Dynamics of Coherent Vortices in Rotation-dominated Flows

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Vortices have been recognized to be key elements in turbulent fluid motion at a wide range of scales. The Coriolis force at rotating planets, galaxies or Lorentz force due to magnetic field in plasmas makes large-scale flows anisotropic, quasi-two-dimensional (e.g., the horizontal velocity of oceanic currents is much larger than vertical velocity). Coherent, long-lived vortices and jets emerge naturally as a result of self-organization of turbulent motion observed in such anisotropic media. Coherent vortices are very efficient in trapping passive tracers for long times and transporting them over anomalously large distances. Thus, they can play a crucial role in global transport processes in rotation-dominated flows.

Typically due to strong density stratification, the circulation in intense vortices is localized both horizontally and vertically around their compact potential vorticity core [1]. Material invariance of potential vorticity is a key for the concept of "balanced" flow when the most significant three-dimensional dynamical information can be obtained by inverting the potential vorticity field at each instant. Balance and invertibility mean that freely propagating sound and inertia-gravity waves contribute only negligibly to the rotation-dominated motion. Analysis of balanced layer-piece-wise models of potential vorticity has greatly improved our understanding of vortex formation, deformation, drift, interactions with other vortices and topography [2-16].

Although baroclinic vortices and jets typically satisfy a momentum-balanced dynamics (e.g., geostrophy and its generalizations [17]), balanced turbulent cascades are very inefficient in energy dissipation. Imbalance in the form of inertia-gravity waves may play a crucial role in general circulation models, thus addressing a critical need in climate modeling, and to the closure of the mechanical energy budget. Several physical mechanisms are described for the situations when inertia-gravity waves are intrinsically coupled with balanced part of the flow.

Boundary imbalance is related to Kelvin gravity waves analyzed for a localized flow in a half-plane bounded by a rigid wall when the total mass is not conserved within the equivalent-barotropic quasigeostrophic (QG) approximation [18]. A simple formula expressing the total geostrophic mass in terms of the QG potential vorticity allows for estimating the range of the geostrophic mass variability. Consideration of the next-order dynamics shows that conservation of the total mass and circulation is provided by a compensating jet expanding with the fast speed of Kelvin waves and taking away the surplus, or shortage of mass from the geostrophic flow.

Permanently unbalanced inertial pulsations of anticyclonic lens-like vortices in stably stratified rotating fluid are described by self-similar analytical nonlinear solutions with rather arbitrary spatial vortex structure and linear radial velocity fields [19-20]. In the self-similar form pulson solutions describe radial expansion and contraction of the vortex which maintains the same spatial structure of its absolute angular momentum in properly rescaled coordinates.

Spontaneous imbalance is related to ageostrophic instability of a horizontally uniform, vertically sheared flow over a slope in two active layers underneath a deep motionless third layer [21]. The variations of the layer thickness are assumed to be small to analyze the sixth-order eigenvalue problem for finite-Froude-number typical for oceanic currents. The dispersion curves for the Rossby waves and the Poincarè modes of inertia–gravity waves are investigated to identify the different types of instabilities that occur if there is a pair of wave components which have nearly the same Doppler-shifted frequency related to crossover of branches when the shear increases. Simple criteria for ageostrophic instabilities due to a resonance between the inertia-gravity and the Rossby wave related to the thickness gradient in either the lower or middle layer, are derived. They exactly correspond to violation of sufficient Ripa's conditions for the flow stability. In both cases the growth rate and the interval of unstable wavenumbers are shown to be proportional to the square root of the corresponding gradient of the layer thickness.

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