

# Electrical Signature of Brine Percolation in Sea Ice

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Fluid flow through sea ice mediates 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 critical to climate modeling, is constrained by drainage through the porous brine microstructure. Fluid flow also facilitates snow-ice formation, the evolution of the salt budget, and biomass build-up sustained by nutrient fluxes. However, for brine volume fractions below about 5%, columnar sea ice is effectively impermeable to fluid flow, which controls these processes. In two different experiments conducted in the Arctic and Antarctic, we have found that this critical transition in fluid flow exhibits a strong electrical signature, with sea ice resistivity sharply rising over three orders of magnitude near the brine connectivity threshold. The data are accurately explained by percolation theory, with the same universal critical exponent of 2 which captures the behavior of the fluid permeability. Our results demonstrate that classical lattice models in statistical physics can help unravel the complexity of electrical and fluid transport in this multi-scale random medium. The theory enables electrical classification of sea ice layers 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. Our findings lay the foundation for electromagnetic monitoring of transport phenomena in sea ice, which can help track key transitions in the state of polar sea ice and improve projections of its fate and impact on ecosystems.

sea ice | percolation | fluid transport | electrical transport

## Introduction

Polar sea ice is a key component of Earth's climate system, and a leading indicator of climate change [1, 2]. It also hosts extensive microbial communities which sustain life in the polar oceans [1, 3].

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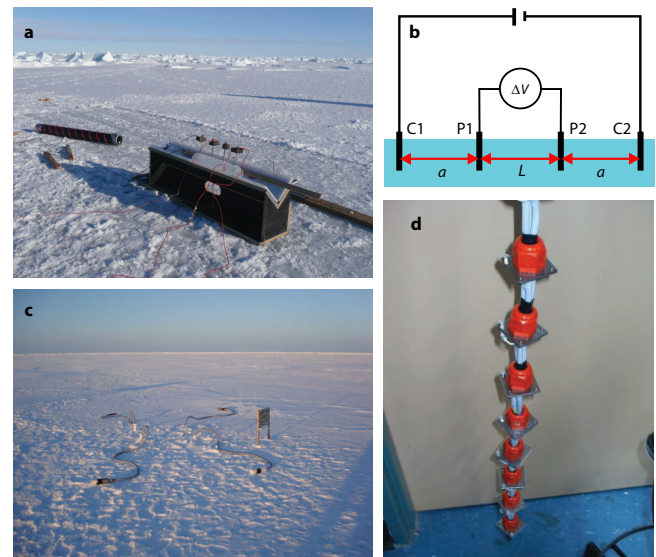
sea ice as porous medium where elec and fluid theories apply

While global climate models predict declines in sea ice area and thickness, they have significantly underestimated recent loss in Arctic summer ice extent [10].

Improving projections of the fate of Earth's sea ice cover and its importance for polar ecosystems depends on a better understanding of key processes and feedback mechanisms. For example, the evolution of melt ponds and summer ice albedo is constrained by drainage through porous sea ice [11]. It is believed that ice-albedo feedback has played a key role in the decline of summer Arctic sea ice [12]. Fluid flow through sea ice mediates the salt budget [1], convection-enhanced thermal transport [13], ocean-ice-atmosphere CO<sub>2</sub> exchanges [14], and biomass build-up sustained by nutrient fluxes [1, 3]. It also enables snow-ice formation, driven by sea water flooding and freezing at the ice surface, accounting for more than a quarter of the ice produced in the Southern Ocean [15].

It has been observed that for brine volume fractions  $\phi$  below about 5%, columnar sea ice

Polar sea ice is a key player in Earth's climate system, and a leading indicator of climate change [1, 2]. It also hosts extensive algal and bacterial communities which sustain life in the polar oceans [1, 3]. While global climate models predict declines in sea ice area and thickness, they have significantly underestimated the recent loss in Arctic summer ice extent [10]. We focus here on sea ice processes which must be better understood to represent the polar ice packs more realistically in climate models. In particular, we investigate the electrical behavior of sea ice associated with key transport phenomena and microstructural transitions.



**Fig. 1.** (a) A Wenner electrode array is configured to measure the vertical conductivity of Antarctic sea ice, by inserting the four probes into an extracted ice core. (b) A current  $I$  is injected into the core through the outer electrodes C1 and C2. The potential difference  $\Delta V$  resulting from the current flow is measured by the inner electrodes P1 and P2. The ratio  $\Delta V/I$  is the resistance  $R$  in ohms. Here the electrode spacing is  $L = 10$  cm and  $a = 10$  cm. (c) A cross-borehole array is frozen into Arctic sea ice. The DC resistivity profile was tomographically reconstructed in the volume enclosed by the electrode strings. One of the strings, with 10 cm separation of the plates, is shown in (d).

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