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Transport properties of sea ice from X-ray microtomographic imaging - evidence for directed percolation

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Percolation theory describes the properties of a large number of objects related to their connectivity. The spreading of fluid through a porous medium is, among other applications, a percolation process that was first described by Broadbent and Hammersley (1) in terms of percolation theory. During the past decades this theory has been formulated and many different applications, like forest fires and soil physics, have been linked and compared to it (2,3). Within cryospheric sciences percolation theory has been discussed for the connectivity of sea ice pore networks (4,5,6). A frequently mentioned conclusion of these studies is that the sea ice pore pace undergoes a percolation phase transition at a porosity of 5%, which since has been adopted to model sea ice (e.g., 5,7). However, the conclusions have been largely based on laboratory experiments, limited sample sizes and resolution.

The present work presents new insight into sea ice pore space percolation based on 3-d X-ray micro-tomographic imaging (XRT) of natural sea ice and an analysis in terms of directed percolation - a class of non-equilibrium phase transitions (9) that differs from isotropic variants employed in earlier studies (4,5,6). From XRT images of young sea ice at different temperatures we derive pore characteristic length scales, open and closed porosity, connectivity and simulate conductivity and permeability numerically. The results are evaluated in terms of critical exponents of percolation properties. The critical exponent of the strength of the percolating cluster was within a few percent of 0.81 known from numerical predictions for directed percolation (9). This finding of directional percolation behavior of sea ice is consistent with its unidirectional growth and desalination driven by gravity. However, while such directional percolation behavior of natural porous media had already been suggested by Broadbent and Hammersley (1), only a few experimental demonstrations of it in nature are known (9), indicating the potential of sea ice studies to advance general knowledge in this field. The phase transition porosity threshold is found close to 2%, considerably lower than 5% estimated in previous work (6). A closer look on pore scale characteristics indicates that the latter was overestimated due to insufficient spatial resolution.

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Significance statement

Sea ice, microstructure, X-ray tomography, phase transition, percolation

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