Two Modes of Sea-Ice Gravity Drainage

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Processes that change the vertical salinity profile of sea ice have a significant impact on sea-ice properties and biogeochemistry. One of the most important processes affecting sea-ice salinity is gravity drainage where cold, dense brine within newly formed sea ice drains out and is replaced by seawater, resulting in a significant desalination of the sea ice. Using time-resolved bulk salinity and temperature observations of forming sea ice, we show that gravity drainage occurs as two distinct modes: (1) rapid drainage at the base of the ice and (2) slow drainage occurring more deeply in the ice. We have developed a parameterization for gravity drainage that includes these two modes and is suitable for inclusion in a global climate model. The parameterization is included in an all-new thermodynamic component, based on mushy layer theory, for the LANL sea ice model (CICE).

Sea ice, the frozen surface of high latitude seas, is not entirely fresh–it is composed of a network of brine pockets surrounded by fresh ice. The brine is not fixed in the sea ice–brine inclusions expand and contract as the temperature of the ice changes and the fresh ice surrounding the brine network melts and refreezes. Brine pockets within the sea ice are connected together as a porous medium, and a number of processes move the brine around and change the properties of the sea ice. The brine also harbors a rich variety of living organisms whose existence in the ice is enabled by the transport of nutrients into the ice with seawater through the brine network.

The vertical salinity profile of sea ice changes shape during its first year, from a "C" shape with higher salinities at the top and the bottom than in the interior, to a profile characteristic of multiyear ice, with much fresher ice near the top surface and less salt content overall. The salinity structure of the ice directly affects heat conduction and melt/freeze rates and strength and has indirect effects through the effect of the sea-ice biology (changing albedo for example). As the seasonal ice fraction of the Arctic ice pack increases [1], the representation of the early evolution of the sea-ice salinity profile becomes more important in models. In the Southern Hemisphere, where the pack ice is already largely seasonal, such a representation will improve simulations of global and regional climate.

One of the most important processes that changes the salinity profile of the ice is gravity drainage. When sea ice forms, the upper layers are colder (and so contain denser brine) than deeper layers. This unstable density profile results in the brine draining out of the ice to be replaced by fresher seawater, resulting in a significant desalination of the ice.

Until now, the salinity profile in CICE was fixed in a form appropriate for multiyear ice that has already largely drained. We present a new 1D parameterization of gravity drainage implemented in an all-new thermodynamic component of CICE, based on mushy layer theory [2]. We solve a set of coupled, nonlinear equations for sea-ice temperature (enthalpy) and salinity using an implicit Jacobian-free Newton-Krylov method.

Time-resolved data [3] reveal two distinct modes of sea-ice drainage: (1) rapid drainage in a narrow region at the base of the ice and (2) slow drainage occurring more deeply in the ice. In this paper we present a prognostic salinity parameterization suitable for inclusion in a global climate model that reproduces both drainage modes apparent in the observed data. The rapid mode of drainage is modeled with an advective operator assuming upflow in the mush and downflow through evacuated channels. The slow desalination is represented as a simple relaxation of bulk salinity to a value based on a critical porosity for sea-ice permeability. We find that these parameterizations can adequately reproduce observational data from laboratory experiments and field measurements.

These observations make use of an instrument capable of measuring the temporal evolution of bulk salinity at various depths within sea ice as it forms [4]. The instrument consists of 14 pairs of platinum wires placed at various depths within the ice (6, 11, 18.5, 26, 36, 46, 56, 66, 81, 96, 111, 131, 151, and 171 mm below the upper ice surface). The electrical impedance is measured between the pairs and is used to infer the liquid fraction of the ice. The instrument also has a series of thermistors that recored temperature at the same depths as the wire pairs that measurements are converted to brine salinity using a liquidus relation. With the measured liquid fraction and brine salinity, bulk salinity may

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be inferred. Notz and Worster [3] used this instrument in Adventfjorden in Spitsbergen during the winter of 2005 to measure sea ice temperature and bulk salinity.

Figure 1 compares the observed and modeled temporal evolution of temperature and bulk salinity at each of the instrumental depths–dark blue colors correspond to sensors near the top surface of the ice. As the ice grows, deeper sensors are gradually incorporated. The two stages of gravity drainage are evident in the lower panels of Fig. 6, showing rapid initial drainage that tapers off into the slow drainage mode at each sensor level. The temperature and salinity fields are reasonably reproduced by the model.

The rapid drainage parameterization presented here is based on an advective operator, unlike other gravity-drainage formulations that have generally used a diffusive parameterization. This more closely models the physical reality of gravity drainage that is thought to consist of an upward Darcy flow in the mush and downward flow through narrow channel features. Diffusion implies mixing of downward and upward flows at each level, something that is not thought to happen in gravity drainage. The parameterization considers explicitly the pressure differences in the mush and channels that drive the flow, and it successfully captures the observed sea ice salinity evolution in a manner suitable for global climate modeling.

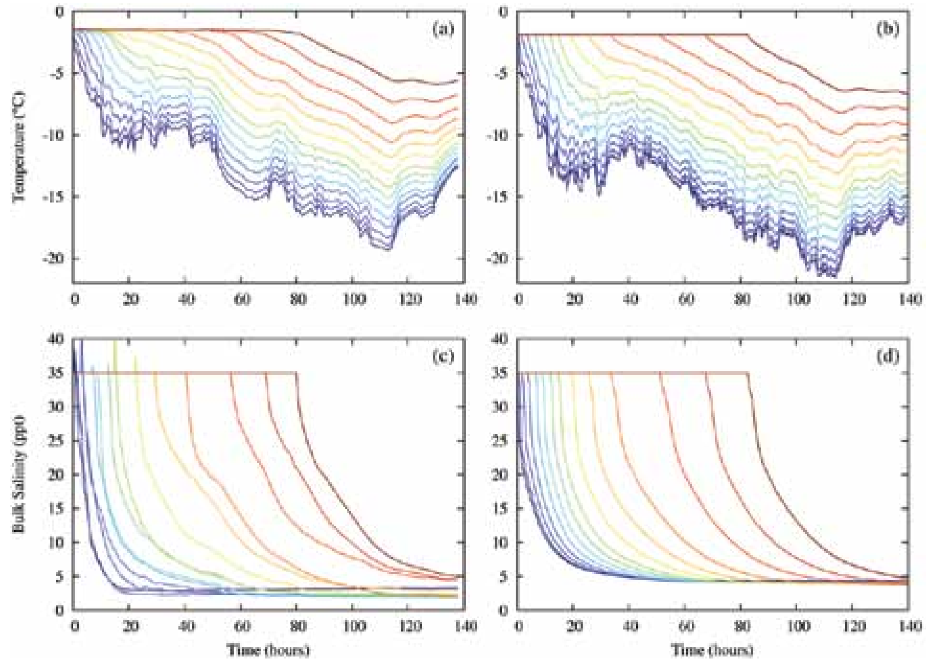

Fig. 1. Temperature (degrees C) versus time (hours) for (a) the individual wire pairs in field observations [3], and (b) the corresponding model simulation with 100 layers. Bulk salinity (ppt) versus time (hours) for (c) the individual wire pairs in field observations [3], and (d) the corresponding model simulation with 100 layers. Model data are interpolated to the same depths as the wire pairs in the experiment.

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