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

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1. Introduction

There exist large differences in temperature and pressure within the mantle of terrestrial planets. In the Earth's mantle, for example, a pressure increases by about 135GPa with increasing depth, while a temperature does by about 3500K. These large differences in temperature and pressure are expected to yield substantial variations in the physical properties of mantle materials and, hence, significantly affect the dynamic behaviors in the mantle. Indeed, as had been inferred by several earlier studies, the spatial variations in mineral properties play an important role in the internal structures observed in the mantle of the Earth and terrestrial planets. We will study how the spatial variation of physical properties of mantle materials affects the flow patterns of thermal convection.

2. Model and Procedure of numerical experiments

We carried out numerical experiments of thermal convection in highly viscous and incompressible fluids, in order to study the influences of the spatial variations in physical properties of fluids (viscosity, thermal conductivity and thermal expansivity) on the convecting flow patterns in the mantle of terrestrial planets. We present the results of a series of numerical calculations using (1) a linear stability analysis on the onset of thermal convection in fluids confined in planar layers, and (2) a nonlinear (finite-amplitude) time-dependent thermal convection in a two-dimensional Cartesian box of aspect ratio (width/height) of 6, with systematically varying the magnitude of (i) decrease in viscosity with temperature, (ii) increase in thermal conductivity with pressure (or depth), and (iii) decrease in thermal expansivity with pressure. By comparing the results with those in the presence of their spatial variations, we will discuss the changes on the critical conditions, dominant vertical flow structures, and the convection regimes caused by their spatial variations.

3. Results

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 by both linear and nonlinear numerical calculations, 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. Especially we focused on the horizontal wave number of perturbation which is largely decreased by the introduction of spatial variations in these properties. We further developed an analytical model of convection cells which consider the thickness of stagnant lid and convective vigor beneath it. The model successfully reproduced the mechanism of increasing horizontal length scale of ST regime convection cells for each condition of spatial variations in physical properties.

4. Discussion and concluding remarks

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.

Keywords: mantle convection, viscosity, thermal conductivity, thermal expansivity, stagnant-lid convection