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The interaction of different scales of convective overturn in planetary mantles

Edgar M. Parmentier
Department of Earth, Environmental and Planetary Science, Brown University, United States

The role of convection in planetary mantles is well established. For the earth's mantle, present day plate tectonics is primarily a manifestation of thermal convection. While the Earth's early history is obscured by the action of plate tectonics, other planetary bodies, the Moon and Mars in particular, preserve abundant evidence of an early evolution in which compositional buoyancy may have played a central role. Based on returned samples and meteorites, both the Moon and Mars appear to have undergone an early chemical fractionation resulting from magma ocean solidification. A relatively thin Fe-rich dense layer is expected to develop at the top of magma ocean cumulates formed by some degree of fractional solidification. The overturn of an early unstable global chemical stratification may explain the hemispheric asymmetry, both physical and chemical, characteristic of both bodies. Numerical experiments in a spherical geometry suggest that degree-one overturn can be generate by the cascade of rapidly developing instability at the small scale of the initial dense layer thickness to the much longer wavelength required to explain hemispheric asymmetry.

Thermal convection in a fluid layer at high Rayleigh number also involves the interaction of convection at several scales. Simple scaling laws follow from the hypothesis that thin thermal boundary layers result in a heatflux is independent of fluid layer depth. Purely dimensional reasoning then leads to a 1/3 powerlaw relationship between heatflux-Rayleigh number. In a more physically based hypothesis (Howard, 1984) the thermal boundary layer thickens by conduction becoming convectively unstable when a critical thickness is attained. The unstable conduction boundary layer is rapidly removed and then reestablished by heat conduction. This hypothesis leads to a critical Rayleigh number based on the thickness and temperature difference across the thermal boundary layer. In the Howard theory, the fluid layer thickness plays no role in the heatflux transmitted by boundary layer instability. 2D and 3D numerical experiments with a fluid layer cooled from above show that convective instability maintains relatively uniform thermal boundary thickness between large-scale downwellings that penetrate the whole thickness of the fluid layer and provide the primary driving buoyancy. Downwellings, with average spacings comparable to the fluid layer depth, interact unstably resulting in their time variable strength and spacing. As the downwelling population evolves, instabilities with a wavelength comparable to the boundary layer thickness are entrained into the downwellings providing the buoyancy that maintains them. New downwellings are generated by boundary layer instability between the most widely spaced downwellings. The numerical experiments thus show that relative time scales of downwelling interactions and boundary layer instability control the rate of heat transfer by convection.