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A variational phase-field model for porous ice and salty water interactions

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Ocean-ice interactions, particularly the dynamics of melting and refreezing at the ice-ocean interface, are critical in determining ice shelf stability and predicting large-scale ice sheet behavior. These processes exhibit significant spatial and temporal heterogeneity due to the complex couplings among the transport of salinity and temperature fields, and density-stratified fluid flow. In this study, we use the phase-field method to model ice as a porous medium to more accurately capture its microstructural properties and the associated transport phenomena at the ice-ocean interface. The phase-field framework enables a robust, thermodynamically consistent representation of phase transitions between solid and fluid phases without requiring explicit interface tracking. While this technique has been used in recent years to model ice melting under turbulent flow, existing models often adopt a nonvariational formulation and focus on evolution of macroscopic ice-water interfaces (e.g., cm to m scale).

In this work, we develop a variational phase-field model based on a temperature-and-salinity-dependent Gibbs free energy functional of water-salt mixtures to describe the coupled interactions between porous ice and salty water at the pore scale (e.g., um to cm). The functional is formulated to recover the phase diagram of seawater in the -10℃ to 0℃ range, capturing the equilibrium phase diagram as controlled by the bulk salinity and temperature of the system. By incorporating diffusion, advection, interfacial effects, and phase transition dynamics via the Allen-Cahn and Cahn-Hilliard evolution equations, the model predicts the co-evolution of the phase field, salinity, temperature, under laminar flow. We present high-resolution numerical simulations that illustrate the melting and refreezing dynamics under diverse environmental conditions, including varying flow configurations, salinity gradients, and temperature distributions. The model effectively resolves these dynamics within complex geometries in the mushy layer of the ice sheet and across different flow regimes. These results illustrate the intricate interplay of salinity, temperature and phase change in ocean-ice interactions, contributing to a more precise understanding of pore-scale mechanisms of mushy ice evolution and their impact on larger-scale ice sheet evolution under dynamic oceanic forcing.

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References

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