Sea Ice Permeability Measurements and the Effect of Granular Sea Ice

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Abstract

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1 Introduction

In the Arctic and Antarctic regions, sea ice plays an important role in the ecosystem and climate. Year round, sea ice provides a habitat for microorganisms. Beginning in the springtime, in particular, sea ice provides a habitat for large algal communities that are a base for the rich foodwebs in the polar regions. When present, sea ice also largely controls the exchange of heat and gases between the atmosphere and ocean, serving as both an indicator and facilitator of climate change. Critical to the dynamics of the biological and geophysical processes is the porous composite microstructure of sea ice, which consists primarily of brine inclusions, pure ice, air pockets, and solid salt deposits. Evaluating the permeability k^* of sea ice is necessary to understand and predict the behavior of sea ice in the environment. The permeability k^* controls the bulk flow of both fluid and to a lesser extent heat through the ice and depends primarily on the brine volume fraction ϕ and the microstructure of the ice. Fluid transport in sea ice controls many important phenomenons. This includes the flooding-freezing cycle associated with snow ice formation. The formation and quantity of snow ice can dramatically affect thickness estimates and the permeability k^* is a necessary parameter when evaluating its impact. The thermal conductivity of sea ice is also affected by fluid transport in the sea ice, largely due to the advection component that becomes much more pervasive than the diffusive component. Freezing, melting, and draining highly correlate with the fluid transport of sea ice, often associated with the creation fresh water layers in the upper ocean and dense bottom current caused by brine drainage. Nutrient replenishment in sea ice is directly affected by the permeability of the sea ice and significant explosions in algae population are observed when the ice becomes permeable. In the summer of 2007, an unprecedented amount of melting occurred and summer sea ice extent reached an all time minimum in the Artic, perhaps indicating an accelerated amount of warming in the region. Instead of being reflected back into space, the absence of sea ice lowered the albedo in the region allowed more solar radiation to be absorbed by the Arctic Ocean, further warming the upper ocean and creating a positive feedback loop. In addition to the absence of sea ice, melt ponds on the surface of the sea ice can also significantly change the albedo constant, which are also controlled by the permeability of the sea ice. Thus, climate change algorithms should begin considering

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the permeability $k(\phi)$ of sea ice, due to the effect this parameter has on melt pond evolution and thus the impact on the albedo levels in the regions.

Columnar sea ice has been long observed to be permeable for fluid transport when $\phi > 5\%$ and impermeable for fluid transport when $\phi < 5\%$. The brine volume fraction of sea ice can be determined through a well-known formula that is obtained from the bulk salinity of the sea ice and the temperature of the sea ice. A brine volume fraction of 5% corresponding to a bulk salinity of 5ppt and a temperature of -5^oC has become known as the rule of fives. We would like to emphasize here that it is the brine volume fraction that is critical for analyzing the permeability and not the temperature. In addition to this observed phenomena, when examining a compressed powder model for columnar sea ice, a critical brine volume fraction of 5% is found. Due to the critical nature of this 5% brine volume fraction in columnar sea ice, this value is referred to as the percolation threshold. The permeability above the percolation threshold is dictated by a universal critical exponent of $e = 2$ for columnar ice. In previous literature, the permeability $k(\phi)$ of sea ice has been assumed to have the same universal properties for all ice types. Columnar sea ice and granular sea ice form differently and have different microstructures, yet due to the dominance of columnar sea ice in the Artic, the permeability properties of granular sea ice have been, generally speaking, incorrectly assumed to have the same permeability properties of columnar sea ice. Here we address the difference between the permeability of columnar sea ice and granular sea ice, using compressed powder theory and further explore it with field data collected from Antarctic sea ice during the 2007 SIPEX cruise. Also, we suggest that the universal lattice exponent for 3D percolation models is still $e = 2$ for both columnar sea ice and granular sea ice, when using a good estimate for the percolation threshold of granular sea ice.

2 Results

Compressed powder model analysis goes here???) (Using a new computation from compressed powder methods, the percolation threshold for granular ice is projected to be somewhere between 8% and 12% brine volume fraction, depending on the size of the crystals.

For our analysis of the in situ field data collected on the 2007 SIPEX cruise, we make several assumptions. Here we consider a low Reynolds number for the flow of brine through sea ice, with viscosity η. We assume sea ice to be primarily a two component material, with brine volume fraction ϕ and ice volume fraction $1 - \phi$. In the brine, the velocity and pressure fields satisfy the Stokes equations for an incompressible fluid. If k is a permeability tensor, with vertical component k_{zz} in units of m^2, then k is defined by Darcys Law

$$v = \frac{-k\nabla p}{\eta} \quad and \quad \nabla \cdot v = 0, \tag{1}$$

where $v(x)$ and $p(x)$ are the homogenized velocity and pressure fields respectively. Fluid transport in sea ice depends on pore size distribution. If A is the lognormally distributed cross-sectional area of a brine inclusion, then $Z = \ln A$ has a normal probability density

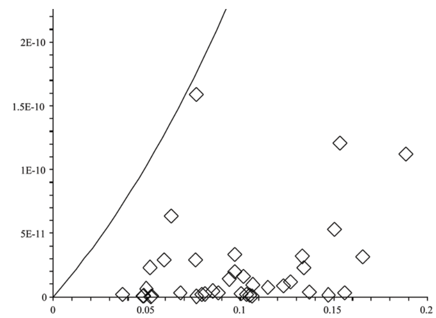

Figure 1: Comparison of in situ field data on the permeability bounds.

with mean μ and variance σ^2,

$$P(Z) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(Z-\mu)^2/2\sigma^2}. \tag{2}$$

Due to the fact that we were collecting in situ field data instead of tank grown sea ice, there was the possibility of having longer pores because of the preferred vertical orientation of brine channels. Thus, we compared our in situ field data to more general void bounds $k \leq \frac{\phi}{8}\langle R^4\rangle/\langle R^2\rangle$, which account for the possibility of larger pore channels. The brine inclusion cross sectional areas are $A = \pi R^2$ in (1). Since $\ln A^2 = 2$, the mean is 2μ and the variance is $4\sigma^2$, with resulting equation

$$k(\phi) \leq \frac{\phi}{8\pi}\langle A(\phi)\rangle e^{\sigma^2}. \tag{3}$$

Letting the variance $\sigma = 1$ and $A = a$ in the above equation, the lognormal pipe bound captures all of the in situ data in figure (1) collected on the SIPEX cruise, when using a hydrological bail test.

Vertical cylindrical holes were drilled into the sea ice and time series measurements were taken. Measuring the water level in the hole across time, knowing the freeboard of the sea ice, and applying several constants, the permeability of the ice underneath the borehole can be accurately estimated using the equation

$$h(t) = h(t_0)e^{-k_{exp}\frac{g\rho t}{gL}}, \tag{4}$$

(eiken), with hydralic head $h(t)$ (m), measured permeability k_{exp} (m^2), ice thickness beneath the borehole L (m), time t (s), density ρ (kgm^{-3}), and gravity g (ms^{-2}). Tubes were not used to seal off the horizontal component of the permeability and two further adjustments were needed to correctly isolate the vertical component of the permeability. In (Eiken) it was suggested that a reasonable ratio for the vertical flow versus the horizontal flow is 10 : 1, although ratios of 100 : 1 and 1 : 1 have also been observed. During the SIPEX cruise, no abnormal flow was observed and therefore we have used a 10 : 1 ratio in our corrections. Thus, the equation

$$k_{vert} = k_{exp}\frac{area_{vert}}{area_{vert} + 0.1area_{horz}}, \tag{5}$$

was used as a first correction to eliminate the horizontal component, where k_{vert} is the first corrected permeability. The horizontal area was calculated to be $2\pi rd$ of the borehole, where r is the radius of the borehole and d is the depth of the borehole. The depth of the borehole was calculated for all regions of the borehole where the sea ice had a brine volume fraction greater than 5%, allowing for any possible horizontal flow regardless of ice type. The vertical permeability was then adjusted to eliminate any vertical flow that did not come directly from beneath the borehole. Using a computation from (eiken)

$$k = \frac{k_{vert}}{0.3 + 3.5m^{-1}L}, \tag{6}$$

the permeability was then further adjusted to account for fluid flow only coming from directly beneath the borehole. The result of these two computations yields a vertical component correction from the raw data that is very close to the correction one would obtain when using the equation (eiken)

$$k = \frac{k_{exp}}{0.17 + 10.7m^{-1}L}, \tag{7}$$

which assumes that when using horizontal blockers, the extra pressure that would normally manifest itself as a horizontal flow, still influences the observed permeability.

Artic sea ice tends to be much more columnar and permeability theory for sea ice has primarily focused on columnar ice. However, Antarctic sea ice can be much different that Artic sea ice. There are many differences in the way that Antarctic sea ice is formed, which (source) give a rise to a much higher concentration and pervasiveness of granular sea ice throughout the entire ice column. For example, during the middle of the SIPEX cruise a large storm occurred off of the coast and a large disturbance past through the ice, causing a significant amount of rafting to occur. The rafting caused snow/granular ice, which is commonly found on the surface of the sea ice, to be present throughout the ice column. We believe this attributed to some peculiarities seen in our permeability results in figure 1. When even relatively small amounts of granular ice are present below a borehole, a smeared-out affect takes place, and the percolation threshold for the sea ice occurs at a brine volume fraction somewhere between what would normally be associated for pure columnar ice and pure granular ice. Determining the ice type directly below the borehole does little good in this senario, because a couple centimeters of granular ice anywhere between the bottom of the borehole and the open ocean could still affect the permeability of the entire ice column below the borehole. Thus, our computations that will be shown shortly, looked at the entire ice column beneath the borehole.

It was not foreseen that there would be the need for profiling the ice types at our location and it was only later realized that there may in fact be a significant difference between columnar and granular sea ice. Therefore, by using ice core profiles collected by Mats . . and Pier Delfine. ., we attempted to compute the percentage of granular ice below the permeability boreholes. It was a rare feat if the ice flows the sites were located on ever had a uniform depth, with some rare occurrences where the difference between our site and

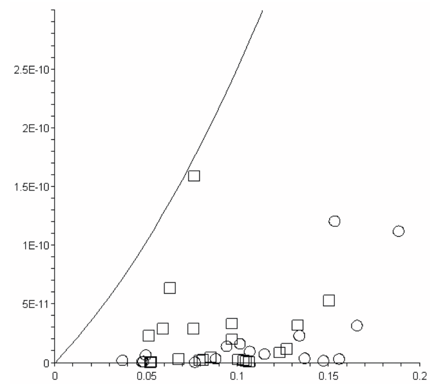

Figure 2: Comparison of in situ field data on the permeability bounds. Here ice with less than 30% granular ice are squares and ice with more than 30% granular ice are circles.

the other two sites approached more than 50 centimeters. Thus, the following interpolation method is certain to have introduced some errors in the results of our individual calculations. However, the analysis later implemented on these individual calculations was an averaging method and the individual errors produced should have minimal impact on the combined result.

The interpolation algorithm begins by scaling the depths of Mats and Piers sites to the depth of our site for each ice flow. Then the percentage of granular ice below each individual permeability borehole are calculated, one for Mats data and one for Piers data. Next, the equation below was used to form a combined result,

$$G_u = \frac{D_{um}}{D_{um} + D_{mp}} G_p + \frac{D_{up}}{D_{um} + D_{mp}} G_m, \tag{8}$$

with the combined percent of granular ice beneath our borehole G_u, the percent of granular ice beneath our borehole using only mats data G_m, the percent of granular ice beneath our borehole using only piers data G_p, the difference in depth between the ice at our site and mats D_{um}, and the difference between the ice at our site and piers D_{up}. It should be noted that in (8), a strong emphasis was given to whichever site was of most similar depth to ours, and thus thought to be of the most similar ice type. Aside from one data point, every permeability borehole was estimated to have some amount of granular ice below it. As seen in figure 2, a dramatic difference can been seen when examining the permeability boreholes for percentages of granular ice above and below 30%, although 30% is only an arbitrary amount. The permeability boreholes where the percentage of granular ice is below 30% can be thought of as primarily columnar ice, although the actual percolation threshold for this data may be greater than 5% because the small amount of granular ice still may be acting like a poison for some data points.

Assuming that the percolation threshold for the primarily columnar sea ice is 5%, the theoretical permeability line $y = (3 \cdot 10^{-8})(x - 0.05)^2$ was compared against the primarily

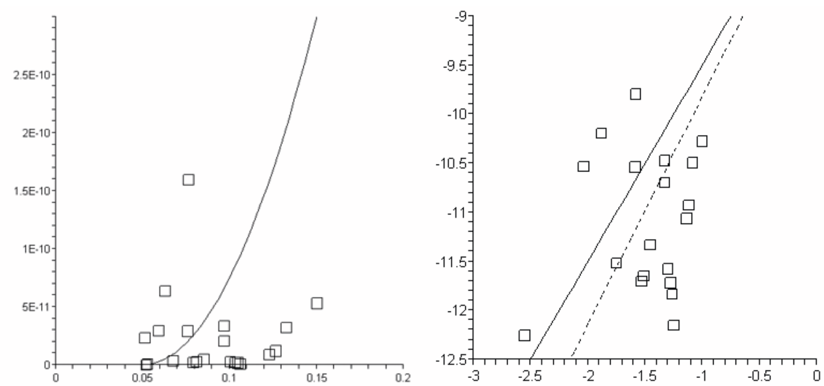

Figure 3: As seen on the left, primarily columnar sea ice permeability data with theoretical line $y = (3 \cdot 10^{-8})(x - 0.05)^2$. The best fit line is red. As seen on the right, primarily columnar sea ice permeability data lognormally scaled with solid theoretical line $y = 2x - 7.5$. The best fit line $y = 2.319290755x - 7.5$ is dashed.

columnar permeability data as seen in figure 3. Further examination of the primarily columnar permeability data found the statistically best fitting exponent to be 2.319290755, when forcing a constant value of $3 \cdot 10^{-8}$. This can be seen in the log log plot of figure 3. This is reasonably consistent with the results in (GRL).

Several permeability boreholes where the percentage of granular ice is greater than 30% still contain a significant amount of columnar sea ice. Although it appears that the granular ice becomes prevalent enough to dominant percolation after crossing this 30% regime. As stated earlier, granular sea ice may have a percolation threshold anywhere between a brine volume fraction of 8% and 12%. Thus, a percolation threshold of 10% was chosen for the analysis of the granular sea ice. When using a percolation threshold of 10% for the sea ice with granular ice content greater than 30%, the theoretical permeability line $y = (3 \cdot 10^{-8})(x - 0.10)^2$ was compared against the primarily granular permeability data as seen in figure 4. The statistically best fitting exponent was observed to be 2.100057904 when forcing a constant value of $3 \cdot 10^{-8}$. This can be seen in the log log plot of figure 4. Therefore, a conclusion may be made that the universal exponent of 2 still pertains for the percolation of both columnar and granular sea ice, although the percolation threshold must be adjusted properly.

In addition to the obvious sources of error that may be produced by the interpolation of ice type under the permeability boreholes, there are potentially several other sources of error that must be considered. The effect of having even 10% granular ice below a borehole must be taken into account. It is possible that this could significantly change the permeability, which could help explain why there appears to be so much variability in figure 3. Another source of error could come from the assumption of a low Reynolds number. In some instances, extremely warm ice was present which may have impacted the true viscosity of the brine. To the authors knowledge, a changing parameter for the Reynolds number has

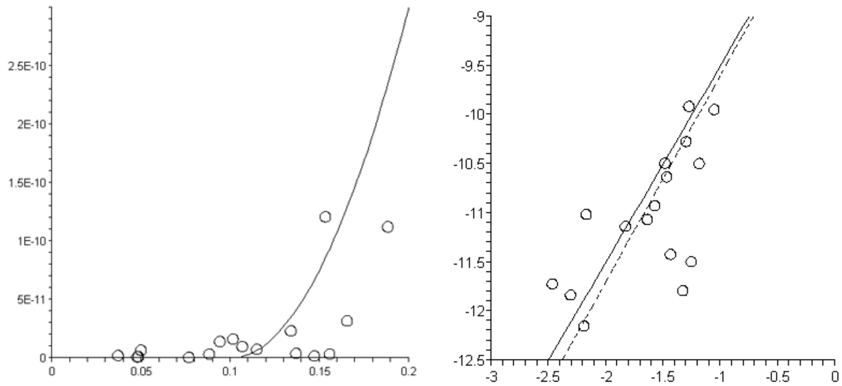

Figure 4: As seen on the left, primarily granular sea ice permeability data with theoretical line $y = (3 \cdot 10^{-8})(x - 0.1)^2$. As seen on the right, primarily granular sea ice permeability data lognormally scaled with solid theoretical line $y = 2x - 7.5$. The best fit line $y = 2.100057904x - 7.5$ is dashed.

never been considered or if it even is practical to consider. Further, all previous work on the permeability of sea ice has only been concerned with the brine volume fraction of the ice directly beneath the borehole, assuming that all ice below has a higher brine volume fraction and is not the controlling factor. Here the argument is made that granular ice anywhere in the ice column may influence the permeability of the sea ice. However, this granular ice may be in a region of the ice column that has a higher brine volume fraction and the granular ice may be permeable in this region and not be a controlling factor at all. Due to the process used to determine the brine volume fraction of the sea ice collected at the permeability site, this analysis can not be done accurately. This is because the brine volume fraction was computed every 10 cm, when the interpolated appearance of granular ice is often only over a $2 - 3$ cm scale.

3 Conclusions

Here we have shown that the true percolation threshold for granular ice could be significantly different from columnar ice and probably is between 8% and 12%. Further, in the Antarctic, where both columnar and granular sea ice are pervasive throughout the ice column, the percolation threshold can possibly be smeared out, forming a hybrid percolation threshold. Simultaneous calculations were done for the electrical transport of the sea ice at the permeability site, which may give more insight and can be found in XXXXX. However, the bottom line is that more accurate in situ field research must be done to verify or negate these findings.

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