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Rotating turbulence: 2D or not 2D?

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Abstract

Rotation tends to uniformize fluid flows along its axis, and, in turbulent conditions, generate an inverse cascade of energy, similarly to 2D turbulence. This results in the formation of a large-scale 2D flow called a condensate. Such a condensate arises even when energy is injected into 3D modes, implying an energy transfer from 3D to 2D. At high rotation rates, 3D modes take the form of inertial waves, each carrying energy and a sign-definite helicity, and interactions are limited to wave resonances. However, exactly resonant interactions do not transfer energy from 3D to 2D modes. Two questions thus arise: (i) Why is energy transferred directionally *from* 3D *to* 2D modes in rotating flows? (ii) How is such energy transfer possible at high rotations? We answer these questions for condensates across different regimes using extensive numerical simulations and wave-mean-flow theory. We show that the answer to (i) is an (approximate) conservation law: at sufficiently high rotation, wave-condensate interactions conserve the waves helicity *separately for each sign*, explaining the energy transfer to the condensate. These interactions are however only approximately resonant, answering question (ii), and are gradually suppressed upon increasing rotation, causing two-dimensionalization to disappear at high rotations when the flow is 3D-forced. In the other direction, decreasing the rotation rate gradually reintroduces wave-condensate interactions which break single-sign helicity conservation and divert energy from the condensate to the waves, via a forward energy flux. This generates a flux-loop of forward and inverse energy fluxes [1]. Quantitatively, our theory reproduces the Rossby and Reynolds number scalings of the condensate in different regimes, Fig. 1(b).

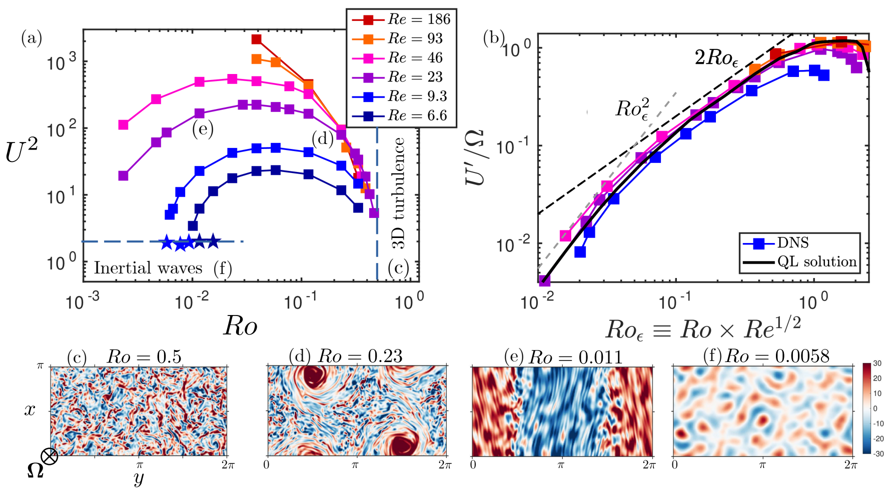

Figure 1: Spontaneously forming large-scale flows in rotating 3D turbulence. (a) Dependence of condensate energy with $Ro \propto 1/\Omega$ and Re. (b) The normalized condensate shear rate collapses as a function of Ro_ε (c-f) Flow visualizations at various values of Ro and fixed $Re = 23$: At low rotation $Ro \geq 0.5$ (c), the flow exhibits 3D turbulence. With decreased Ro, the flow first forms an array of 2D vortices (d); replaced by box-fitting jets at lower $Ro \leq 0.1$ (e) and eventually no condensate forms (f), replaced by 3D inertial waves (stars in (a))

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[1] Clark Di Leoni et al., *Phys. Rev. Fluids* **5**, 104603 (2020)