Thermal convection experiments in a rotating spherical shell: A review

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Studies on thermal convection in a rotating spherical shell is important for understanding convection and magnetic field generation in planetary cores as well as in the atmospheres of giant planets. (see Zhang and Schubert (2000) for a review). As with all other studies in fluid mechanics, combination of theory, numerical calculations and experiments are used to study such convection. Here we review the results obtained from the experimental approaches and discuss the unsolved issues.

Experiments in spherical shells were first made by F.Busse and coworkers by using centrifugal force as a substitute for a radially dependent gravity (Busse and Carrigan, 1974). In these works, they primarily studied the linear regime where comparison between the analytical theory and experiments are possible. Experiments at lower Ekman numbers and higher Rayleigh numbers were explored in the 90s. Cardin and Olson (1994) used a spherical shell and Sumita and Olson (2000; 2003) used a hemispherical shell to study the basic properties of the turbulent convection at these parameters. In Sumita and Olson (1999, 2002) experiments with thermally heterogeneous boundary conditions were made to simulate similar conditions at the core-mantle boundary of the Earth. Most recently, experiments with detailed flow field measurements and experiments using gallium have been made (Aubert et al., 2001).

As a working fluid we use water and 1cst silicone oil, and by rotating a spherical shell with a diameter of 30cm at a rotation rate of 207 rpm, we achieve an Ekman number of 4.7 x 10^-6. By circulating a cooling water through the inner sphere, we impose a radial temperature gradient, and achieve a Rayleigh number of upto 600 times the critical value. This parameter is still beyond that which can be achieved using numerical methods. Thermal convection consists of plumes that form from inner and outer boundaries. These plumes have different wave numbers, and as a consequence results in turbulence. In 3-D, plumes are uniform in the direction of rotation axis, and take the form of sheets. Temperature amplitude and flow velocity in the convecting fluid agree well with the scaling relation obtained from quasi-geostrophic approximation. We also find that the mean zonal flow is westward.

We next study how the mean convection is affected when there is a thermal heterogeneity at the outer boundary. We find that the warm fluid generated by the heater flows eastward, and is separated by a stationary front with a cold westward flow. The stationary front take the form of a spiral and extends from the outer boundary towards the inner boundary, along which a localized fast flow (jet) flows towards the inner boundary. Such flows exhibit features that are similar to the geophysical flows in the atmospheres and in oceans.

Currently, there are no numerical simulations at the same conditions as in the experiments. Simulating the narrow plumes, front and jets would become a challenge to numerical computations. There are many fruitful avenues of research for numerical computations, such as how the spiraling shape of the front changes with the magnitude of the thermal heterogeneity, and whether we can verify the scaling relations obtained from simple force balance arguments.

References

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