

ENTRAINMENT AND DYNAMICS OF OCEAN DERIVED IMPURITIES WITHIN EUROPA'S ICE SHELL. J. J. Buffo¹, B. E. Schmidt¹, C. Huber², and C. C. Walker³ ¹Georgia Institute of Technology, 311 Ferst Dr., Atlanta, GA 30318 (jacob.buffo@eas.gatech.edu) ²Brown University (Christian_Huber@Brown.edu) ³Woods Hole Oceanographic Institution (cwalker@whoi.edu)

Introduction: Geologic features and areas of irradiation on the icy surface of Jupiter's moon Europa are often dark and red in color, produced by locally high salt content within the ice [1]. Compositional heterogeneities within Europa's ice shell can arise from and facilitate geologic processes [2-5], providing a pathway for potential expression of ocean-derived materials at the moon's surface. The detailed chemistry and transport of these solutes play an imperative role in the dynamics and habitability of the ice and subsurface ocean [6, 7], but the total inventory and distribution of impurities within Europa's ice shell is unknown. In sea ice on Earth, the local thermochemical environment at the ice-ocean interface governs impurity entrainment into the ice, which has been successfully reproduced by multiphase reactive transport models that capture the physics occurring at this dynamic boundary [8-10].

A key process occurring in these ice-ocean/brine systems is fractional crystallization. While more commonly used to describe high temperature magmatic processes, or the carefully controlled separation of chemical species in a laboratory, perhaps the most familiar example of fractional crystallization is the freezing of water into ice. When an aqueous solution is depressed below its freezing point pure crystalline ice begins to form, rejecting impurities into the remaining, concentrated, solution. The result is a complex and ever evolving two phase system, governed by a combination of diffusive and advective heat and mass transport, ever seeking thermodynamic and chemical equilibrium [8-10]. The complex physics governing these two-phase systems pose a significant hurdle to numerical representations of these environments, and thus they are frequently parameterized, if not wholly excluded from models.

Here we discuss the ubiquity and importance of these environments in our own polar oceans as well as the oceans and ice shells of other bodies in our solar system. We present a one-dimensional reactive transport model capable of simulating the solidification dynamics of these interfaces using both terrestrial and putative European ocean/brine chemistries. The model is validated against terrestrial sea ice and is applied to Europa to investigate the thermochemical evolution of its ice shell as well as basal fractures and perched water lenses. We report constraints on the total impurity load of, and potential compositional heterogeneity within, the European ice shell derived from constitutive relationships between impurity en-

trainment and local thermal gradient for a variety of ocean compositions. Our results demonstrate how ocean materials are entrained and processed within Europa's ice shell, affecting the formation of geologic terrain as well as the interpretation of a broad swath of spacecraft observations of Europa and other ice-ocean worlds.

Multiphase Reactive Transport Model: The one-dimensional model is a stand-alone code built in MATLAB that was designed using mushy layer theory to simulate the two-phase ice-ocean/brine system using conservation equations. Mushy layer theory is well documented in the literature [8, 9, 11] and a full description of the model can be found in [10] and [12].

Salt Entrainment in Sea Ice: The top-down solidification of sea ice bears many similarities to the formation of Europa's ice shell, and as such provides an excellent terrestrial analog with which to validate the model. Using the model, we simulate the evolution of first year terrestrial sea ice under realistic thermal conditions and compare the compositional profile with empirical measurements of sea ice bulk salinity (See Figure 1).

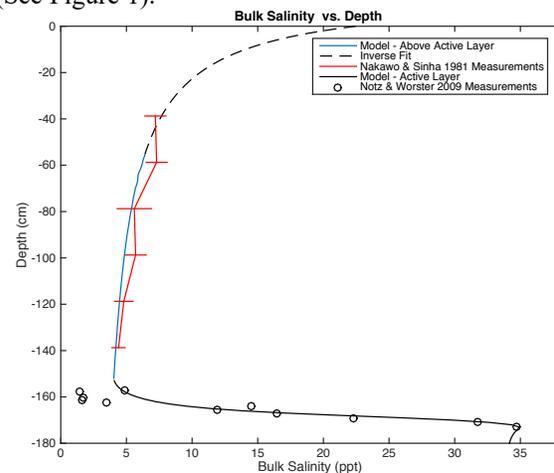


Figure 1: Modeled (blue and black solid lines), empirical (red line [13] and black circles [14]), and interpolated (black dashed line) bulk salinity profiles of terrestrial sea ice. The numerical model assumes a preexisting 50 cm thick layer of sea ice in conductive equilibrium (linear temperature profile) with an atmospheric temperature of 250K and an ocean temperature of 271.5K. A conductive heat flux is maintained throughout the simulation at the upper boundary. The model was run for 1.5×10^7 sec (~ 174 days, a typical sea ice annual cycle) with a time step of 100 sec. The dashed line is the product of a Levenberg-Marquardt algorithm fit to the function $S(z) = a + b/(c-z)$, where S is bulk salinity, z is depth, and a , b , and c are constants, applied to the modeled bulk salinities above the active layer (blue solid line).

The model successfully reproduces the observed bulk salinity values both above and within the active layer, validating the model and bolstering confidence in its application to more exotic ice-ocean environments.

Application to Europa's Ice Shell: Modifying the model to accommodate the physical and thermochemical environment of Europa, it was utilized to simulate the temporal and spatial evolution and ensuing composition of Europa's ice shell and hydrological features contained therein. A variety of ocean compositions and concentrations were investigated, ranging from a 34 ppt NaCl dominated terrestrial chemistry to a saturated (282 ppt) MgSO₄ dominated ocean (a composition predicted assuming aqueous differentiation of carbonaceous chondrites [15]).

Most notably, we found that ice composition is uniquely determined by the local thermochemical environment of the ice-ocean interface at the time of solidification and derived constitutive equations describing these relationships [12]. The constitutive equations can then be generally applied to solidification scenarios, removing the need for computationally expensive explicit simulation. Thus, the reactive transport model provides a method for deriving globally applicable relationships between state variables (e.g. thermal gradient) and ice properties (e.g. composition, density, conductivity) that can be directly implemented in ice shell, ocean, geodynamic, and transport models of icy worlds, as well as aid in mission design and data interpretation. An example application of the constitutive equations can be seen in Figure 2, where the re-solidification of an isolated (not in contact with the underlying ocean) perched water lens, and the resulting compositional profile, is investigated. This resolidification leads to a concentrative process which results in a heterogeneous compositional profile and a high salinity layer near the base of the lens, a location which would likely exhibit unique thermal, mechanical and dielectric properties that could influence geophysical behavior as well as spacecraft observations (e.g. ice penetrating radar).

Conclusion: The ice-ocean/brine one-dimensional reactive transport model presented here can be broadly applied to a diverse array of ocean worlds to investigate the thermochemical evolution and distribution of ocean-derived impurities within icy shells. Additionally, with many ice-ocean worlds exhibiting ongoing geological processes the model is primed for use in dynamic hydrologic and cryovolcanic simulations. Reactive transport has changed our understanding of nearly every field of terrestrial geophysics and with ever improving spacecraft resolution and computing power, implementing the same physics in simulations of ice-ocean worlds promises to improve estimates of geophysical, physicochemical, and astrobiological properties of these lucrative worlds.

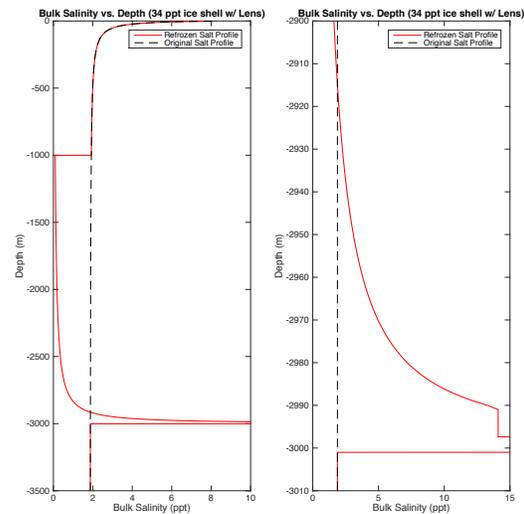


Figure 2: Bulk salinity profile of a perched water lens upon re-solidification. **Left)** A 2 km thick lens is assumed to form via the *in situ* melting of a preexisting ice shell, whose original composition is given by the black dashed line. Initially the lens salinity is less than that of the original ocean, but upon top down solidification salt is concentrated in the remaining liquid phase, leading to an increase in ice bulk salinity [red line] near the base of the refrozen lens as well as ~2.23 m of precipitated salt on the lens floor (1000 ppt values excluded from plot). **Right)** A magnified view of ice bulk salinity near the bottom of the lens (2.90 – 3.01 km). The lens saturates (282 ppt) when the ice reaches 2991 m, resulting in salt precipitation (2997.77 – 3000 m).

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