Stagnant-lid convection in a three-dimensional spherical shell

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A few numerical studies of mantle convection using a three-dimensional (3-D) spherical shell model have specifically addressed the one-plate terrestrial planets, i.e., Venus and Mars (e.g., Schubert et al., 1990). They have shown that structures of convection are dominated by long-wavelength component with a few strong upwelling plumes, which is consistent with the thermal structures of mantle convection inferred from the observed geopotential fields. Their simulation models are, however, far from the actual convecting system because: (1) The convective fluid has constant viscosity, and (2) the top surface boundary of the shell is taken to be the rigid (no-slip) condition which assumes the base of the thick immobile lithosphere of Venus and Mars. The immobile lithosphere is, however, a part of mantle convection system. It should naturally arise due to the very high viscosity in the upper boundary layer when the temperature-dependent viscosity is considered in numerical models of mantle convection with the free-slip condition on the top surface. It is crucial to study the 3-D spherical shell mantle convection with the strongly variable viscosity, and to examine what mechanism makes low-degree convection under the immobile lithosphere.

Some numerical calculations for the thermal convection with the strongly temperature-dependent viscosity have been reported using the 3-D Cartesian models with wide aspect ratios and the spherical shell models (e.g., Ratcliff et al., 1997). Their studies have revealed that an immobile, cold layer develops on the top surface of the convection. This layer, called ``stagnant-lid'', appears both in the box and spherical shell geometries when the viscosity contrast across the shell (E) reaches 10^4 to 10^5. Systematic calculations in the spherical shell geometry, however, have not been performed in the previous works. In this study, we carried out a series of numerical simulations of thermal convection of a Boussinesq fluid with infinite Prandtl number and with strongly temperature-dependent viscosity in a 3-D spherical shell. Our results basically support the previous ones; the convecting pattern is classified into three regimes as E is increased; (i) the small-viscosity-contrast regime, (ii) the sluggish-lid regime, and (iii) the stagnant-lid regime. With the moderate viscosity contrast (E = 10^3 to 10^4), the convecting pattern has long-wavelength structures, i.e., the sluggish-lid regime. When the Rayleigh number defined by the viscosity of the bottom layer (Ra) is 10^6, the convection pattern comes to be dominated by the degree-2 component, which consists of two cells with two upwelling, cylindrical plumes and one sheet-like downwelling plume in between (Yoshida and Kageyama, 2004). In contrast, when Ra = 10^7, the convection pattern come to be dominated by the degree-1; the one cell structure that consists of a pair of cylindrical downwelling plume and cylindrical upwelling plume in the opposite is formed. This indicates that the convecting feature on the sluggish-lid regime strongly changes on the Rayleigh number in the regime searched here. When Ra = 10^7 that is comparable to the Rayleigh number of the actual mantle, the convective flow pattern that belongs to the stagnant-lid regime emerges when E is greater than 10^4. The thermal structure under the stagnant-lid has short wavelengths with degree 7 to 9, comparable to the thickness of the convecting layer, and is characterized by numerous, cylindrical upwelling plumes surroundings sheet-like secondary cold plumes arising from the base of the lid. When E is extremely large, 10^8, we have observed several mushroom-shaped hot plumes underneath a rather thick stagnant-lid. This convective feature is, however, inconsistent with the low-degree structures of mantle convection in the Venus and Mars. We found that the pressure- (depth-) dependent viscosity is a key to produce the low-degree structures in the 3-D spherical shell geometry.