Abstract

On rotating planets, turbulent flow often self-organizes into large-scale structures, such as vortices and zonal flows, which play a crucial role in the transport of heat, momentum, and tracers. These structures emerge from the interplay of planetary rotation, latitudinal variation in the Coriolis parameter, gravity, and topographic effects, which are effectively captured by the quasi-geostrophic (QG) turbulence framework.

First, using statistical measures and complex networks, we examine the influence of the Rossby deformation wavenumber (λ), which quantifies the relative tendency of gravity to relax the free surface and of background planetary rotation to maintain free-surface height anomalies. Irrespective of λ, the inertial energy spectrum scaling is obtained based on a self-similar distribution of vortices of different areas, while the large-scale energy spectra are obtained solely from network hubs identified using network analysis. This approach significantly reduces the degree of freedom needed to study QG turbulence. Network analysis further extends the conclusions of statistical analysis by capturing nonlocal interactions at small λ and local interactions at high λ.

Secondly, we use complex network measures to examine the transition from isotropic turbulence to anisotropic states for different values of planetary vorticity gradient (β). For small β, the flow is vortex-dominated and forms disassortative networks, while large β produces strong zonal jets and more assortative networks. At intermediate β, we identify that an increase in network length to a constant value acts as an efficient precursor for the transition from vortex-dominated, which are highly vulnerable to targeted perturbation on vortices, to robust jet-dominated dynamics.

Finally, we study the influence of topographic roughness on the self-organization of turbulence and its deviation from the theoretical minimum-enstrophy state. The isolated vortices, either roaming or topographically trapped depending on roughness, initial length scale, and energy, are responsible for these deviations. Increasing topographic roughness suppresses vortex mobility and size, leading to closer agreement with the MES for low initial energy and topographically trapped eddies at high initial energy. The degree to which numerical results deviate from MES depends on topographic roughness and initial conditions in complex ways, suggesting a rich range of ways in which turbulence organizes the long-term flow.

Overall, this thesis demonstrates that statistical, complex network, and variational approaches provide powerful tools for uncovering the mechanisms governing interactions, transitions, and self-organization in quasi-geostrophic turbulence. These findings improve our understanding of large-scale geophysical flows, which can lead to better weather predictions and offer new perspectives on the reduced-order characterization of turbulent dynamical systems.

Keywords: Quasi-geostrophic turbulence, Two-dimensional turbulence, Topographic turbulence, Complex networks, Statistical study, Variational principles.