Turbulent thermal convection at very small but finite Ekman numbers

Edgar Knobloch*[1], Adrian Van Kan[2,3], Keith Julien[4], Benjamin Miquel[5], and Geoff Vasil[6]

[1]University of California at Berkeley – United States
[2]Texas AM University – United States
[3]University of Muenster – Germany
[4]University of Colorado Boulder – United States
[5]CNRS, INSA Lyon – Ecole Centrale de Lyon – France
[6]University of Edinburgh – United Kingdom

Abstract

Geophysical and astrophysical fluid flows are typically driven by buoyancy and strongly constrained at large scales by planetary rotation. Rapidly rotating Rayleigh-Bénard convection (RRRBC) provides a paradigm for experiments and direct numerical simulations (DNS) of such flows, but the accessible parameter space remains restricted to moderately fast rotation rates (Ekman numbers Ek 10ˆ{-8}), while realistic Ek for astro- and geophysical applications are orders of magnitude smaller. On the other hand, previously derived reduced equations of motion describing the leading-order behavior in the limit of very rapid rotation (Ek → 0) cannot capture finite rotation effects. Thus the physically most relevant part of the parameter space with small but finite Ek has remained inaccessible to both theory and simulation. Here, we employ rescaled rapidly rotating incompressible Navier-Stokes equations (RRRiNSE), a reformulation of the Navier-Stokes-Boussinesq equations informed by the scalings valid for Ek → 0 (Julien et al., J. Comp. Phys. 541, 114274 (2025)), to provide fully resolved DNS of turbulent RRRBC at Ekman numbers down to Ek = 10ˆ{-15} and below, revealing the gradual disappearance of cyclone-anticyclone asymmetry at previously unattainable Ekman numbers (Ek ≈ 10ˆ{-9}). We also identify an overshoot in the heat transport as Ek varies at fixed scaled Rayleigh number RaEkˆ{4/3} associated with dissipation due to ageostrophic motions in the boundary layers. The simulations validate theoretical predictions based on thermal boundary layer theory for RRRBC and show that the solutions of RRRiNSE agree with the reduced equations at very small Ek (van Kan et al., J. Fluid Mech.1010, A42 (2025)). These results represent a first foray into a largely unexplored parameter space of thermally driven rapidly rotating turbulence rendered accessible by RRRiNSE.

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*Speaker

sciencesconf.org:rbc2026:693724