

Geophysical Research Letters



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Title *		Electrical Signature of the Percolation Threshold in Sea Ice Change	
Running Title *		Electrical Transport in Sea Ice Change	
Abstract *		<p>Fluid flow through sea ice governs a broad range of geophysical and biological processes in the polar marine environment. For example, the evolution of melt ponds and sea ice albedo, which is important in climate modeling, is constrained by drainage through the porous brine microstructure. However, for brine volume fractions below about 5%, columnar sea ice is effectively impermeable to fluid flow. In two different experiments conducted in the Arctic and Antarctic, we have found that this critical fluid transition exhibits a strong electrical signature, with sea ice resistivity rising sharply over three orders of magnitude near the brine connectivity threshold. The data are accurately explained by percolation theory, with the same universal critical exponent which captures fluid permeability. These results enable us to connect specific electrical profiles to important transport processes such as melt pond drainage, CO2 pumping, and the flux of nutrients which sustain biomass build-up.</p> Change	
Authors *		<p>Kenneth Morgan Golden (University of Utah) (Corr)</p> <p>Hajo Eicken (University of Alaska) (Contrib #1)</p> <p>Adam Gully (University of Utah) (Contrib #2)</p> <p>Malcolm Ingham (Victoria University) (Contrib #3)</p> <p>Keleigh Ann Jones (Victoria University) (Contrib #4)</p> <p>Joyce Lin (University of Utah) (Contrib #5)</p> <p>James Reid (Groundprobe Geophysics) (Contrib #6)</p> <p>Christian Sampson (University of Utah) (Contrib #7)</p> <p>Anthony P Worby (Australian Antarctic Division and Antarctic Climate and Ecosystems Cooperative Research Center) (Contrib #8)</p>	

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Contributing Author Notification *	Type your initials to confirm that all Contributing Authors know of and concur with the submission of this manuscript. Single authors please also initial. KMG Change
Keyword(s) *	sea ice electrical conductivity rule of fives percolation threshold EM monitoring melt ponds Change
Index Terms *	0750 4465 0793 1640 0694 Change
Special Section	[Empty] Change
Subset *	Cryosphere (CRY) Change
Does your submission have auxiliary material? *	Does your manuscript have auxiliary material? If yes, upload your auxiliary material files, including a readme file. About README file
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Question 1. *Major Topic or Scientific Question *	Improving projections of the fate of sea ice and its ecosystems depends on a better understanding of key processes such as melt pond evolution, snow-ice formation, and nutrient fluxes. The results open the door to new ways of studying such processes. Change
Question 2. *New Scientific Knowledge *	The rule of fives governs sea ice transport processes. Our results provide the first observations and theory of the electrical signature of this "on-off" switch for fluid flow in sea ice, thus enabling new techniques for remotely monitoring transport. Change
Question 3. *Broad Implications *	The results impact the study of sea ice in climate, as well as gauging the effects of warming through remote sensing of ice thickness. The following communities will be impacted: polar climate, sea ice biogeochemistry, sea ice modeling, and porous media. Change
Related Manuscript	N/A [Empty] Change
Key Points *	Please state the three main points of the article. Main point #1: (80 character limit) Data on the conductivity of sea ice were taken in the Arctic and Antarctic Main point #2: (80 character limit) A strong electrical response near the brine percolation threshold is observed Main point #3: (80 character limit) The results enable remote monitoring of key processes and transitions Change
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	<p>Yes, some portion of this manuscript has been published or is under consideration for publication elsewhere. The main results of the manuscript we are submitting to GRL include the following:</p> <ol style="list-style-type: none">1. Vertical electrical resistivity data on sea ice in the Arctic and Antarctic clearly display critical behavior associated with a percolation transition in bulk electrical transport near the threshold for vertical connectivity of the brine phase.2. Through mathematical analysis relating electrical and fluid transport properties of sea ice, this transition is shown to be a strong electrical signature of the "rule of fives," which largely controls whether or not fluid can flow through sea ice.3. Percolation theory specific to the electrical conductivity problem in sea ice is developed, and agrees closely with the data from both experiments. Moreover, the same universal critical exponent of 2 which describes fluid permeability also captures the electrical conductivity, and critical path analysis is used to determine the scaling factor.4. By relating the fluid and electrical properties, we are able to electrically classify various layers in sea ice in terms of their fluid flow properties, thus connecting specific electrical signatures to important transport processes such as melt pond drainage, CO2 pumping, and nutrient fluxes.5. The method of directly measuring the vertical conductivity by extracting sea ice cores and adapting a four-probe Wenner array to measure along the core axis, which we developed in Antarctica, is presented here. Numerical analysis establishing the accuracy of the method is also briefly presented. <p>The electrical conductivity data used in this manuscript was obtained in Antarctica in late 2007 and in the Arctic in mid 2008. It wasn't until about 2010, after substantial preliminary analysis, that I (KMG) realized that our Antarctic data clearly displayed a classic percolation transition, and that it likely was the electrical signature of the rule of fives. Subsequently we also examined Malcolm Ingham's Arctic data and found almost exactly the same striking behavior. Over the next two years with students we conducted mathematical and numerical analysis leading to the above results, explaining the data theoretically and relating it to the fluid permeability. Recently Hajo Eicken conducted a related analysis leading to result 4 above.</p> <p>Given when the raw data was collected, it is not unusual that some of the data, but not the detailed analysis, theory, and conclusions that form the core of this paper, have appeared in previous, preliminary publications. For example, a brief paper by Zhu, Golden, Gully, and Sampson in Physica B in 2010 was published in the proceedings of a conference on electrical and optical transport in inhomogeneous media, and the Antarctic data was simply used to validate a network model of electrical conductivity in composites. The experimental method we developed was not discussed, and no connection to percolation theory or the results of this paper were included. Once we realized the significance of our findings, it was always intended that the current manuscript would serve as the announcement of these results. Similarly, the Arctic data taken by Ingham and colleagues (two references in this manuscript) were used to establish the cross-borehole tomography method as a viable way of non-destructively obtaining the in-situ electromagnetic properties of sea ice.</p> <p>In summary, the main results and figures presented in this manuscript have not been published or submitted for publication elsewhere. We believe that we have rigorously adhered to the condition that the submitted manuscript does NOT contain "the same basic scientific content reaching the same fundamental conclusions previously published in materially the same form."</p> <p>Change</p>
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