that typo

* line 26. The ice texture interpretation is not very precise. I'm not a specialist, but please check. A quick look in the literature (eg haas et al. Jglaciol 2001) indicates that polygonal granular does not support snow ice formation, but rather superimposed ice formation.

* line 26 "through percolation and refreezing of brine and seawater into snow" would reflect state-of-the art knowledge of the process more precisely, I believe.

page 5046

line 10 orbicular granular ice crystals reflect frazil ice in general (see Eicken, Encyclopaedia of the Antarctic - just google it). The most likely scenario to explain an

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orbicular granular layer on top of the ice is just new ice formation in open water (frazil ice that consolidates). Snow ice could also form such structures. Then, why invoking brine expulsion here: it is not needed to explain textural features.

line 17 supercooling at the ice-ocean interface... this also can occur at depth :-)

line 19 remove "the presence of"

page 5048

* The "temporal" adjective in the title section is not really supported by observations made in this paper

* line 15 "dynamic conditions of" -> i would remove

* line 16 Understanding this dynamic would be-> "Constraining the rates of ikaite formation as a function of temperature and brine chemical composition would be"

* from line 18 on. You must at least explain what are the basics of the model. What are the parameters you specify (in particular temperature)? It would also be nice to compare the output in terms of brine salinity and solid ice fraction of the FREZCHEM model to see whether you reach a value that is comparable to your observed-temperature-derived values. Elaborate here or in the discussion, if you can, why calculations are lower than observations.

page 5049

* line 5:

- what did you actually see moving with your microscope? solutes ? gases ? micro-organisms ?

- "are entrapped and transported within the brine system" -> "accumulate and move within brine".

- transport velocity -> are you sure it is a transport velocity and not diffusion ?

* line 12

- this sentence sounds as if CaCO₃ crystals would freshen seawater and decrease pCO₂. Be more explicit. Is the pCO₂ decrease driven by the melt of TCO₂-poor ice ? Would CaCO₃ enhance CO₂ depletion ? That question could be examined by looking at the TA-S ratio in sea ice and seawater. If the TA-S ratio is higher in sea ice than in seawater, then the role of CaCO₃ release would add a further contribution to the simple melt of the ice.

* line 17 in the bottom layer of the sea ice -> reword, be more precise

* lines 19 on, starting from "One explanation".

I was not really convinced by the physical part of this argument which relies on downward brine expulsion of CO₂, which sounds quite unlikely in your situation. Clearly, you are in a system where local chemical sources and sinks must interact with physical transport by convection.

These paragraphs need to be rewritten. Use the following items or reject them:

1) Brine volumes are higher than 5 everywhere (permeable ice) and the temperature gradient points downwards (unstable brine network). All these suggest that full-depth convection (see Jardon et al., JGR2013) is possible. Hence, your brine might well be convectively exchanging with seawater below. CaCO₃ would extract Ca and DIC from brine and could pump them out of the liquid brine, while convection could replenish in brine the elements required to form ikaite. This all depends on the time scales associated with CaCO₃ precipitation and brine convection. See Vancoppenolle et al., JGR 2010, section 6.4 where a similar argument is developed for ice algae and nutrients.

2) Besides, the most natural explanation is that CaCO₃ stock is equal to a a temperature-dependent production rate multiplied by time. The upper layers are older and colder, hence more prone to higher ikaite stocks.

3) I don't know what your pH measure means, but clearly the pH of brines should be

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used. Full-depth convection of brine may explain an apparent downward migration of pH equivalents. Any downward transport of pH equivalents should be driven by an upward vertical gradient of pH equivalents within brine, provided by the brine network is open.

4) Looking at your curves, it appears that CaCO_3 concentrations are higher than TA. Be more precise on the sampling and observation errors. Give TA/ CaCO_3 numbers in a table or put the profiles on the same plot to make this clear.

page 5050

line 6 "Another mechanism that could affect". -> use instead something like "Physical supplies by brine convective motion that impacts the stocks of required elements driving the ". This second paragraph could also be rewritten using the aforementioned elements.

page 5051 line 5 Again, brine expulsion is unlikely to be the main driver here.

page 5052 line 21 this Papakyriakou paper is not cited.

Figures and tables

Fig1. I don't see the dark and light stars mentioned in the caption for panel B. Besides, could you delimit sea ice and land on panel B using dark lines ?

Tab1 is not helpful. The meaning of the numbers is not detailed, no units. I would remove this table, unless it is described and explained properly.

Fig 2. For even easier reading, you may add the name of the site for each panel and suggest what the lines mean with a legend, but this is more an advice than an order :-). If you know the location of the freeboard, add it on the plot.

Fig 6. You could add a line in the text to explain why the relation between crystal numbers and concentrations is not linear. Obviously, you find out smaller crystals upper in the sea ice. If you know where freeboard is, add it on the plot.

Good luck with this paper...

Interactive comment on The Cryosphere Discuss., 6, 5037, 2012.

TCD

6, C2942–C2950, 2013

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