Answer to Reviewer 1 of tc-2020-288

We like to thank the reviewer for this detailed review that helped us considerably to improve the paper and clarify open issues. Below we repeat the *reviewers comments in italic font* followed by our answers, and **additions and changes to the manuscript in red font**.

1 Summary

This paper presents a new experimental characterization of the pore space and permeability of natural sea ice. The techniques are advanced and novel for natural sea ice. These measurements have a wide importance to those studying the evolution of sea ice, since many processes are very sensitive to permeability. The experimental technique is well described and careful. The results are presented clearly and provide strong evidence in contrast to widely-cited previous studies showing a percolation threshold at 5 % porosity. The limitations of the study are discussed very well, although there are three significant areas in which I think limitations need more discussion. The writing quality is excellent. Overall, I think the paper is excellent and should be accepted subject to minor revisions.

Answer:
Thank you for this motivating evaluation. We agree with most aspects to be revised, and answer the reviewers comments below. In advance we give the modified abstract:

Abstract. The hydraulic permeability of sea ice is an important property that influences the role of sea ice in the environment in many ways. As it is difficult to measure, so far not many observations exist and the quality of deduced empirical relationships between porosity and permeability is unknown. The present work presents a study of the permeability of young sea ice based on the combination of **brine extraction in a centrifuge,** X-ray micro-tomographic imaging and direct numerical simulations. The approach is new for sea ice. It allows to relate the permeability and percolation properties explicitly to characteristic properties of the sea ice pore space, in particular to pore size and connectivity metrics. For the young sea ice from the present field study we obtain a brine volume of **2 to 3%** as threshold for the vertical permeability (transition to impermeable sea ice). We are able to relate this transition to the necking of brine pores at a critical pore throat diameter of ≈ 0.07 mm, being consistent with some limited pore analysis from earlier studies. **Our optimal estimate of critical brine porosity is half the value of 5 %** proposed in earlier work and frequently adopted in sea ice model studies and applications. **From a discussion of our results with respect to earlier studies we conclude that the present threshold is more significant, in particular through the combination of 3D image analysis and centrifuge experiments. We also find some evidence that the sea ice pore space should be described by *directed* rather than *isotropic* percolation. Our revised porosity threshold is valid for the permeability of young columnar sea ice dominated by primary pores. For older sea ice containing wider secondary brine channels, for granular sea ice, as well as for the full thickness bulk permeability, other thresholds may apply**.

2 General comments

2.1 Experimental procedure and the texture of sea-ice:

There is insufficient discussion of how the procedure followed might have affected the texture of the sea ice, such that the images collected are not necessarily representative of natural sea ice. Several aspects of the description of the procedure raised questions about this matter. For example, L65 describes an equilibration over 1-3 days. L71 describes a loss of brine during storage. I would expect the storage period to result in change in texture or pore space geometry. Loss of brine will generally increase the solid fraction and reduce the permeability. L83-89 suggests that it might have been worthwhile varying the centrifuging procedure to demonstrate more clearly that results don't depend too sensitively on it.

Answer:

We have written a more detailed description of the procedure of sampling, transport, centrifugation and storage. First, we expand the methods section by an additional paragraph:

L137 **2.5. Sampling, transport, storage and textural changes: Special care was taken to minimise undesired temperature changes and variability prior to centrifugation and imaging. The cut samples of the relatively isothermal sea ice were transported in an isopleth box (inside a larger insulated aluminium box) to the laboratory. Transport and sorting into small temperature controlled freezers happened within half an hour. As each sub sample was packed in a conical plastic cup, temperature changes are, due to the large effective specific heat capacity, considered negligible. The box temperature was logged by a temperature logger, as well as temperatures were directly measured on samples, being within 0.2 K of in sit values. The next step, cooling of sub samples in the laboratory, took place within these freezers set to lower than in sit temperatures. With samples within the plastic cups cooling rates (with most heat loss due to internal freezing) were moderate and in the range 1-5 K per day, comparable to natural cooling rates. An important aspect of the approach was also that samples were only cooled, not warmed. This avoids the known hysteresis, that brine expelled during cooling is not reintroduced into a sample upon warming.**

Though we have no strict proof for this, we believe that microstructure changes during 1 to 2 days of close to isothermal storage are minor (this is based on unpublished work of repeated scanning). More relevant could be effects due to freezing and redistribution of brine. First, one could expect that simultaneous cooling of sub samples from all sides may redistribute brine in a way that differs from mostly vertical heat loss of ice in the field. We do not find brine accumulation in the center of samples, indicating that also the multi-directional sample cooling redistributes brine along the predominantly vertically oriented pores. Brine could be redistributed vertically in some non-uniform way within a 3 cm thick sub sample, and implications will be considered in the discussion. Second, we treat our sample isothermally, which is justified as the in sit temperature profile suggests a difference of 0.1 K along the vertical direction. Third, sample storage after centrifugation at

low temperature (-80 °C) has likely led to almost complete precipitation of all residual brine. During XRT imaging these salt crystals have dissolved again. As the microstructure of these pores will very likely differ from field values, we do not analyse it here. We regard it as unlikely, that this hysteresis of disconnected pores has affected the networks of connected pores.

We finally note that the small in sit temperature range made this study logistically easier as if the ice had been sampled during a cold period.

Second, loss of brine only would increase the solid fraction if replaced by freezing seawater. In our case, loss of brine simply results in air-filled open channels, that are not distinguished from channels emptied during centrifuging. They are identified as open, in sit filled with brine, and contribute to permeability in our simulations. However, we add a note about the relevance of drained brine in the description of the centrifuge procedure: L103 **The centrifuged brine mass on which the effective porosity is based also includes brine that has leaked from the sample during storage, prior to centrifuging. In our study this pre-drained brine volume was not negligible and contributed on average 28% of the total (leaked and centrifuged) brine volume. On the one hand this value may be an overestimate, as it could include small ice particles that fell into the cup during sampling. On the other hand, there is very likely some brine lost during coring and cutting, which will underestimate the centrifuge-based effective porosity. Both effects imply a difference between CT-based and centrifuge based estimated of effective porosity that we cannot resolve with our data.**

Third, we clarify the information about the centrifuging procedure.
L89 **The centrifuge parameters depend on centrifuge type and were carefully chosen on the basis of several tests. (i) Ice samples were centrifuged with temperature loggers to determine temperature stability. Slight warming of the centrifuge was observed, leading us to the choice of an in initial centrifuge temperature 1K below the ice in-situ temperature. A similar value was chosen by Weissenberger et al. (1992) similar centrifuge times. (ii) Varying the centrifuging time from 10 to 20 minutes showed that more than 95% of brine where extracted during the first ten minutes, and we selected 15 minutes. (iii) Freitag (1999) noted that incomplete centrifugation of brine might lead to brine remnants which, after cooling and freezing, might block pores and decrease the permeability. We have indeed found such a result in an earlier study with centrifuge acceleration of 15 g (Buettner, 2011) and thus tested the effect of relative centrifuge acceleration for three ice cores at 10, 25 and 40 g. The result was on average 20% less centrifuged brine at 10 g, but only a slight non-significant 5% difference between 25 and 40 g. We thus are confident that 40 g is a proper choice for extracting the connected brine.**

2.2 Porosity threshold ϕ_c:

The experimental evidence provides very strong evidence that sea ice is permeable beneath the often-cited threshold of$\phi_c = 0.05$. However, the evidence in support of $\phi_c = 0.024$ is very much weaker. As an example, figure 6 and the text that discusses shows several samples beneath this critical threshold (to the left of the dashed red line). I'm not convinced *it makes sense to extend the dashed red line outside of the data range, especially in panel b). I think the text should be altered to discuss this threshold more tentatively, perhaps arguing instead that any threshold must be smaller than about 0.024 (see also final point).*

Answer:

We agree that the optimal threshold porosity $\phi_c = 0.024$ cannot be deduced from the CT measurements alone as these data are scattered, and the CT samples are $1/50$ in volume of the centrifuged samples (L266-269). However, the evidence based on the larger centrifuged samples is much stronger. We base our confidence on the the power law fit of the centrifuged porosity in Figure 4a (critical exponent $\beta = 0.832$) and its consistency with the theoretical critical exponent from direct percolation. We are stating more carefully that, if the sea ice pore space can be characterised by directed percolation (with a theoretical critical exponent $\beta \sim 0.82$) then the centrifuge experiments are consistent with a threshold in the range $0.020 < \phi_c = 0.029$. We have now determined these wider confidence bounds as described in 3.2.1:

L245 **For the critical ϕ_c we obtain confidence bounds by using $0.803 < \beta < 0.861$ and $\phi_c = 0.0240$ as input to a power law regression, which in turn resulted in 95% bound range of $0.20 < \phi_c < 0.29$.**

We add the following to beginning of 4.5:

L513 **The present analysis has enabled us to deduce a porosity threshold of $2.0 < \phi_c < 2.9\%$. This optimal threshold cannot be deduced from the CT measurements alone as these data are scattered, and the CT samples are 1/50 in volume of the centrifuged samples. However, the evidence based on the larger centrifuged samples is much stronger. Our confidence is related to the power law fit of the centrifuged porosity in Figure 4 (critical exponent $\beta = 0.83 \pm 0.03$) and its consistency with the theoretical critical exponent from directed percolation (critical exponent $\beta = 0.82$). Based on this agreement we can state that, if our hypothesis is correct, that the pore space evolution of sea ice follows the behaviour of *directed percolation*, then this implies a threshold porosity for percolation in the range 2 to 3 %. The CT-based microstructure analysis supports these results, and further can be interpreted in the way, that the threshold is related to the necking or close-off of pores at a critical diameter of 0.07 mm. Our deduced porosity threshold is just half of the value of $\phi_c = 5\%$ once proposed by Golden et al. (1998), that since then has been confirmed in other studies and become the mostly accepted threshold for sea ice permeability and desalination (Weeks, 2010). In the following we discuss these studies in the context of our results.**

We have modified the abstract to make clearer, that the threshold is based on the combination of centrifuge experiment and 3D imaging. We finally note that we recently submitted a manuscript on X-ray tomography of another sea ice core set (M. L. Salomon, S. Maus and C. Petrich, 'An Investigation of the Microstructure Evolution of Young Sea Ice from a Svalbard Fjord', submitted to the Journal of Glaciology, March 2021). The latter focuses on higher porosities, with few data points near the threshold, but the latter are consistent with the present study.

2.3 Texture and porosity threshold:

I think it remains an outstanding physical question whether a porosity threshold should *be expected at all. I am more familiar with this discussion in the context of partially molten mantle rocks. For a period in the 1990s, the dominant view was that there was a porosity threshold (e.g. Faul, 1997, JGR). But the general view today (partly as a result of experimental improvements) is that there is no such threshold. If the sample is at textural equilibrium, then the texture is controlled by the ratio of surface energy, often expressed as a dihedral angle. If this angle is beneath 60°, the melt network remains connected to arbitrarily small porosities (Rudge, 2018, Proc. Roy. Soc., building on, e.g. von Bargen and Waff , 1986, JGR). The present study pushes the porosity threshold smaller than that suggested by previous studies, but perhaps rather close to the imaging threshold (see Table 3). Therefore, I would suggest that the conclusions/abstract should be more tentative. I would also expand section 4.5 to discuss the relationship further the relationship between texture and a threshold, building on the good discussion suggesting that the microstructure is controlled by morphological instabilities during ice growth rather than surface energy (in section 4.3). It would be good to see a bit more evidence for this claim and to consider whether the validity of this statement might evolve over time? .*

Answer:

We agree that the conclusions/abstract in terms of the porosity threshold should be more tentative. We have rewritten and extended 4.5. for the porosity threshold and added a section 4.6., where we clarify the need to distinguish between granular and columnar ice texture, young and old ice and local and full-thickness permeability, and discuss (requested by the second reviewer) scale effects. We point out that our results only apply to columnar young sea ice, and add figure 10 and its description in 3.4 to make the overall pore size distribution of our ice more clear. However, many of the studies that had led to the conjecture of ϕ_c 5% were studies of young ice, and our general conclusion to revise this threshold remain the same.

Description of figure 10 in subsection 3.4:

L320 **Average pore size distributions of our data are shown in Figure 10, emphasizing the pore size change during cooling. The left hand figure shows results for open brine pores. The distribution for the two warmest cores with temperature -2 to -4 °C in Figure 1 is shown with red bars, the distribution for the two coldest cores with temperatures -6 to -10 °C with blue bars. The corresponding cumulative distributions are shown as dashed (warm) and dotted (cold) lines. The left y-axis refers to the bars and gives the fraction of open pores in each size class, while the right hand y-axis refers to the cumulative fraction. it is seen that, for the warm and cold sample populations, more than 95% of the pores have a diameter of less than 1 mm. Relative changes due to temperature are largest below 0.4 mm. The median of the open pore diameter, given by the fraction 0.5 in the cumulative distribution, changes from 0.20 mm for the warm ice to 0.16 mm for the cold ice. Note that the distribution for both warm and cold ice has two modes, one near 0.15 mm and another one near 0.10 mm. The throat size distribution, is similar to the open brine pore distribution with slightly smaller median values of 0.14 mm and 0.10 mm for the warm and cold ice cores, and modes near 0.14 ad 0.08 mm.**

The rewritten and extended subsection 4.5 for the Porosity threshold:

L513 **The present analysis has enabled us to deduce a porosity threshold of**

$2.0 < \phi_c < 2.9\%$. This optimal threshold porosity cannot be deduced from the CT measurements alone as these data are scattered, and the CT samples are 1/50 in volume of the centrifuged samples. However, the evidence based on the larger centrifuged samples is much stronger. Our confidence is related to the power law fit of the centrifuged porosity in Figure 4 (critical exponent $\beta = 0.83 \pm 0.03$) and its consistency with the theoretical critical exponent from directed percolation (critical exponent $\beta = 0.82$). Based on this agreement we can state that, if our hypothesis is correct, that the pore space evolution of sea ice follows the behaviour of *directed percolation*, then this implies a threshold porosity for percolation in the range 2 to 3 %. The CT-based microstructure analysis supports these results, and further can be interpreted in the way, that the threshold is related to the necking or close-off of pores at a critical diameter of 0.07 mm. Our deduced porosity threshold is just half of the value of $\phi_c = 5\%$ once proposed by Golden et al. (1998), that since then has been confirmed in other studies and become the mostly accepted threshold for sea ice permeability and desalination (Weeks, 2010). In the following we discuss these studies in the context of our results.

The first proposal of a critical brine porosity and permeability of sea ice was once published by Golden et al. (1998). These authors proposed that observations and modelling indicated that sea ice typically becomes impermeable when its salinity is 5 ppt, its temperature -5°C, and its brine porosity 5%, which is now known as the 'rule of the fives'. To support this hypothesis the authors used a percolation approach based on the compressed powder analogy, where the threshold depends on the ratio of critical brine inclusion to ice crystal thickness scales. The experimental evidence was based on the experiments from Ono and Kasai (1985) discussed above, for which Golden et al. (1998) proposed a porosity threshold of 5% associated with a temperature -5 °C. However, on the one hand the model is simplistic and not backed up by detailed microstructure observations. On the one hand, our analysis above indicates that the experiments from Ono and Kasai (1985) were likely far away from a porosity of $\phi \approx 5\%$ and can not validate the behaviour near that porosity. Also, there is reason to believe that the ice salinity has changed during these experiments, making the results difficult to interpret. Due to these considerations, and comparison to our simulations in Figure 12, we think that the data points from Ono and Kasai (1985) can hardly be associated with a percolation threshold.

An earlier proposal of a critical brine porosity $\phi_c = 5\%$ has once been suggested by Cox and Weeks (1988), based on observations of observed salt fluxes from sea ice (Cox and Weeks, 1975). The data has been later analysed in more detail by Petrich et al. (2006), coming to the conclusion that sea ice permeability limited to brine porosities above $\phi_c \approx 5.4\%$. However, there is a general problem with this argument: It is not the vertical permeability that has been observed by Cox and Weeks (1988), but the desalination of the ice. The latter however depends on other factors, like the brine salinity gradient in the ice and as well as the horizontal permeability to drive internal flow. The analysis may thus be interpreted to represent a porosity threshold at which convection sets in, rather than at which the ice becomes impermeable.

The most stringent approach to estimate ϕ_c was proposed by Pringle et al. (2009), based on the first 3D analysis of CT images. These authors focused on the vertical connectivity ϕ_{zz} and investigated its scale dependence to estimate the connectivity threshold based on assumptions from isotropic percolation theory (Stauffer and Aharony, 1992). They investigated artificial sea ice images, cubic and with side lengths 2 to 7 mm. From the scale dependence of ϕ_{zz} they deduced a critical value of $\phi_c = 4.6 \pm 0.7$ % for the vertical percolation threshold. This result thus seemed to support the earlier work and 'rule of the fives'. However, in view of the present study and in particular the throat size threshold, also this result may need some revision. The critical aspect is that the detectability of pores was likely limited to widths of 83μm (Nyquist criterion of two times the voxel size). In our study, with a 36μm Nyquist criterion, we are observing larger scatter in connectivity and pore scales, when the porosity threshold is approached. We thus suppose that such problem may have influenced the percolation behaviour of the samples from Pringle et al. (2009) at two times coarser resolution. E.g., considering our deduced critical throat size of 70μm, a similar value would not have been resolved by imagery with a 83μm Nyquist criterion. A simplistic quantitative argument may be obtained by looking at Figures 10b for the throat size D_{thr} and 10d for the maximum path diameter D_{thr}. We can ask at which porosity the lowest observed median throat sizes drop below 83μm, which indeed happens in the range $5 < \phi < 6$ %. Finally, though likely of minor importance, the results from Pringle et al. (2009) can be expected to change if critical exponents for directed rather than isotropic percolation, supported by the present study, would have been used in the derivation.

In summary, we interpret the earlier work as follows. The proposal of the 'rule of the fives' by Golden et al. (1998) was based on permeability measurements in young ice (Ono and Kasai, 1985). As this ice likely had an initial porosity much larger than 5%, and the data are difficult to interpret, their analysis cannot provide evidence for a 5% percolation threshold. Results from a CT-image based study by Pringle et al. (2009) in support of ϕ_c of 5% may have been resolution limited (in view of the present higher resolution results). An indirect approach by Petrich et al. (2006) using desalination data from Cox and Weeks (1975) also indicated a 5% threshold, yet the latter strictly only applies to the driving force of internal convection, not to permeability itself. Hence, many studies and datasets of young sea ice that have been proposed earlier in favour of a 5% porosity threshold seem to require a revision, while our confident threshold range of 2 to 3% from centrifuging is a factor of 2 lower. We finally add a note on the question if the true threshold porosity might be even smaller, and was limited by our centrifuge acceleration of 40g. As discussed in connection with equation 4, we estimated that our settings should be valid to retrieve permeabilities as low as 10^{-14} m^2. Hence, though we may have missed lower values, our overall data are consistent with percolation theory and the here proposed porosity threshold.

The novel sub-section in the discussion :

4.6. Other ice types and growth conditions **The discussion of earlier work, and the** present results apply to the permeability of young columnar sea ice during its growth phase, at a stage when mostly primary brine channels and pores exist. Here we discuss possible implications for other ice types, age, thickness, and scale effects. We consider four aspects to be most relevant to generalize our results. These are dependence of permeability on (i) ice growth velocity, (ii) ice type/texture, (iii) ice age and (iv) scale effects due to full thickness finite sample sizes. The first three aspects are related to natural variability in growth conditions and thermal history. The fourth aspect is related to the process to be investigated (e.g. full depth permeability for surface flooding versus near-bottom permeability for desalination/internal convection). It also relates to the question, if tested samples are representative volume elements for the process and represent sea ice macrostructure.

(i) Our range of $2-3\%$ for ϕ_c is valid for young ice that has grown at moderate growth rates (2-5 cm/day for both our and Freitags experiments). We conjecture that this threshold is not a constant for sea ice but depends on growth conditions. The basic argument is that, if the critical length scale for necking of throats controls the transition, the critical brine volume ϕ_c may be expected to simply scale inversely with the spacing of these throats. Assuming that this spacing is proportional to the basic brine layer or plate spacing a_0, one would expect that $\phi_c \sim a_0^{-1}$, implying that the percolation threshold in slower growing ice (with larger a_0) should be smaller. This effect may potentially also explain differences between our results and other studies discussed above, yet would require more data to be proven.

(ii) Sea ice may grow as columnar or granular ice, and the latter ice type often prevails at the surface or the upper centimetres. In our ice cores the upper two samples were granular and these have been excluded from the present pore scale analysis of columnar ice. In Figure 13 we also show results for these granular samples. The number of data points is limited yet seem to indicate a higher porosity threshold. While the small number of granular samples are insufficient for a statistical significant conclusion (contrasting the large number of columnar samples), the larger porosity thresholds reported by Golden et al. (1998) for surface flooding and full depth percolation may be viewed in this context.

(iii) During aging and thermal cycling, sea ice develops wide secondary brine channels systems (Weeks, 2010). These larger pores will then control the permeability that can be orders of magnitude larger. In our young ice there are some wider channels, leading to samples with 1-2 orders of magnitude larger permeability. However, as shown in Figure 10, the majority of the samples is lacking such wider secondary channels, and the permeability is controlled by the primary network. There is in general a lack in data on permeability and pore sizes as well as the the porosity threshold of older sea ice (Freitag, 1999; Freitag and Eicken, 2003; Golden et al., 2007). E.g., sack-hole measurements of permeability reported by Golden et al. (2007) show considerable scatter. It will be a future challenge to determine how secondary channels evolve in time and space, and how this depends on fluid flow and permeability within the finer primary pores.

(iv) Scale effects are related to the question: Which is the length scale of

internal fluid flow for which we need to know the effective permeability? In Figure 11 and 12 we have presented our permeability results for samples of vertical extension 5.5 mm. These indicate a scale effect due to finite sample sizes visible in the sample to sample variation of permeability. The reason for this variation is that the frequency of wider brine channels is too low to be presented in all our samples. However, due to the large dataset, and the constraints on ϕ_c from the centrifuge-experiments, this effect of finite samples sizes is not critical for our results. In Figure 13 (new) we further compare these results to (harmonic) mean permeabilities of 3-5 sub-samples, corresponding to sample heights of 17-28 mm, and do not find a significant difference in the permeability-porosity relationship. We thus believe that our volumes have been sufficiently large to be interpreted as representative volume elements for young sea ice, also when comparing them to only moderate finite size effects in connectivity reported by Pringle et al. (2009) for 2 to 7 mm sample sizes. The present results should thus be relevant for convection and desalination modelling in the near-bottom regime and skeletal layer of sea ice. Processes like surface flooding and melt pond drainage would depend on the full depth permeability, and thus depend on the lowest local permeability values. This again raises the question, if the percolation threshold of granular ice is given by a higher brine porosity. There is a need for more data.

With regard to morphological stability and future needs and options we add at the end of 4.3.: L452 **Due to these factors it seems more likely that morphological freezing instabilities in supercooled brine layers play a role for the necking, in the similar way as they do for the plate or brine layer spacing at the ice-water interface (Wettlaufer, 1992; Maus, 2020). A concise physical explanation for the necking phenomenon is lacking so far. Progress could be made by direct observations of the 3D pore space evolution by X-ray tomography, building on 2D visual observations of pore necking described by Niedrauer and Martin (1979) for a thin growth cell. Such an approach may be feasible through fast time-lapse synchrotron-based X-ray tomography for low contrast materials (Beckmann et al., 2007; Buffiere et al., 2010, e.g.,). Also conventional laboratory-based XRT with higher spatio-temporal resolution may provide new insight into the details of necking and pore instabilities.**

2.4 Specific comments and technical corrections

4. L38-46: This paragraph made me wonder whether it would be worth comparing this approach to laboratory permeameter measurements in future?

We are adding the following suggestion for future work in the conclusions:

L574 **The present work presents new insight into the sea ice pore space evolution of young sea ice and theoretical interpretation of the latter. It demonstrates the large potential of 3D X-ray micro-tomographic imaging to make progress in our fundamental understanding of sea ice properties. For future work we suggest several directions to make further progress. First of all, the result for permeability-porosity relations and thresholds, are not directly transferable to the thicker, older and warmer summer ice. The latter often contains coarser secondary brine channels that are lacking in young ice and**

that are relevant for processes melt pond percolation and melt pond albedo feedbacks (Freitag and Eicken, 2003; Polashenski et al., 2017). This reflects one of the challenges in sea ice physics, which is to improve our understanding how the sea ice pore space, as well as permeability and other physical properties evolve over time. To make progress more 3D CT data of sea ice and its pore space evolution over time are needed. Second, while the present study may be seen as a starting point to a concise understanding and modelling of this evolution, it should be verified with higher spatial resolution to clarify any resolution limit with respect to necking and porosity thresholds. Third, there is a need for comparing granular and columnar ice, as the granular surface layer will be important for the through-flow permeability. And last but not least, due to the lack in experimental data, carefully controlled laboratory experiments in the lines of Ono and Kasai (1985) would be of high value. Combing such experiments with repeated CT imaging to monitor flow-induced microstructure changes, could provide valuable insight about the evolution of the sea ice pore space and its permeability. A useful concept with centrifuged sea ice would be measurements of kerosine permeability in a permeameter (Saito and Ono, 1978; Saeki et al., 1986), allowing validation of permeability computed from CT imagery and the question if there are sub-resolution pathways.

Also a slight change to the conclusions was made for clarifying our technique:

L571 **The connected and open air fractions are deduced by XRT image analysis, and the connected air is associated with connected brine. The approach also considerably increases the image quality, as XRT imaging of brine networks at high temperatures suffers from contrast limitation between ice and brine (Pringle et al., 2009; Bartels-Rausch et al., 2014).**

5. *L52: 'not shown' is a typo?*

Ok, removed.

6. *L58: given the effort made to transport the samples rapidly, was any estimate made of the temperature change the samples might have experienced during the time*

See next comment.

7. *L60: consider noting that if samples were collected at a colder period, there would be a substantial it situ temperature gradient even across a 3.5 cm sample. This procedure would need adapting for a colder collection period.*

We added, in addition to the novel subsection 2.5., the following:

L59 **For the given field conditions the temperature change that samples may have experienced during this transport might be a few tens of a Kelvin (see below in section 2.5). We note that less isothermal ice would have required a more advanced temperature control of the different levels in the ice.**

8. *L63: I didn't have a clear sense as to why the samples were collected in an usually warm period? This should be explained at some point (perhaps it was not by design?) Does it limit the relevance of the results?*

We add:

L54 **The insulation through the snow cover resulted, in spite of air temperatures varying by 7 K during the sampling period, in only minor ice temperature changes over 5 days, and a temperature range of less than 1 K over 35 cm thickness. While originally sampling of ice at different temperatures was planned, the stable temperature turned out as an advantage for temperature control, and allowed to harvest and analyse ice cores of very similar salinity and structure, and rather to perform a controlled cooling sequence in the laboratory.**

9. L81: I would make it clearer that the stated accuracy is an analytical or measurement accuracy. The sample treatment errors might be larger.
We add the word L81 **measurement** to accuracy:

10. L96: What is ϕ_b?
Should be ϕ_b, changed.

11. L108 (footnote): Do these approaches agree?
We add:
L108 **We tested also this approach and only found relative differences of a few percent.**

12. L145: I think this part should be explained more clearly. Ordinarily, the term 'hydrostatic pressure' refers to the part of the pressure that does not drive fluid flow.
We remove 'hydrostatic' and keep the formulation, as we have referred to porous media textbooks

13. L155-156: sentence structure could be clearer (perhaps missing a comma or split into two sentences).

We reformulate:
L155 **In ice samples with a lower permeability than that value, one can expect incomplete removal of brine. Upon cooling this brine will partially freeze and may render the sample impermeable.**

14. L187: I think this makes sense, but perhaps explain the rationale for neglecting solid salts.
We add:
L187 **Including solid salts in the calculations would decrease brine volume fractions at the lower end of our porosity range by 0.1-0.2 % (Cox and Weeks, 1983, see), and have little effect on our results.**

15. L213: typo/referencing issue.
Corrected.

16. L226: another occasion when the unusually temperature could be mentioned.
We add:
L227 **Note that, due to a 10 cm snow cover, the ice temperature from the other two sampling dates, two days earlier and later, was very similar**.

17. Fig 4(b): figure quality is very poor (hard to read).

Lines and font have been adjusted. We added also in the caption:
Caption Fig. 7 **Optimum exponent β in dependence on porosity threshold ϕ_c and the R^2 of double-logarithmic least square fits of ϕ_{cen} versus $(\phi - \phi_c)^\beta$. The point of maximum correlation is shown as a star.**

18. Fig 7 (and 9 and 10): I found the legend confusing (e.g. what does (5) mean?)
We checked that in all Figures the shown curves and legends are properly described. The following should explain the legend better:
Caption Fig. 7 **Two log-log fits are drawn and specified in the legend, corresponding to power laws of the form $K = a(\phi)^b$ (green curve), and $K = a(\phi - \phi_c)^b$ as red curve. The numbers in brackets are the uncertainties in the last decimal of the log-log least square fit.**

19. Fig 11: Consider explaining what 'upward' and 'downward' mean in the figure caption (or refer readers to the main text).
We extend the figure caption to:
Caption Fig. 11 **Relationship of simulated vertical permeability K and $(\phi - \phi_c)$ as shown in Figure 7 as red dashed curve, here compared to two earlier investigations. As the measurements from Freitag (1999) are only available in terms of ϕ_{cent}, we plot the least square fit from Freitag (cyan curve, numbers given in the legend). The data points from Ono and Kasai (1985) represent downward and upward permeation of brine through the ice - see text for more information.**

20. L298: Perhaps clearer to say a factor of 100? Or 'two orders of magnitude'?
We correct to 'two orders of magnitude'.

21. L371: Consider adding a reference for the 5 % here.
References added (the same ones as given in other parts of the paper).

22. L414: inconsistent italicisation of D and L.
Corrected.

23. L424: missing space
Corrected.

24. L505: Consider adding a citation of Wettlaufer, J.S., Worster, M.G. and Huppert, H.E. 1997; The phase evolution of young sea ice; Geophysical Research Letters
These authors indeed discussed a permeability function and we add this reference.

25. L577: I'm not sure of the practicalities but it would be good to make the data available as soon as possible. https://wiki.pangaea.de/wiki/Data-submission seems to suggest that you could have 20 files each up to 100 MB here which might be suitable?
The raw data files have a total size of over 670 GigaBytes. However, we are going to publish the cropped files (170 Gigabytes), on which the present analysis is based, in the open NIRD research data archive. This is under processing and the DOI will be added in the revised manuscript.

References

Bartels-Rausch, T., Jacobi, H.-W., Kahan, T. F., Thomas, J. L., Thomson, E. S., Abbatt, J. P. D., Ammann, M., Blackford, J. R., Bluhm, H., Boxe, C., Domine, F., Frey, M. M., Gladich, I., Guzmán, M. I., Heger, D., Huthwelker, T., Klán, P., Kuhs, W. F., Kuo, M. H., Maus, S., Moussa, S. G., McNeill, V. F., Newberg, J. T., Pettersson, J. B. C., Roeselová, M., Sodeau, J. R., 2014. A review of air-ice chemical and physical interactions (aici): liquids, quasi-liquids, and solids in snow. Atmospheric Chemistry and Physics 14 (11), 1–47.
URL `www.atmos-chem-phys.net/14/1/2014/`

Beckmann, F., Grupp, R., Haibel, A., Huppmann, M., Nöthe, M., Pyzalla, A., Reimers, W., Schreyer, A., Zettler, R., 2007. In-situ synchrotron x-ray microtomography studies of microstructure and damage evolution in engineering materials. Adv. Engin. Mater. 9 (11), 939–950.

Buettner, J., February 2011. Permeability of young sea ice from microtomographic images. Master's thesis, University Bergen, 107 pp.

Buffiere, J., Maire, E., Adrien, J., Masse, J., Boller, E., 2010. In situ experiments with X-ray tomography: an attractive tool for experimental mechanics. Exper. Mechan. 50, 289–305.

Cox, G. F. N., Weeks, W. F., 1975. Brine drainage and initial salt entrapment in sodium chloride ice. Research Report 345, U.S. Army Cold Regions Research and Engineering Laboratory, this research report consists of the dr.-philos. thesis *Brine drainage in sodium chloride ice* (1974) by G. F. N. Cox, Dartsmouth College, 179 pp.

Cox, G. F. N., Weeks, W. F., 1983. Equations for determining the gas and brine volumes of sea ice samples during sampling and storage. J. Glaciol. 32, 371–375.

Cox, G. F. N., Weeks, W. F., 1988. Numerical simulations of the profile properties of undeformed first-year ice during the growth season. J. Geophys. Res. 93 (C10), 12449–12460.

Freitag, J., 1999. Untersuchungen zur Hydrologie des arktischen Meereises - Konsequenzen für den Stofftransport. Ph.D. thesis, Universität Bremen, ber. z. Polarforsch., Bd. 325, 1999.

Freitag, J., Eicken, H., 2003. Meltwater circulation and permeability of Arctic summer sea ice derived from hydrological field experiments. J. Glaciol. 49, 349–358.

Golden, K. M., Ackley, S. F., Lytle, V. I., 1998. The percolation phase transition in sea ice. Science 282, 2238–2241.

Golden, K. M., Heaton, H. E. A., Miner, J., Pringle, D. J., Zhu, J., 2007. Thermal evolution of permeability and microstructure in sea ice. Geophys. Res. Lett. 34, L16501.

Maus, S., May 2020 2020. Microstructure and solutal boundary layer at the sea ice - ocean interface. EGU General Assembly 2020, Online, 4-8 May 2020, eGU2020-6039.

Niedrauer, T. M., Martin, S., 1979. An experimental study of brine drainage and convection in young sea ice. J. Geophys. Res. 84 (C3), 1176–1186.

Ono, N., Kasai, T., 1985. Surface layer salinity of young sea ice. Ann. Glaciol. 6, 298–299.

Petrich, C., Langhorne, P. J., Sun, Z. F., 2006. Modelling the interrelationships between permeability, effective porosity and total porosity in sea ice. Cold Reg. Sci. Techn. 44, 131–144.

Polashenski, C., Golden, K., Perovich, D. K., Skyllingstad, E., Arnsten, A., C.Stwertka, Wright, N., 2017. Percolation blockage: A process that enables melt pond formation on first year arctic sea ice. Journal of Geophysical Research: Oceans 122 (1), 413–440.

Pringle, D. J., Miner, J. E., Eicken, H., Golden, K. M., 2009. Pore space percolation in sea ice single crystals. J. Geophys. Res. 114.

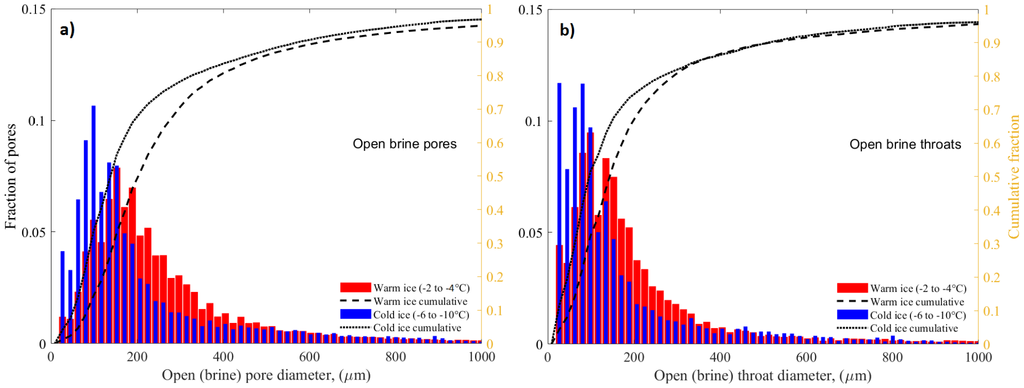

Figure 1: L513 **New Figure 10** Pore size distributions based on XRT imaging of 4 young ice coresles. a) Fraction of open brine pores in 18 μm wide size bins for the two warmest (red) and two coldest (blue) cores. The corresponding cumulative fractions are also shown, with y-axis on the right hand side; b) same as a) but for the porosimetry/ fraction of pores throats.

Saeki, H., Takeuchi, T., Sakai, M., Suenaga, E., 1986. Experimental study on the permeability coefficient of sea ice. In: T.K.S. Murthy, J. C., C.A.Brebia (Eds.), Ice Technology, Proceedings: 1st International Conference. Springer-Verlag, New York, pp. 237–246.

Saito, T., Ono, N., 1978. Percolation of sea ice. I: Measurement of kerosine permeability of nacl ice. Low Temp. Sci. A37, 55–62.

Stauffer, D., Aharony, A., 1992. Introduction to Percolation Theory, 2nd Edition. Taylor & Francis.

Weeks, W. F., 2010. On Sea Ice. University of Alaska Press.

Weissenberger, J., Dieckmann, G., Gradinger, R., Spindler, M., 1992. Sea ice: A cast technique to examine and analyze brine pockets and channel structure. Limnol. Ocean. 37 (1), 179–183.

Wettlaufer, J. S., 1992. Directional solidification of salt water: deep and shallow cells. Europhysics Letters 19 (4), 337–342.

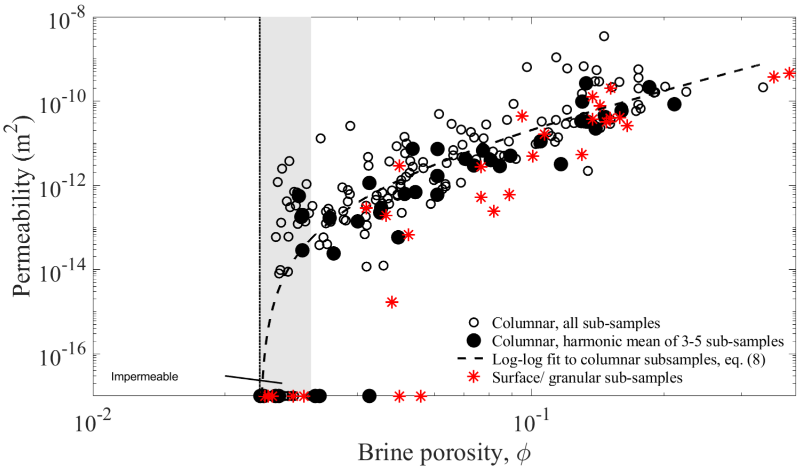

Figure 2: **New Figure 13** Comparison of simulated vertical permeability K and $(\phi - \phi_c)$ for columnar samples (as shown in Figure **??** and here as open circles) to two other simulation results. The solid circles are harmonic means of all subsamples (normally four to five) from each basic sample cut in the field (and centrifuged). The red stars are permeability results for near-surface samples (up to 5 cm from the surface) that were classified as granular ice and thus excluded from the basic analysis.