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Mantle Convection in a Spherical Shell: The problems of using Frank-Kamenetskii Approximation for the viscosity law

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Mantle convection in terrestrial planets is strongly influenced by the temperature dependence of its viscosity. Considering this property, the mantle convection is basically divided into three different regimes depending on the viscosity contrast: stagnant lid, sluggish and mobile lid regime [1]. In the first regime the mantle is divided into two parts an active part which is convecting and another one on top which is immobile. In the last two regimes the surface material can move and is incorporated into the mantle convection.
The temperature dependence of the mantle viscosity can be modeled using the so called Arrhenius Law. In the Arrhenius formulation the temperature dependence of the viscosity for a silicate mantle is given by the activation energy. Using realistic values for the activation energy in the Arrhenius formulation will result in large viscosity contrasts ($\sim 10^{40}$) which cannot be handled very well by the numeric. Therefore, an approximation of the viscosity is commonly used to model the mantle convection, i.e., the Frank-Kamenetskii approximation. This approximation linearises the Arrhenius law, suggesting a viscosity which is many orders of magnitude smaller at the surface. Although the approximation has been shown to represent only the stagnant lid regime correctly, it is widely used in the literature also for the other regimes.
We present a comparison of the mantle convection for stagnant lid cases using either the Arrhenius law or the Frank-Kamenetskii approximation with a 3D spherical code, GAIA [2,3].The results confirm earlier studies that the Frank-Kamenetskii approximation can be used in the stagnant lid regime for a fixed Rayleigh number and a sufficiently thick stagnant lid. However, several problems arise when using this approximation in numerical simulations for a cooling mantle or for convection with a thin stagnant lid. A systematic study is presented highlighting the differences in various control parameters of mantle convection, e.g. degree of convection, Nusselt number, and stagnant lid thickness.

References:

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