# Turbulence and jet-driven zonal flows: Secondary circulation in rotating fluids due to asymmetric forcing

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We report on experiments and modeling on a rotating confined liquid that is forced by circumferential jets coaxial with the rotation axis, wherein system-scale secondary flows are observed to emerge. The jets are evenly divided in number between inlets and outlets and have zero net mass transport. For low forcing strengths the sign of this flow depends on the sign of a sloped end cap, which simulates a planetary $\beta$ plane. For increased forcing strengths the secondary flow direction is insensitive to the slope sign, and instead appears to be dominated by an asymmetry in the forcing mechanism, namely, the difference in radial divergence between the inlet and outlet jet profiles. This asymmetry yields a net radial velocity that is affected by the Coriolis force, inducing secondary zonal flow.

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## I. INTRODUCTION

Zonal flows in rotating fluids, from Jovian atmospheric banding to the edge of tokamak plasmas, may emerge from smaller scales in a process of inverse energy transfer when the turbulent dynamics are essentially two dimensional (2D). This energy condensation was originally theorized via statistical arguments [1]. It has since been observed experimentally in flows that are effectively 2D due to rotation, stratification, magnetization, and actual thinness (e.g., soap films). This transfer or cascade of energy can ultimately lead to large-scale self-organized flows, i.e., ones comparable to the system scale. Such a zonal flow, once formed, may in turn regulate the turbulence from whence it originated, e.g., in mitigating transport [2].

The inverse cascade of energy in 2D turbulence may be understood to be the spectral manifestation of vortex merging. However, energy transfer to larger scales can also occur through nonlocal interactions (via parametric or modulational instability), where a large-scale component emerges directly from small-scale interactions—understood vectorially as an acute resonant triad—due to the nonlinear advection of

 