Thermomechanical Modeling of Icy Worlds: Insights from Ocean-Ice Interface Dynamics. N. Gilkyson¹, C. Huber¹, and J.J. Buffo². ¹Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI (nina_gilkyson@brown.edu), ²Thayer School of Engineering, Dartmouth College, Hanover, NH

Introduction: Geological and geochemical diversity on the surfaces of icy worlds is strongly modulated by subsurface ocean chemistry [1-2], dynamics at the ice-ocean boundary [3-4], tidal forcing [5-6], and stress generation through freezing [7-9]. Soon, data from upcoming missions (e.g., Europa Clipper, JUICE) will further inform our understanding of these crucial processes and their roles in shaping the geologic and chemical diversity of icy worlds [10-12]. Thus, there is a pressing need for models that can account for the internal chemical and thermal mechanisms that modify satellite surfaces. Such models should be capable of exploring how these processes interact over long timescales and under different chemical and energy budgets.

Substantial advancements have been made in modeling geodynamic processes at various spatiotemporal scales relevant to icy worlds. While these models offer valuable insights, a comprehensive approach to the long-term thermomechanical evolution of an icy body, inclusive of crucial small-scale transport mechanisms occurring at the ocean-ice interface, remains to be developed. A model of this type can expand our understanding of the processes that impact the longevity of subsurface oceans (e.g., ocean chemistry, tidal dissipation) and facilitate a connection between evolving ocean chemistry, ice chemistry, and internal heat budget to geologic and chemical features at the surface.

Here we present a thermomechanical model for a coupled cryosphere-hydrosphere system that considers an ocean with a starting concentration of NaCl. Surface and magnetic field observations of several icy worlds indicate the presence of salts, including NaCl and MgSO₄, as well as NH₃ and CH₄ in their oceans [1]. These solutes will affect the freezing point of the brine at the ocean-ice boundary, the composition of the growing ice, and the material properties of that ice [13].

Our model accounts for complex behavior at the solid-liquid boundary, as investigated in the work of Buffo et al. 2020. Their comprehensive study of solute entrainment in this region employs multiphase reactive transport modeling to simulate the detailed dynamics of the mushy layer. They find that the amount of salt entrained into the ice shell is a function of the ice shell's thermal gradient and the composition of the subsurface ocean.

Methods: Our approach uses a one-dimensional thermomechanical model. The model is derived from mass, momentum, and energy conservation laws, assuming a differentiated body with an ice shell and ocean overlying a silicate "core." Heat flux occurs from the core to the well-mixed subsurface ocean, and conductive heat flux out of the ocean and across the ice shell allows for top-down solidification. Stress on the ice shell is induced by pressurization of the ocean through freezing. Viscous relaxation of deviatoric stresses within the ice is also considered. Mass exchange mainly occurs through loss of ocean mass to the ice shell by freezing. When the tensile stress at the ice shell's base surpasses the ice's strength, fractures develop, alleviating excess pressure by allowing for removal of brine from the ocean. Initial surface temperature, ocean composition and concentration, and planet size (core and ocean), can be modified to reflect a diverse array of icy bodies. A schematic figure of the model’s dominant features is shown in Fig. 1.

![Schematic diagram of dominant features of the thermomechanical model](image)

**Solute**: The presence of salt in the ocean will suppress its freezing point [13-14]. At present, we consider an NaCl ocean composition. However, the model can include other relevant salt compositions and their effect on freezing point depression. Entrainment of brine into the growing ice shell is incorporated into the model with an efficiency (partitioning K) that depends on the chemical species considered and the thermal gradient, as parameterized in Buffo et al. (2020).

Results: Model outputs for an Enceladus sized body (mean radius = 252km, core radius = 190km) are shown in Fig. 2. Three scenarios are evaluated: an ocean...
devoid of solutes, an ocean with an initial salinity of 34 ppt NaCl (mirroring terrestrial ocean concentration), and a higher initial salinity environment of 100 ppt NaCl. While the ice shell grows, most of the solute is expelled, leading to an increase in oceanic salinity (Fig. 2a) and a consequent depression of the freezing point. This results in a reduced freezing rate of the ice shell, as depicted in Fig. 2b. Upon saturating the ocean, solid NaCl begins to precipitate.

In these example simulations, a 45 km thick ice shell forms within approximately 70 Myrs. The inclusion of solutes delays this formation by up to 20% of that time. While these simulations do not incorporate heat sources within the ice shell, such as tidal dissipation, and thus may not be directly applicable to a body like Enceladus, they do shed light on the impact of ocean solutes on the freezing rate. This in turn influences the pressure history of the subsurface ocean and the development of ice shell fractures (sharp decreases in overpressure shown in Fig. 2c). It is observed that although fractures are prevalent early in the system's evolution when the ice shell is thinner, the freezing rate subsequently diminishes significantly. This reduction becomes comparable to the rate of pressure relaxation due to the viscous creep in the lowermost part of the ice shell, as depicted in Fig. 2c.

Brine entrainment in the ice shell is solved using the parameterization from Buffo et al. 2020. Resultant salinity profiles for these different initial ocean concentrations are depicted in Fig. 3. The initial phase of freezing demonstrates a gradual change in salinity that begins to approach a lower limit. Thus, Fig. 3 focuses on the upper 50-300m of the ice layer, where the most substantial concentration variations with depth are observed.

**Future Work:** The effects of tidal dissipation in the ice shell will be incorporated into model using the method outlined in Mitri and Showman (2008). We intend to refine the model of stress distribution in the ice shell and fracture initiation and propagation according to Rudolph et al. (2022).

**References:**