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Fluid dynamics of sea ice

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Sea ice is a two-phase, two-component, reactive porous medium, which is the general description of a *mushy layer*. It comprises solid crystals of essentially pure ice separated and bathed by concentrated liquid brine. The primary components are water and salt (dominantly sodium chloride). And the solid ice crystals form a porous matrix through which the interstitial brine can flow. The mechanical and thermodynamical properties of sea ice depend significantly on the *brine volume* – the volume fraction of liquid brine – or equivalently the *solid fraction* – the volume fraction of solid ice. These fractions vary spatially and temporally (the medium is thus reactive) in response to heat and salt fluxes driven by diffusion, convection of the interstitial brine and, in the case of heat, by radiation. The only significant mechanism for salt transport in sea ice is by fluid flow: either buoyancy driven convection driven by gradients in interstitial brine concentrations or flushing by melt water in the summer months.

The thermodynamics and fluid dynamics of mushy layers have been studied extensively both theoretically and experimentally over the past couple of decades in contexts ranging from metal casting to igneous rock formation and including sea ice formation and evolution. The fundamental physical interactions are common to all these systems and can be represented within a common theoretical framework. In the context of sea ice, the principal thermodynamic conservation laws were presented by Untersteiner (1964 *J. Geophys. Res.* **69**, 4755–4766), who determined the heat conduction through sea ice given empirically constrained profiles of brine volume. Since then, significant developments have been made, mostly in other contexts, in the prediction of convective, fluid-dynamical processes within sea ice, which determine the brine-volume distribution.

A major advance has been the prediction and experimental confirmation of the conditions under which *brine channels* will form in sea ice. These essentially vertical channels (often called *chimneys*) are caused by dissolution of the ice matrix in response to fluid flow and form the principal route by which dense brine drains from sea ice and is delivered to the ocean.

I shall discuss the essential properties of fluid flow within mushy layers, relating these to the evolution of sea ice. An important consequence is the manner by which brine enters the ocean, injected as concentrated narrow plumes emanating from brine channels rather than by turbulent scouring of laminar sublayers. I shall therefore also describe a new parameterization of heat and salt fluxes from the sea-ice–ocean interface that incorporates our fundamental physical understanding of the dynamics of mushy layers.