Zonostrophic beta-plumes, breaking waves and zonal jets in locally-forced, large-scale shallow water experiments

Eddy-driven zonal jets and Rossby waves are common features of planetary atmospheres and oceans, organising the large-scale flow and influencing the dispersion and transport of material tracers and constituents. In the presence of relatively weak friction and forcing, zonal jets form a dominant component of the flow in a regime known as “zonostrophic", characterized by strongly anisotropic energy spectra and the formation of slowly evolving systems of alternating zonal jets. This regime is characterized by two scales, $L_\beta \sim (\Pi_\varepsilon/\beta^3)^{1/5}$ and $L_R \sim (U_{rms}/\beta)^{1/2}$, where Π_ε is the transfer rate of the inverse energy cascade and β is the radial gradient of the Coriolis parameter. Their ratio is known as the zonostrophy index, $R_\beta = L_R/ L_\beta$. Zonal jets become discernible at $R_\beta \geq 1.5$ but are much stronger for $R_\beta > 2$. Achieving such high values of R_β in a laboratory is non-trivial however. The atmospheres of gas giant planets are probably well within such a regime with $R_\beta \sim 5$ [Galperin et al 2014], though the Earth's atmosphere and oceans are in a more friction-dominated state where $R_\beta \sim 1.5 – 1.8$. In this study we have investigated the flow obtained in a rapidly rotating fluid on a topographic beta-plane in a cylindrical tank, subject to localised, periodic mechanical forcing along a radius. The experiments were carried out in the 5 m diameter rotating tank at the Turlab facility in Turin, Italy under the European High-Performance Infrastructures in Turbulence (EUHiT) programme. Velocity measurements were obtained using PIV in a horizontal plane a short distance below the free surface, while discrete particles floating on the surface were tracked to obtained their Lagrangian trajectories. The flow exhibited the spontaneous formation of persistent zonal jets, nonlinear topographic Rossby waves and intense vortical eddies (see Fig. 1). The large-scale flow was found to lie within the zonostrophic regime with $R_\beta \geq 2.4$. Diagnostics indicate the presence of an anisotropic dual (inverse/direct) KE cascade. The KE spectrum, however, seems unexpectedly consistent with recent f-plane turbulence models based on Quasi-Normal Scale Elimination (Galperin & Sukoriansky 2020), the implications of which will be discussed.

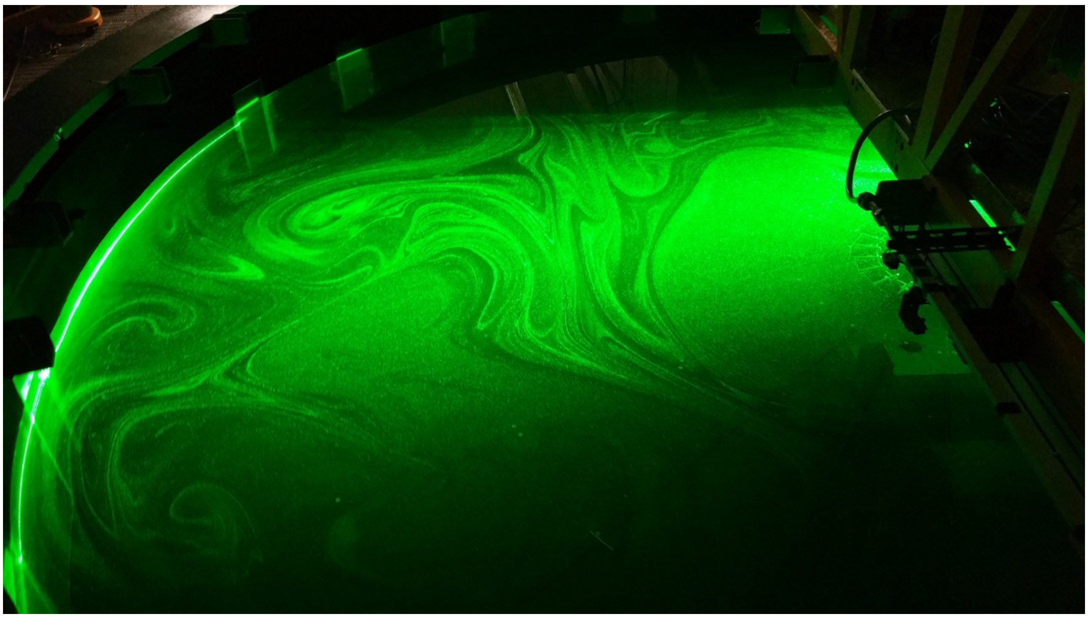

Figure 1: Photograph of a typical well-developed flow field, illuminated by the laser sheet and visualised with tracer particles.

References

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