-----TO THE EDITOR-----

We would like to thank the anonymous reviewer for their comments. Please find our responses immediately following each comment in blue text.

-----START REVIEW-----

The Cryosphere Discuss., 7, C2661–C2665, 2013 www.the-cryosphere-discuss.net/7/C2661/2013/

Interactive comment on "Morphology and distribution of liquid inclusions in young sea ice as imaged by magnetic resonance" by R. J. Galley et al.

Anonymous Referee #2

Received and published: 6 December 2013

In this contribution, the authors present MRI measurements of sea-ice microstructure and compare the inferred liquid fractions to those traditionally derived from ice-core studies.

I find that this paper requires a major revision before it might become suitable for publication, in particular since there is too little reference to existing similar work. This makes it difficult to assess the scientific progress presented here.

In particular, a discussion of the progress relative to the following, as of yet uncited work (and often references therein) would be necessary. Much of what is stated as "new" for the recent study has already been done before:

Hunter, M.W., Dykstra, R., Lim, M.H., Haskell, T.G., Callaghan, P.T.: Using Earth's field NMR to study brine content in antarctic sea ice: Comparison with salinity and temperature estimates, Applied Magnetic Resonance, 36 (1), pp. 1-8, 2009.

Aussillous, P., A.J. Sederman, L.F. Gladden, H.E. Huppert, M.G. Worste, "Magnetic Resonance Imaging of structure and convection in solidifying mushy layers", Journal of Fluid Mechanics, 552, 99-125, 2006.

Bock, C. and H. Eicken, A magnetic resonance study of temperature-dependent microstructural evolution and self-diffusion of water in Arctic first-year sea ice, Anal. Glac., 40(1), 179-184, 2005.

Callaghan, P. T., Dykstra, R., Eccles, C. D., Haskell, T. G. & Seymour, J. D.: A nuclear magnetic resonance study of Antarctic sea ice brine diffusivity. Cold Regions Sci. Tech. 29, 153–171, 1999.

Menzel, M. I., Han, S. I., Stapf, S. & Blumich, B., NMR characterization of the pore structure and anisotropic self-diffusion in salt water ice. J. Magn. Reson. 143(2), 376–381, 2000

From a more theoretical point of view, the structure of brine channels was discussed by: Wells, A. J., J. S. Wettlaufer, and S. A. Orszag, Brine fluxes from growing sea ice, Geophys. Res. Lett., 38, L04501, doi:10.1029/2010GL046288, 2011.

Also the following references are of interest for this study, though they are obviously somewhat harder to find:

Maus S, Huthwelker T, Enzmann F, Miedaner MM, Stampanoni M, Marone F, Hutterli MA, Ammann M, Hintermuller C, Kersten M. Synchrotron-based X-ray micro-tomography: Insights into sea ice microstructure. Proceedings of The Sixth Workshop on Baltic Sea Ice Climate, Vol. 61. Report Series in Geophysics. Helsinki: University of Helsinki; 2010, 28–45. Available at https://helda.helsinki.fi/bitstream/handle/10138/39291/Report_series_in_geophysics_61.pdf?sequence=1 C2662
Buettner, J., Permeability of young sea ice from microtomographic images, Master Thesis, University of Bergen, 2011, available at https://bora.uib.no/handle/1956/5633

We would like to thank the anonymous reviewer for their insight into work on using the technique and application of magnetic resonance, in particular nuclear magnetic resonance, to infer the vertical distribution of liquid fraction in sea ice volumes. In light of the referees' comments, we never intended this work to signify a methodological improvement in the area of magnetic resonance, rather our intention was to illuminate the three-dimensional morphology of liquid inclusions in a sea ice core sample of which the physical atmospheric and water/sea ice physical properties are known. Magnetic resonance imaging of these features presented in this work served only as an available observational technique. We understood this technique was available because of the previous work on the subject, some of which was mentioned by the reviewer above. So, although it will make the manuscript introduction longer, we will include some of the citations above among others, resulting in a more complete contextual environment for the reader. The objectives of the presented work will be re-written for clarity in the last paragraph of the introduction section. That is, (as has been written in our response to the comments of anonymous referee 1 (tc-7-C2628-2013)), to (1) to present a three-dimensional image of a brine drainage channel feature in young sea ice, (2) give the physical context for its formation by presenting the physical conditions of the atmosphere and water/sea ice volume (the sea ice volumes' life history) from prior to sea ice growth through the date of the sample discussed, (3) give observation of it's physical properties/characteristics and (4) the amount of time in which it formed. Finally, we (5) present a vertical brine volume distribution profile of our sea ice sample using magnetic resonance image data to extend the (non-imaging) nuclear magnetic resonance work of Callaghan et al. (1999) and Hunter et al. (2009) who first showed that their technique well-replicated calculated brine volume fractions in sections of Antarctic sea ice up to 220cm thick and 180cm thick respectively, but were unable to determine pore sizes, shapes or distributions within the sea ice volume. Mercier et al. (2005) show isotropy and anisotropy in sea ice diffusion coefficients using the NMR method, highlighting the need for a greater library of physical observations of liquid inclusions in sea ice under a variety of sea ice types/environments.

Should the authors find that despite this long (and probably not exhaustive) list of existing previous work on this topic their study still provides sufficient scientific progress to warrant a revised version, the following additional points should also be addressed:

In the light of the objectives of our work presented in the response above, we firmly believe our work warrants the submission of a revised manuscript.

Abstract:
This will likely have to be substantially rewritten in the context of existing work.

We will re-write the abstract to highlight the objectives and results of this work as clearly as possible.

Introduction:
The introduction is sometimes hard to read since its structure is not always clear. It seems, in particular on p 4979 and 4980, currently a little bit too much like a listing of previous work rather than a concise summary of our current knowledge. In particular, given the scope of this paper, it seems better to focus on our recent understanding and to not spend too much time on outdated insights. This holds in particular for p. 4980 l. 19 -p. 4981 l.13 (compare Notz and Worster, 2009).

We tried to structure the introduction to highlight the current library of observations of liquid inclusions in sea ice, and a chronological arrangement of these works seemed appropriate to show that there actually relatively few observations of liquid inclusions given the number of years that have past since their study was begun in detail (e.g. page 4980 Line 19: the citation of Malmgren (1927) and page 4981 Line 13 the citation of Bennington, (1967) to which this anonymous referee refers). Notz and Worster (2009) contains great detail on the modelling of desalination processes in sea ice and contains in situ bulk impedance data to present inferred vertical bulk salinity profiles, but does not contain morphological observations of liquid inclusions. We view our images and morphological observations as complementary to the work of Notz and Worster (2009) among many others.

p.4979, l.19: Add solid salts to this list

We agree that solids salts should be added to this list. Thanks.

p.4980, l.6ff: Brine channels are sites of downward movement of salt, the upward movement occurs through the bulk of the sea ice between the channels.

We think the anonymous referee is referring to the sentence beginning on Page 4980 Line 7 beginning “Brine drainage channels are…”. We will modify the sentence as follows: “.....the bulk of the liquid convection (i.e. gravity drainage) to the sea ice-seawater interface.”.

p.4980, l.14ff: The suggestion that sea ice might become impermeable at a fluid volume fraction of 5 % was first made by Weeks and Ackley (1986) based on data by Untersteiner (1968).

Since submitting this manuscript, we've become aware of this fact as a result of an article on sea ice microstructure by Jones et al. (2012). In the revised manuscript we will cite this work and appropriately amend the statement mentioned above. We thank the anonymous referee for pointing this out.

Citation to be included: Jones, K. A., M. Ingham, and H. Eicken, 2012. Modeling the anisotropic brine microstructure in first-year sea ice, Journal of Geophysical Research, 117, C02005, doi: 10.1029/2011JC007607.

p.4981, l.14: In the discussion of the horizontal movement within the ice, some of the theoretical insights gained in recent years should be discussed, see for examle the paper by Wells et al. mentioned above, and references therein.

We agree that the discussion of the horizontal movement of liquid within sea ice in our introduction could benefit from the work of Wells et al. (2011), and the experimental work of Aussillous et al. (2006) among others to expand the theoretical background and provide additional information on the subject. We think the observations we present are complementary to both these efforts.

Citations to be included along with relevant discussion of the horizontal liquid motion in sea ice:
Wells, A. J., J. S. Wettlaufer, and S. A. Orzsag, 2011. Brine fluxes from growing sea ice, Geophysical Research Letters, 38, L04501, doi: 10.1029/2010GL046288.
Aussillous, P., A. J. Sederman, L. F. Gladden, H. E. Huppert and M. G. Worster, 2006. Magnetic resonance imaging of structure and convection in solidifying mushy layers, Journal of Fluid Mechanics, 552:99 – 125.

p.4983, l.12: Reference to the "law of the fives" is unclear in the context of this study.

We agree that the in light of the context in which both reviewers have taken this work we need to re-examine the presentation of the objectives of this work as we state in responses above. It might be best to leave discussion of how our data fits into the current literature (including Golden et al., 1998) for the discussion section of the paper once the results have been presented rather than include it in the objectives paragraph at the end of the introduction.

Methods:
Either here, or in the results section, more discussion of sampling biases were needed:
-How much salt is likely lost during the sampling of the relatively warm, thin ice? (compare, for example, Fig. 9 of Notz et al., J. Glac., 51(172), 159-166, 2005, which

shows in-situ measurements of salinity in a core of roughly the same length and temperature as considered here against data from traditional ice cores.

This is a good point. We think this is best accomplished in the methods section. We'll add this citation on page 4984 at about Line 9. This information is an appropriate caveat for any study using sea ice core samples to calculate bulk salinity.

-Which impact does the storing of your ice core at -20C has on its microstructure and salinity? Compare Cox and Weeks, J. Glac., 32(112), 371-375, 1986.
-What's the impact of horizontal inhomogeneity? Compare Gough, A.J., Mahoney, A.R., Langhorne, P.J., Williams, M.J.M, & Haskell, T.G. (2012). Sea ice salinity and structure: A winter time series of salinity and its distribution. Journal of Geophysical Research–Oceans, 117, C03008. doi:10.1029/2011JC007527

These are also appropriate caveats to any study containing sea ice salinity data from extracted sea ice core samples that we will include in the methods section of a revised manuscript. Scenarios more complicated to the one we undertook in this work described by Cox and Weeks (1986) indicate small porosity changes where the core sampled was cooled to a storage temperature <-10C and then warmed to in situ temperatures. However, we did not warm the stored core to its in situ temperature but we have calculated the brine volume at the storage temperature as they have recommended. Gough et al. (2012) conclude that deviations from the mean salinity profile occur for no less than 40cm in the vertical, and caution against too much interpretation of any single core. We present our results for precisely this reason as we have indicated earlier, to increase the number of observations of these brine channels in the literature that are variable under varying atmospheric and water/sea ice physical conditions.

Citations to be included:

Cox, G. F. N. and W. F. Weeks, 1986. Changes in the salinity and porosity of sea-ice samples during shipping and storage, Journal of Glaciology, 32(112):371 – 375.
Gough, A. J., A. R. Mahoney, P. J. Langhorne, M. J. M. Williams, and T. G. Haskell, 2012. Sea ice salinity and structure: A winter time series of salinity and its distribution, Journal of Geophysical Research, 117, C03008, doi: 10.1029/2011JC007527.

Results:
This is possibly the most critical section for a possibly revised version of this manuscript. It is currently unclear what one really is to take away from this section and the given details on the experimental protocol and environmental conditions. In particular, there is no discussion as to which of these results are generally valid and which are probably only valid because the ice was grown under these particular, somewhat synthetic conditions in a tank without much turbulence. For the results that fall into the latter category, the authors should critically assess how much the scientific community will profit from their presentation. If more fundamental

insights based on our modern understanding of the evolution of sea-ice microstructure were possible, this should more clearly be elaborated.

Given the caveat that our sea ice volume was grown in a mesocosm tank the clarity and pertinence of the results section should be much improved by our proposed changes to the introduction and objectives sections of the manuscript. Although there was no current in the water below the ice, the granular frazil layer that caps our sample sea ice was grown in the presence of wind, and the typical transition zone followed by columnar ice growth is also present. Our results indicate that a brine channels in young sea ice can be imaged very quickly (4 min 30 sec) in three-dimensions using MR imaging; we can put the formation of this brine drainage feature in the context of the atmospheric and water/sea ice volume physical characteristics since prior to the sea ice volumes' inception; we quantify the time this feature took to form as well as it's morphology at the time of sampling; we conclude that simple, fast MR imaging results in MR-derived brine volume estimates that match reasonably with empirically derived ones and finally we discuss the implications of these results in the context of ocean-atmosphere exchange.

Discussion:
p.4991, l.19ff: This sentence is unclear to me.

In this line, we are discussing that the brine drainage channel feature that exists in the bottom 8cm of the sea ice core sample imaged is only as old as the sea ice in which it formed. Since we logged and presented the air temperature, sea ice thickness and temperature data for the duration of the sea ice growth, we surmise that the brine drainage feature imaged here was formed during the time the sea ice volume was formed in the absence of any warming. So, what were alluding to in this sentence was that we have experimental evidence that this is a first generation feature (as defined in the introduction on page 4981 line 8ff) and that it formed in less than 6 days as the sea ice volume thickened.

p.4992, l.13: The convectional patterns of gravity drainage imply that indeed all of the sea ice in which brine moves has some horizontal and some vertical movement of the brine, simply to close the path of upward and downward movement. See the paper by Wells et al. referenced above. The fact that brine also flows horizontally into sack holes has long been known, which is why for quantitative studies the walls of these sackholes should be covered (e.g., Freitag J., and H. Eicken (2003) Melt water circulation and permeability of Arctic summer sea ice derived from hydrological field experiments. J. Glaciol., 49(166), 349-358).

We agree, and have presented observational data to corroborate the facts mentioned above, and note in the following lines some citations consistent with the ideas the referee mentions in their comment above. We will add the citation mentioned above in the referee's comment to the citation list on line 20 of page 4992.

p.4992, l.21ff: This sentence is unclear (or simply inconsistent with our modern understanding as to how brine inclusions in sea ice form)

We agree, that this sentence is unclear, and the intended idea adds little to the discussion. This sentence can be removed from a revised version of the manuscript.

p.4992, l.26-p.4993, l.19: This discussion is very speculative and only relevant to this particular core. Which general insights can we gain from it?

We agree that the paragraph in question is speculative, however the description of the relevant physical processes contained therein is based on what we know of sea ice formation and implements (and cites) the work of others on the subject. It is meant as a synthesis of the situation as we see it in our sea ice core sample using the data we have presented and the knowledge of the processes from the work of others. As a result of this work, we are not entirely sure that generalities are the best message to glean from work like this and modeling studies of these processes, because as we try to show, the physical forcing and resultant sea ice processes are complex and should be studied further.

p.4993, l.20ff: I do not see how the current work contributes to this entire discussion beyond the previously known functioning of brine dynamics.

The morphological data we present here, specific to the brine drainage channel feature are instructive due to the sizes of the individual brine drainage channels, particularly because the effect of ikaite precipitation on under-sea ice pCO_2 depends on whether these crystals are retained in the ice matrix or exported with brine drainage. As we state in our response to anonymous referee 1, our imaging results indicate that the attending channels to the main brine drainage channel range from 0.8 to 1.5 mm in diameter, which is greater than the ikaite crystal lengths of <0.1 mm to 1 mm reported by Rysgaard et al. (2012) Arctic sea ice. Our imaging results are thus consistent with recent investigations of ikaite dynamics that suggest ikaite removal from sea ice through brine drainage is a process affecting the alkalinity of under-sea ice seawater and consequent effects on air-atmosphere CO2 exchange. Also the brine diameters will have implications for gas vertical gas bubble transport and hence affect the air-sea gas (CO2) exchange.

Conclusions:

p. 4995, l.4ff: This discussion can be made much more directly from the ice-core data, which also allow for an estimte of porosity. The relevance of the MR images for this discussion is not brought out clearly enough.

Although we mention the ice core data on lines 4 and 5 of page 4995, we realize that this paragraph is not clear enough. So, we will edit it to make the comparison the referee mentions above more directly. This paragraph was an attempt linking the "typical" physical data (sea ice temperature, bulk salinity, and the resultant brine volume) we presented (in Figure 3) that illustrate the permeability of the sea ice volume theoretically using the law of fives, and the image data showing the location, size and shape of the liquid inclusions (e.g. Figure 4) which literally illustrate the permeability of the sea ice volume.

Interactive comment on The Cryosphere Discuss., 7, 4977, 2013.
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