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Heat transfer and stirring efficiency of 3D stagnant-lid convection

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Convection in the mantle of terrestrial bodies other than the Earth is characterised by a strong temperature dependence of the viscosity that naturally leads to the formation of a stagnant lid. The style and vigor of convection beneath the lid ultimately control planetary cooling and determine the ability of the mantle to preserve or homogenize compositional heterogeneities. In particular, understanding the efficiency of convective stirring is key to the interpretation of petrological, geochemical, and cosmochemical data inferred remotely by spacecrafts or obtained from meteorite or in-situ analysis (as for Mars and the Moon). Although a large body of work has been devoted to characterise heat transfer and stirring efficiency in the mobile lid regime that is distinctive of Earth's plate tectonics, the study of these processes for stagnant lid convection has received much less attention, particularly in the framework of 3D simulations.

We conducted series of numerical convection experiments in 2D and 3D Cartesian domains heated from below and cooled from above. We used a strongly temperature-dependent viscosity based on the Arrhenius law for dry diffusion creep and varied systematically the (basal) Rayleigh number from 10^6 to 10^{10}. We determined stirring efficiency by computing the finite-time Lyapunov exponents, which provide a measure of the Lagrangian deformation. This systematic exploration allows the degree of heterogeneity and its spatial variability to be quantified. Despite exhibiting a similar behavior in terms of heat transfer, 2D and 3D simulations show significant differences in terms of stirring efficiency. 2D cases are characterised by a Gaussian distribution of the Lyapunov exponents, which correlate with the root-mean-square flow velocity over the entire spectrum of Rayleigh numbers. By contrast, 3D cases are characterised by a threshold Rayleigh number below which stirring efficiency is not homogeneous, which leads to multi-modal distributions of the Lyapunov exponents. Above this threshold, stirring efficiency is again homogeneous and the correlation between Lyapunov exponents and root-mean-square flow velocity is restored.

Scaling laws for heat transfer and stirring efficiencies are derived that serve as a basis to discuss applications to planetary mantles.