Low-degree mantle convection with strongly temperature- and depth-dependent viscosity

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   Numerical simulations of thermal convection of Boussinesq fluid with infinite Prandtl number, with Rayleigh number 10^7, and with the strongly temperature- and depth- dependent viscosity in a three-dimensional spherical shell are carried out to study the mantle convection of single-plate terrestrial planets like Venus or Mars without an Earth-like plate tectonics [Yoshida and Kageyama, 2006]. The basic equations governing the mantle convection are solved by a second-order finite difference discretization. A kind of the overset grid system, Yin-Yang grid [Yoshida and Kageyama, 2004], is used for the computational grid. The strongly temperature-dependent viscosity (the viscosity contrast across the shell is more than 10^5) make the convection under stagnant-lid short-wavelength structures. Numerous, cylindrical upwelling plumes are developed because of the secondary downwelling plumes arising from the bottom of lid. This convection pattern is inconsistent with that inferred from the geodesic observation of the Venus or Mars [e.g., Schubert et al., 1990; Zhong and Zuber, 2001]. Additional effect of the stratified viscosity at a depth, corresponding to a boundary between upper and lower mantle in the Earth, is investigated. The viscosity contrast is varied from 30 to 300. We examine two cases (1) in which the viscosity jumps at the boundary of the upper/lower mantle, and (2) in which the viscosity smoothly increases with depth in the lower mantle. It is found that the combination of the strongly temperature- and depth-dependent viscosity causes long-wavelength structures of convection in which the spherical harmonic degree L is dominant at 1-4 (low-degree convection). The geoid anomaly calculated by the simulated convections shows a long-wavelength structure, which is compared with observations. To date, several mechanisms have been proposed for the degree-one (L = 1) convection of the Martian mantle. For example, the endothermic phase transition just above core-mantle boundary in Martian mantle with the rigid boundary condition [e.g., Harder and Christensen, 1996], and a priori high-viscous lid [Harder, 2000] on the top surface boundary without any phase transitions. The small core, in other words, the thicker convecting shells of the mantle may lead to the degree-one convection in the ancient Mars [Schubert et al., 1990] and the Moon [Zhong et al., 2000a]. McNamara and Zhong [2005] have recently found that the internal heating plays a role in increasing flow wavelength and forming the degree-one convection in convections in which the viscosity moderately depends on temperature. One of our findings in this paper is that the degree-one convection can be relatively easily reproduced when both effects of the temperature- and depth-dependence on the viscosity are taken into account. Although the degree-one convection appears even when the temperature-dependence of viscosity is moderate and the depth-dependence of viscosity is absent, the parameter range for this pattern is rather narrow; it is sensitive to the Rayleigh number. On the other hand, the degree-one convection is realized in the wide range of viscosity contrast from 30 to 100 when the viscosity is continuously increased with depth at the lower mantle. The previous convection models without the temperature-dependent viscosity [e.g., Bunge et al., 1996] have already produced the large scale flow pattern by considering the viscosity stratification. This could be explained by the enhanced value of viscosity in the lower mantle. In our model with strongly temperature-dependent viscosity, the large scale convection seems to be realized by the change of convecting regime, from the stagnant-lid regime into the sluggish-lid regime, which is caused by the viscosity stratification. A major difference between their results and ours is that a highly viscous lid is naturally formed on the top owing to the inclusion of the temperature-dependent viscosity effect.