Energy transfers in turbulence under rotation

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Geophysical and astrophysical flows, which are generally turbulent, are affected by several physical processes, such as stratification, thermal convection, magnetism in the case of conducting fluids, etc. One key ingredient of these flows is the presence of a global rotation which, through the action of the Coriolis force, is known to strongly influence the statistical and geometrical properties of turbulence. It is in particular well established that turbulence tends to become two-dimensional, invariant along the rotation axis. This evolution is intrinsically a nonlinear effect, and cannot be described by the (purely linear) Taylor-Proudman theorem, which predicts an exact two-dimensionality at zero Rossby number $Ro = U/2\Omega L$. Moreover, in the asymptotic state of exact two-dimensionality, the Coriolis force can be absorbed in the pressure gradient, so that it no longer affects the dynamics of turbulence. Turbulence under the action of rotation is therefore intrinsically a system at the frontier between two and three dimensionality.

A major question that arises at this point concerns the direction of the energy cascades through spatial scales which probably stand as the most clearly established feature of both 2D and 3D turbulence. During this lecture, we present different experiments illustrating the origins and the consequences of the partial two-dimensionalisation of rotating turbulence, focusing on the energy transfers between scales.

Part 1

In a first part, we present an experiment which shows how energy transfers in a triad of inertial waves (specific to rotating fluids) constitute the elementary process at the origin of transfers towards slow, quasi two-dimensional, motions in rotating turbulence at low Rossby number. A plane inertial wave is generated using a wavemaker in a rotating water tank. Using particle image velocimetry (PIV), we show that this plane wave is subject to a subharmonic instability which excites two secondary plane waves through the triadic resonance mechanism. We show in particular that the secondary wavevectors are found systematically more normal to the rotation axis than the primary wavevector transferring, energy towards more 2D modes.

As a second step, we will discuss the two-dimensionalisation process of rotating turbulence in a more general framework considering the example of a decaying rotating turbulence experiment, with an isotropic initial state. Turbulence is generated by translating a grid in a water tank mounted on a rotating platform and measurements are performed using a corotating PIV system. We measure the evolution of the scale-by-scale anisotropic distributions of energy and energy transfers as a function of time, and show in particular that the scale of maximum anisotropy follows a non-trivial dynamics. From these results, we discuss the relevance of standard scaling arguments used to describe the scale dependance of the anisotropy.

Part 2

In a second part, we consider another major question related to the peculiar dimensionality of rotating turbulence: the direction of the energy cascade in the plane normal to the rotation axis.

We discuss that question thanks to a new experiment where turbulence is forced by a set of vertical flaps which continuously injects velocity fluctuations towards the center of a rotating water tank. The energy transfers are evaluated from stereoscopic PIV measurements in the rotating frame. As the rotation rate is increased, we evidence the emergence of two coexisting energy cascades of opposite direction (forward and inverse) for the horizontal energy in the horizontal plane. The energy of vertical fluctuations is at the same time always transferred from large to small scales, a behavior reminiscent of the stretching and folding of a passive scalar in 2D. Finally taking into account the energy injection through the boundary of the region of interest, we obtain a quantitative closure of the Kármán-Howarth-Monin equation which drives the scale-by-scale energy conservation. These results allow to discuss the consequences of the subtle interplay between 2D and 3D features of rotating turbulence for the energy transfers in the horizontal plane.