
Affiliation: Hampton University
Title: Thermo-Mechanical
Evolution of Icy Shells and Interiors of the Galilean Satellites and Outer Solar System Icy Bodies from 3-D Convection Modeling
Authors: [Kiran Iyengar](#), [William Moore](#)
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Abstract/Content (250–300 words):

Europa, Ganymede, and Callisto represent a broad range of icy satellite interior evolution, ranging from active tidal dissipation and rapid resurfacing on Europa to intrinsic magnetism and a layered interior on Ganymede, and comparatively limited resurfacing and internal differentiation on Callisto. We present three-dimensional thermo-mechanical convection simulations designed to investigate how variations in ice-shell thickness, internal heating (radiogenic and tidal), temperature-dependent viscosity, and buoyancy structure influence convective planform, heat transport, and the chemical differentiation of icy shells.

Our modeling framework employs two-dimensional, Cartesian simulations of convection for a range of values in the parameters listed above. Time-dependent velocity and temperature fields are analyzed to track the persistence of impurities in parts of the icy shell that remain cold enough to prevent brine segregation. Impurities are generally preserved only in the rigid upper boundary layer, which is structured by the dynamic convection in the layer beneath. Depending on the relevant temperature for brine segregation, different degrees of brine preservation are observed.

We analyze the depth over which impurities are preserved and the horizontal scale of variations in impurity preservation as a function of the convective parameters in the shell (thickness, internal heating, Rayleigh number). The thermal and impurity structures of the icy shells are the dominant controls on the propagation of radar signals through the ice.

We further outline how this modeling strategy can be extended to other outer solar system icy ocean-world candidates, including Ceres, Enceladus, Miranda, Pluto, and Charon, among others. These simulations provide a quantitative framework for interpreting surface geology, assessing ocean longevity, and constraining heat flow in the context of current and upcoming mission observations, particularly those from the ESA JUICE and NASA Europa Clipper missions. The resulting thermal and mechanical conditions also provide first-order constraints on cryovolcanic viability and ice-shell failure mechanisms on ocean worlds.

References (If needed): [1] Magnanini, Andrea, et al. "Joint analysis of JUICE and Europa Clipper tracking data to study the Jovian system ephemerides and dissipative parameters." *Astronomy & Astrophysics* 687 (2024): A132. [2] Steinbrügge, G., et al. "Brine migration and impact-induced cryovolcanism on Europa." *Geophysical Research Letters* 47.21 (2020): e2020GL090797. [3] Durham, W. B., and L. A. Stern. "Rheological properties of water ice—Applications to satellites of the outer planets." *Annual Review of Earth and Planetary Sciences* 29.1 (2001): 295-330. [4] Tackley, Paul James. Three-dimensional models of mantle convection: Influence of phase transitions and temperature-dependent viscosity. *California Institute of Technology*, 1994. [5] Green, A. P., L. G. J. Montesi, and C. M. Cooper. "The growth of Europa's icy shell: Convection and crystallization." *Journal of Geophysical Research: Planets* 126.4 (2021): e2020JE006677. [6] Nagel, K., D. Breuer, and T. Spohn. "A model for the interior structure, evolution, and differentiation of Callisto." *Icarus* 169.2 (2004): 402-412.

