Turbulent convection on the tilted f-plane

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Abstract

In planetary cores and in the subsurface oceans of icy moons, turbulent convection is constrained by the rotation of the celestial body. These rapidly rotating flows characteristically operate in quasi-geostrophy (QG): a state where the dominant force balance is between the Coriolis force and pressure. In this regime, the Proudman-Taylor theorem promotes anisotropy and the formation of rotationally-aligned structures, observed in direct numerical simulations of Rayleigh-Benard convection in rapidly rotating spherical shells (see e.g. Gastine and Aurnou, J. Fluid Mech. 2023). The regional flow transport properties (of heat, momentum, etc.) are functions of the relative orientation of gravity and rotation, and thus of colatitude (the angular distance to the pole).
Here, to circumvent the difficulty associated with the spherical geometry, we analyse rapidly rotating Rayleigh-Benard convection in a local model: the tilted f-plane.

In this paradigm, the fluid layer is bounded by parallel surfaces with gravity orthogonal to the plates, heated from below and cooled from top, and subjected to slantwise rotation. The tilt angle between gravity and rotation represents the colatitude and, importantly, breaks the rotational symmetry in the horizontal plane.
Employing sheared (non-orthogonal) coordinates, one of which is aligned with rotation, we obtain a natural formulation for the leading order geostrophic balance and a set of governing equations for the non-hydrostatic quasi-geostrophic dynamics on the tilted f-plane (fNHQGE), valid in the asymptotic limit of rapid rotation.

We numerically compute solutions to the fNHQGE using a spectral solver (Miquel, J. Open Source Softw. 2021) and explore regimes of laminar and turbulent convection by varying the reduced Rayleigh number and the tilt angle. We observe that, as the tilt increases, the barotropic condensate transitions from large scale vortices (near the pole) to East-West jets (near the equator). We note the existence of bistability at intermediate latitudes. Concomitantly, both heat transport (Nusselt number) and the vertical kinetic energy (Reynolds number) decrease monotonically as colatitude increases.

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