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Stagnant lid convection in the outer shell of icy moons

Chloe Yao (1), Frédéric Deschamps (2), Paul Tackley (1), Julian Lowman (3), and Carmen Sanchez-Valle (4)

(1) Institute of Geophysics, ETH Zurich, Zurich, Switzerland (chloe.yao@erdw.ethz.ch), (2) Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan (frederic@earth.sinica.edu.tw), (3) Department of Physical and Environmental Sciences, University of Toronto, Toronto, Canada (lowman@utsc.utoronto.ca), (4) Institute of Geochemistry and Petrology, ETH Zurich, Zurich, Switzerland (carmen.sanche@erdw.ethz.ch)

In the past decade, from both theoretical studies and spacecraft missions measurements, the internal structure of large icy moons including a subsurface ocean has gained an increasing support. The exact thickness of subsurface ocean, if present, depends on the detailed thermal evolution of each moon, and on its primordial composition. A crucial process is the heat transfer through the outer ice I layer, which controls the cooling of the satelitte interior. Convection is the most likely and efficient way to transfer heat through this layer, but the regime of convection (and therefore the heat transfer) depends on the rheology of the fluid. The viscosity of ice is strongly temperature dependent and thermal convection in the outer ice shell follows a stagnant lid regime : it means that a conductive stagnant lid forms at the top of the system, and convection is confined in a sublayer. Previous numerical studies including strongly temperature-dependent viscosities have already been performed in 2D Cartesian geometry allowing the determination of scaling laws relating the mean temperature and heat flux to the vigor of convection (described by the Rayleigh number) and the ratio of the top to the bottom viscosity, but 3D spherical geometry may provide a more accurate description of convection within the outer ice layer of icy moons. In this work, we model the heat transfer in spherical shells for a strongly temperature-dependent viscosity fluid heated from below. We use StagYY to run simulations for different ratios of the inner to outer radii of the ice layer (f), Rayleigh number (Ra), and thermal viscosity contrast ($\Delta\eta$). The inversion of the results of more than 30 numerical experiments allows the determination of scaling laws for the temperature of the well-mixed interior and surface heat flux. In particular, we find that depending on the curvature, the stagnant lid regime does not appear for the same values of the Rayleigh number and the viscosity contrast. These parameterizations, combined to mineral physics data (including melting curves of water + volatile systems), may be used to model the evolution of the radial structure and thus the cooling of icy moons.