Numerical investigations of effects of spatial variations in physical properties on the mantle convection patterns

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A series of numerical simulations is carried out on the onset of thermal convection of Boussinesq fluid of an infinite Prandtl number in a planar layer in the presence of spatial variation of physical properties such as viscosity, thermal conductivity and expansivity. The viscosity of the fluid is exponentially dependent on temperature, while thermal conductivity and expansivity are linearly dependent on pressure (or depth). Based on the linear stability analysis, velocity and temperature distributions are solved for infinitesimal perturbations for given horizontal wave number. We seek for the condition for the onset of convection by changing the horizontal wave number of perturbation as well as the amplitudes of spatial variations in physical properties (viscosity, thermal conductivity and thermal expansivity). Then, we examine influences on both the critical conditions and the dominant flow patterns of spatial variations in those physical properties. From the changes in flow patterns with increasing the amplitudes of temperature dependence of viscosity, we successfully identified the transition into the "stagnant lid" (ST) regime, where the convection occurs only beneath a thick and stagnant lid of cold fluid at the top surface. We also found that the transition takes place regardless of the spatial variations in thermal conductivity and/or expansivity.

However, detailed analysis of the numerical results showed a quantitative difference in the critical condition for the onset of ST convection due to the presence of spatial variations in thermal conductivity and expansivity. First, the horizontal wave number of perturbation is decreased by the introduction of spatial variations in these properties. In particular, the variation in thermal conductivity can significantly reduce the wave number: the horizontal length scale of convection can be enlarged by up to 50% when viscosity is strongly dependent on temperature. Another difference can be found in threshold values of temperature dependence of viscosity for the transition into the ST regime: the spatial variations in thermal conductivity slightly decrease the threshold viscosity contrast, while those in thermal expansivity increase them. These two differences can be successfully reproduced by our analytical estimates, which consider the thickness of stagnant lid and convective vigor beneath it.

The results of present studies indicate that, under certain conditions, the convection of fluids with strongly temperature-dependent viscosity takes place which is characterized simultaneously by (i) large horizontal length scales of convective cells and (ii) thick stiff lid of highly viscous fluid above it. This is in a stark contrast with earlier numerical studies using constant thermal conductivity and expansivity where the convection beneath stagnant lids is always associated with cells with small horizontal length scales. Our findings therefore highlight the essential roles of the spatial variation of the thermal conductivity and thermal expansivity on the convection patterns in the mantle of terrestrial planets.

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