Numerical simulation of mantle convection: 3D, spherical shell, temperature- and pressure-dependent viscosity

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The style of convection in planetary mantles is presumably dominated by the strong dependence of the viscosity of the mantle material on temperature and pressure. While several efforts have been undertaken in cartesian geometry to investigate convection in media with strong temperature dependent viscosity, spherical models are still in their infancy and still limited to modest parameters. Spectral approaches are usually employed for spherical convection models which do not allow to take into account lateral variations, like temperature dependent viscosity. We have developed a scheme, based on a finite volume discretization, to treat convection in a spherical shell with strong temperature dependent viscosity. Our approach has been particularly tailored to run efficiently on parallel computers. The spherical shell is topologically divided into six cubes. The equations are formulated in primitive variables, and are treated in the cartesian cubes. In order to ensure mass conservation a SIMPLER pressure correction procedure is applied and to handle strong viscosity variations up to $\Delta\eta = 10^6$ and high Rayleigh-numbers up to $Ra = 10^8$ the pressure correction algorithm is combined with a pressure weighted interpolation method to satisfy the incompressibility condition and to avoid oscillations.
We study thermal convection in a basal and mixed-mode heated shell with stress free and isothermal boundary conditions, as a function of the Rayleigh-number and viscosity contrast. Besides the temperature dependence we have further explored the effects of pressure on the viscosity. As a general result we observe the existence of three regimes (mobile, sluggish and stagnant lid), characterized by the type of surface motion. Laterally averaged depth-profiles of velocity, temperature and viscosity exhibit significant deviations from the isoviscous case. As compared to cartesian geometries, convection in a spherical shell possesses strong memory for the initial state. At strong temperature dependent viscosity ($\Delta\eta = 10^4 - 10^6$) typically a few upwelling plume structures develop. The large scale structure of the plume stays intact over a long time while the plume geometry varies on a smaller scale. The downflows are generally organized in two-dimensional sheetlike flows. Additional pressure dependence strongly influences the dynamics even if the magnitude of pressure variation is relatively small. For an appropriate combination of pressure- and temperature-dependence, we observe a well developed high-viscosity zone in the lower mantle.

References:

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