

The polar sea ice packs form a key component of Earth’s climate system, and are leading indicators of climate change (1,2). They also host extensive algal and bacterial communities which sustain life in the polar oceans (1,3). While global climate models predict declines in sea ice extent, they have significantly underestimated the dramatic losses observed in the Arctic (4,5). On the other hand, Antarctic sea ice has increased, along with some significant regional losses (6).

Improving projections of the fate of Earth’s ice packs and their complex 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 (7). It is believed that ice-albedo feedback has played a key role in the decline of summer Arctic sea ice (8). Fluid flow through sea ice mediates the evolution of salinity profiles (1), convection-enhanced thermal transport (9, 10), ocean-ice-atmosphere CO<sub>2</sub> exchanges (11), and biomass build-up fueled by nutrient fluxes (3, 12, 13). It also enables snow-ice formation, where sea water floods the ice surface and then freezes, accounting for more than a quarter of the ice produced in the Southern Ocean (14, 15).

It has been observed that for brine volume fractions  $\phi$  below about 5%, columnar sea ice is effectively impermeable to fluid flow, yet is increasingly permeable for  $\phi$  above 5% (16). For a typical bulk salinity of 5 ppt, this critical brine volume fraction  $\phi_c \approx 5\%$  corresponds to a critical temperature  $T_c \approx -5^\circ \text{C}$ , which is known as the *rule of fives*. This critical behavior of the fluid permeability reflects a connectivity or percolation threshold in the brine microstructure (16–18), although accurate measurements of permeability in sea ice are difficult and time consuming. However, if the fluid transport properties of sea ice can be directly related to its electrical properties, then a new class of techniques can be brought to bear in monitoring sea ice transport processes. For example, it could open the door to the development of easily deployed,

expendable sensors providing information that could be integrated with satellite data.

The electrical conductivity of sea ice has been studied over the past five decades (19–25). Attempts at relating the electrical transport properties to microstructural characteristics of sea ice, however, have largely been unsuccessful. In particular, there have been no observations of critical behavior in electrical properties corresponding to the important microstructural transition articulated by the rule of fives. Here we report on two new types of experiments conducted on sea ice in the polar regions. In both cases we have obtained extensive data on the electrical resistivity which clearly display critical behavior at the brine percolation threshold. Our mathematical description of this behavior provides a rigorous link between fluid and electrical transport in sea ice, laying the foundation for the types of techniques described above.

In the Antarctic, we have made the first *direct* measurements of the vertical resistivity of sea ice by using a four probe Wenner array on extracted cores. In the Arctic, we have used the technique of cross-borehole DC tomography, utilizing vertical strings of electrodes frozen into the ice. We obtain the vertical component of the resistivity from direct measurements of the horizontal and geometric mean resistivities. Although the two data sets were obtained at opposite poles of the Earth and by quite different methods, they agree very closely and are both accurately captured with the same universal exponent from lattice percolation theory used to predict fluid permeability (17). Moreover, our Arctic data was taken in late spring and exhibits temporal behavior which is closely correlated with the onset of melt ponds.

The findings presented here also have implications for measuring ice thickness, an important gauge of the impact of global warming. Not only is thickness data important in comparing climate model predictions to observed behavior, but in specifying the initial conditions necessary for long-term numerical simulations. Almost all methods for obtaining such data depend on the interaction of electromagnetic (EM) fields