Description of proposal:
The formation of large-scale coherent structures is widely observed in atmospheric and oceanic flows and ascribed to the nearly bi-dimensional nature of these flows. It is well known that the energy of two-dimensional (2D) turbulent flows, is transferred from the forcing scale to larger scales due to the conservation of both energy and enstrophy by the inviscid dynamics [1]. In a square domain, the energy accumulates at the largest possible scale, thus generating coherent structures in the form of large-scale vortices (see Fig. 1 top). It has been also demonstrated that zonal jets (see Fig. 1 bottom) are spontaneously generated by changing the aspect ratio of the domain [2]. Moreover, recently it was observed in laboratory experiments that the large-scale circulation generated by forcing a nearly 2D flow at small scales can display random flow reversals in a confined geometry [3]. It is an open question, whether zonal flows in rectangular domains confined in one direction can spontaneously generate zonal flows, whose mean flow directions reverses randomly in time. The dynamics of zonal jets is an outstanding challenge to understand further planetary atmospheres, which has important implications to the Earth’s climate.

This project will involve numerical simulations of the incompressible 2D Navier-Stokes equation

$$\partial_t \omega + u \cdot \nabla \omega = \nu \nabla^2 \omega + f$$

where $u$ is the velocity field, $\omega = e_z \cdot \nabla \times u$ is the vorticity, $\nu$ is the kinematic viscosity of the fluid and $f$ is an external mechanical force driving the flow. The computations will be performed in rectangular domains with periodic boundary condition in $x$-direction and free-slip in the $y$-direction using a pseudospectral code that is designed to run on parallel computer clusters [4].

Possible avenues of investigation:
The main focus of this project is to systematically vary the aspect ratio of the domain to study a) the transition from large scale vortices to zonal flows and b) the reversals of zonal jets. The results will provide new insights into the non-linear, multi-scale and statistical dynamics of these flows. This project will provide a unique experience on geophysical fluid dynamics, turbulence theory, numerical methods and scientific computing. Important results will be prepared for publication in a peer-reviewed journal.

Pre-requisite knowledge (listed as essential, recommended, useful)
Essential: some familiarity with numerical methods for PDEs and a programming language will be helpful.
Useful: The analysis is going to be based on tools from turbulence theory, bifurcation theory and statistical mechanics.
Useful reading


