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Numerical Modeling of Mantle Convection with Heat-pipe Melt Transport

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During the early evolution of terrestrial bodies, a large amount of mantle melting is expected to affect significantly the energy budget of the interior through heat transport by volcanism. Partial melt, generated when the mantle temperature exceeds the solidus, can propagate to the surface through dikes, thereby advecting upwards a large amount of heat. This so-called heat-pipe mechanism is an effective way to transport thermal energy from the meltregion to the planetary surface. Indeed, recent studies suggest that this mechanism may have shaped the Earth's earliest evolution by controlling interior heat loss until the onset of plate tectonics [1]. Furthermore, heat-piping is likely the primary mechanism through which Jupiter's moon Io loses its tidally generated heat, leading to massive volcanism able to cause a present-day heat-flux about 40 times higher than the Earth's average heat-flux [2]. However, despite its obvious importance, heat-piping is often neglected in mantle convection models of terrestrial planets because of its additional complexity and vaguely defined parameterization.

In this study, adopting the approach of [1] we model mantle convection in a generic stagnant lid planet and study heat-piping effects in a systematic way. Assuming that melt is instantaneously extracted to the surface and melting regions are refilled by downward advection of cold mantle material in order to ensure mass conservation, we investigate the influence of heat-pipes on the mantle temperature and stagnant lid thickness using the numerical code Gaia [3]. To this end, we run a large set of simulations in 2D Cartesian geometry spanning a wide parameter space. Our results are consistent with [1] and show that in systems with strongly temperature-dependent viscosity the heat-pipe mechanism sets in at a Rayleigh number $Ra \sim 2 \times 10^7$. Upon increasing Ra up to $\sim 6 \times 10^7$, we observe a systematic decrease of the average mantle temperature accompanied by an increase of the lid thickness compared to cases where heat-piping effects are neglected. By increasing further the Rayleigh number, the effect levels off, eventually leading to an average mantle temperature $\sim 10\%$ smaller and a stagnant lid almost twice as thick.

References

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