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Experiments on highly supercritical thermal convection in a rapidly rotating hemispherical shell

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Introduction:

Flow in the Earth's fluid core is dominated by rotation and the Ekman number is very small, of the order of 10-15. Rotation inhibits convection, and consequently, thermal convection in the Earth's core occurs at high Rayleigh number. Convection under low Ekman number is characterized by fine scales, and that at high Rayleigh number by turbulence. The study of convection under such conditions forms the basis of understanding core flow, which is considered to be the cause of geomagnetic field generation, as well as of atmospheric motions in Jovian planets. However, because of the dominance of non-linearity, our understanding of these flows are far from being sufficient. In the recent years, there have been several experimental studies focusing on convection at low Ekman numbers (Ek = 10-7 to 10-6) and at high Rayleigh numbers (up to 50 times critical), using water (Sumita and Olson, 2000), and gallium (Aubert et al., 2001), as the working fluid. The parameter range of these experiments are about an order of magnitude closer to that of the Earth, compared to that which can be achived by present numerical computations. Furthermore, because there are no effects arising from numerical diffusion and finite grids, it is better suited to study fine-scaled turbulence.Sumita and Olson (2000) studied convection at Ekman number of 4.7 x 10-6 and Ra/Rac upto 50, and found that the flow was dominated by geostrophic turbulence. Here, we extend their study to even higher Rayleigh numbers to see whether geostrophic turbulence prevails. To do so, we use 1cSt silicone fluid, which enables us to study convection up to 500 times critical at the same Ekman number 4.7 x 10-6. The Prandlt number of 1cSt silicone fluid is 13.9, and weakly non-linear theory (Zhang, 1992) show that the flow would not differ much from that of water (Pr = 7.1).

Experimental Method: We use a copper hemispherical shell of an outer dimeter of 30 cm and an inner diameter of 10 cm, and spin it at a rotation rate of 206 rpm. We maintain the temperature of the inner boundary (ICB) at a lower temperature than the outer boundary (CMB) to obtain the thermal buoyancy needed to drive convection. Temperature in the fluid is measured using thermistor probes. Flow velocity is measured by using neutrally buoyant tracers of fluorescent methanol solution.

Results:

Average temperature structure: Radial temperature profile indicate that there is a significant thermal boundary layer near the ICB, whose thickness decreases with Rayleigh number. Radial temperature gradient elsewhere is small and becomes nearly isothermal at the highest Rayleigh numbers. Temporal variation of temperature: The temperature fluctuates irregularly, and its amplitude decreases towards CMB, indicating that it is determined by the temperature gradient there. The amplitude scales as 0.6 power of the heat flow, which agrees with that predicted by the scaling of Cardin and Olson (1994). High frequency component increases with Rayleigh number, suggesting larger advection of radial plumes by the zonal flow.Flow velocity: Zonal flow is westward, and is about 3mm/s at Ra/Rac=277, which is about an order of magnitude larger than that at Ra/Rac=44 (Sumita and Olson, 2000). Layered convection: We also studied layered convection with the lighter silicone oil in the inner region, and the heavier water in the outer region, and measured how the total heat flow changes with the thickness ratio, under the fixed radial temperature difference. We find that the heat flow increases with the thickness of the inner layer by about a factor of 2, which can be understood from the effect of sphericity.

Conclusions: Convection up to Ra/Rac=500 can be understood by the scaling of geostrophic turbulence. Heat flow measurement of a layered convection in a spherical shell show that the heat transfer is strongly inhibited when there is a thin dense layer above the ICB, and can be relevant to the Earth's core.