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## Geophysical Research Letters

AN AGU JOURNAL

2015GL064846

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Manuscript *No errors found.***Title \***Electrical Signature of the  
Percolation Threshold in Sea  
Ice[Change](#)**Running Title \***

Electrical Transport in Sea Ice

[Change](#)**Abstract \***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 processes such as melt pond formation and drainage, CO2 pumping, and the flux of nutrients which sustain biomass build-up.

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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. Our results open the door to new ways of studying such processes.

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**Question 2. \*New Scientific Knowledge \***

The rule of fives governs transport processes in sea ice. We obtain the first observations and theory of the electrical signature of this "on-off" switch for fluid flow, thus enabling new techniques for remotely monitoring transport and key transitions.

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**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.

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**Related Manuscript**

Resubmission

Manuscript of same title, submitted in May 2013.

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**Key Points \***

*Please state the three main points of the article.*

*Main point #1: (100 character limit)*

Data on the electrical conductivity of sea ice were taken in the Arctic and Antarctic.

*Main point #2: (100 character limit)*

A strong electrical response as the brine phase percolates is observed and explained theoretically.

*Main point #3: (100 character limit)*

The results enable non-destructive and remote monitoring of key sea ice processes and transitions.

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**Dual  
Publication \***

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:

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, CO<sub>2</sub> pumping, and nutrient fluxes. We explore in some detail how our findings can help study such processes and provide data which could improve climate models.

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.

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. The results in 4 are much more recent, having been obtained in the past two years.

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.



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."

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**Figure/Table Permissions \***

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**Cover Letter**

*Additional Comments:*

Dear Dr. Stroeve, We thank you for your very helpful comments on a previous, more technical version of the manuscript we are submitting here. You indicated that one option which could make the paper more suitable for GRL would be to "include much of the technical detail in a Supplement and focus more on the wider impacts in the body of the manuscript." In particular, you indicated that for a GRL version of this study, you would like to see "an expansion on the discussion on how these results will enable us to connect specific electrical profiles to important transport processes such as melt pond drainage, CO<sub>2</sub> pumping, and the flux of nutrients which sustain biomass build-up that you mention in your abstract." In the new manuscript we believe we have accomplished exactly what you suggested. Most of the more technical material has been put into a supplemental section. Moreover, the discussion has been expanded to include an examination of how our findings can help enable studies of the key processes mentioned in the abstract and provide data which could improve climate models. We believe that these changes have significantly improved the manuscript. Thank you very much for your consideration of our paper. Sincerely yours, Ken Golden

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