# TRANSPORT OF PASSIVE TRACERS BY COHERENT VORTICES
## Final Report

Turbulent rotating flows can reveal the occurrence of long-lived coherent vortices, when they are observed with enough resolution. Examples include Gulf Stream rings and Mediterranean salty eddies in the ocean, rotating plumes in turbulent cyclones and so on.

These entities form naturally in rotating flows, as a result of a self-organization of a random initial vorticity field into long-lived vortices dominating the dynamics of the flow and emerging as individual coherent structures from the turbulent background. They are typically associated with an inverse cascade of energy from small to large scales, even if this mechanisms, in itself, is not enough to explain why coherent vortices are generated.

At present, general circulation models of the ocean and the atmosphere do not resolve the full spectrum of eddies which are present in the system and rely on some forms of parameterization of their activity which however could not be correct for coherent vortices.

In addition, coherent vortices showed to be able to trap passive tracers for long times and can provide a mechanism of anomalous transport which is absent in unstructured turbulence.

The foregoing statements suggested to support the theoretical and numerical studies with refined laboratory observations that, allowing a better control of governing parameters and the repeatability of experimental conditions, can give a contribution toward finding out some solutions to the problems mentioned before.

A set of laboratory experiments, meant to simulate the onset and growth of long-lived coherent structures naturally occurring in turbulent rotating flows, have been carried out in the large-scale platform (14 m in diameter) of the Coriolis Laboratory of LEGI-IMG.

The main objective of these experiments was to give a contribution toward finding out some solution of two specific problems regarding the foregoing coherent structures, namely:

a) their generation mechanism, not yet fully explained by the inverse cascade of energy; and
b) their ability to trap passive tracers for long time and to provide a mechanism of anomalous transport, which is not found in unstructured turbulence.

The laboratory experiments measured both the evolution of coherent 2D structures generated by the inverse cascade in a background rotating turbulence and the anomalous dispersion on individual Lagrangian tracers injected inside and outside the cores of these structures, on account of the fact that linear relative dispersion and limited radial mixing of tracers is expected inside the vortex while, on the contrary, chaotic advection and more rapid tracer dispersion should occur outside. Another objective of the study was the evaluation of the statistical difference between the inside and outside of a vortex, in controlled laboratory conditions that allow for varying the control parameters (Rossby number [Ro], Rossby deformation radius [Rd], etc.) and for achieving more significant statistics than in the natural environment.

The following experimental conditions for the final state dynamics have been selected :

| Rossby number | Rossby deformation radius R(m) | Rotation period T(s) | Water depth H(m) |
|---|---|---|---|
| $4\ 10^{-2}$ | 12.0 | 50 | 0.90 |
| $8\ 10^{-2}$ | 24.0 | 100 | 0.90 |
| $4\ 10^{-2}$ | 7.4 | 50 | 0.35 |
| $8\ 10^{-2}$ | 14.8 | 100 | 0.35 |

for a total of about 40 runs (each run took approximately half a day).

For the larger values of the Rossby number, possible ageostrophic effects can be measured and studied: they will be the object of a subsequent study.

In our experiments, addressed to study barotropic turbulence in the shallow water or the quasi-geostrophic approximation, only fresh water was introduced in the rotating tank of the LEGI-IMG Coriolis facility. In order to establish simple geometrical boundary conditions for our study domain, a closed linear channel, 8.4 m long and 4.05 m wide, has been built and set in the tank, in a off-diametral position allowing to keep aside the central pivot (fig. 1a).

A sliding rigid frame (fig. 1b) of equally spaced vertical flat roads (1 m long and with a varying horizontal spacing from 10 to 25 cm) called “vertical comb”, has been fitted in the linear channel for generating the initial field of turbulence.

Another specific facility, designed for this kind of experiments and aimed at creating an isolated coherent vortex, was a rotating cylinder (1m in diameter) hanged from a small rotating hand-crane allowing to lower it in the water at pre-determined positions of the channel.

With reference to the previously mentioned problem of the dispersion inside and outside vortices, we used few float-like tracers calibrated with the flow density in order to get some direct Lagrangian information at a fixed depth. They were furnished by a fluorescent bright stick to visualize them.

Both qualitative and quantitative measurements of velocity, vorticity and dispersion have been obtained using different measurement techniques of Coriolis facility: *Particle Image Velocimetry*, *Laser Induced Fluorescence* and *Float Tracking*.

In order to use PIV, water inside the channel was evenly seeded with a mixture of optical tracers, made up by Argasol particles of 90 μ and Optimage particles of 150 μ. A laser beam, emitted by a powerful Neodymium YAG laser, was expanded by an optical system to produce a thin light sheet, illuminating the optical tracers in the channel, so as to visualize with a Kodak Megaplus (1008x1016 pixels) camera the turbulent motion field in horizontal planes, whose typical size was of the order of (3x3) $m^2$ (fig. 2).

Images taken in this way at different times were treated two by two with a cross-correlation based algorithm (*VSV*© by Fincham et al.) and post-processed in order to produce a velocity vector field and a vorticity field on a regular grid (see figure 3 as an example).

The work in progress now consists in interpolating in time these experimental velocity fields and in getting a high rate sample, aimed at using it later on to integrate numerically the equation of motion for passive tracers $d\vec{X}_{Lagr} / dt = \vec{u}_{Euler}$ .

Laser Induced Fluorescence images have been taken using *fluorescein* as tracer. This technique has let us to visualize the coherent structures and to follow qualitatevely their evolution, together with the possibility to identify the positions of the float-like tracers with respect to the vortices.

Preliminary results about Eulerian dynamics, got from the PIV analysis of the velocity and vorticity fields, show $K^{-a}$ energy spectra, with $a \approx 4$ in the enstrophy cascading range, which confirm the results of the numerical simulations (see for example McWilliams 1990, “The vortices of 2D turbulence”, *JFM* 219)

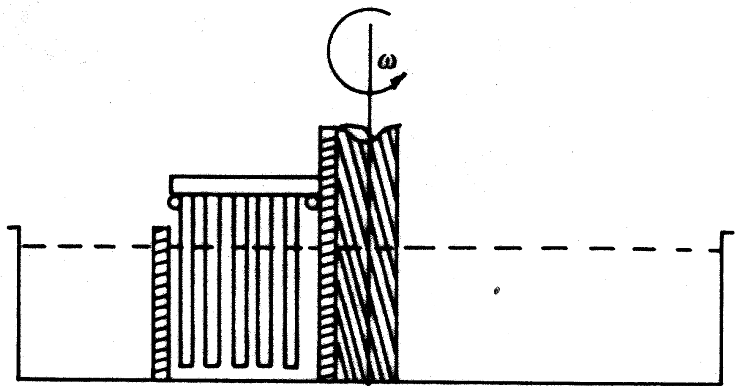


Figure 1b

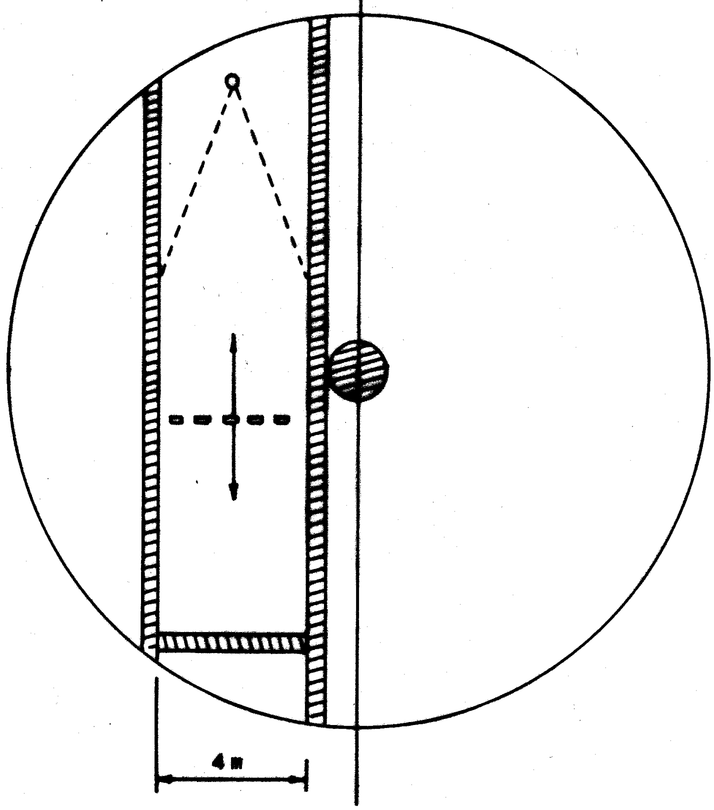


Figure 1a

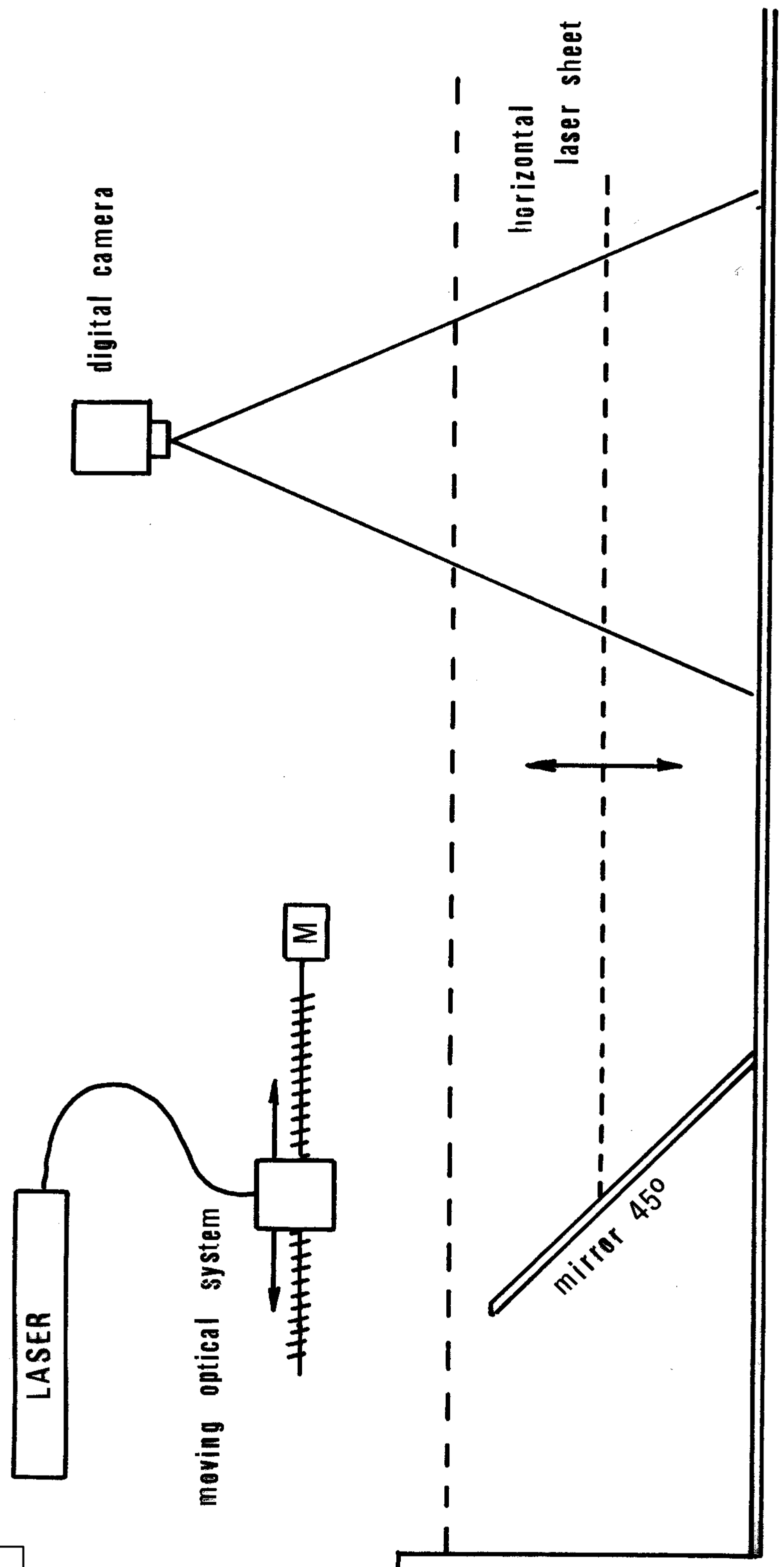
digital camera
horizontal
laser sheet
M
LASER
moving optical system
mirror 45o

Figure 2

H90T100v2000 at time t = 12 min

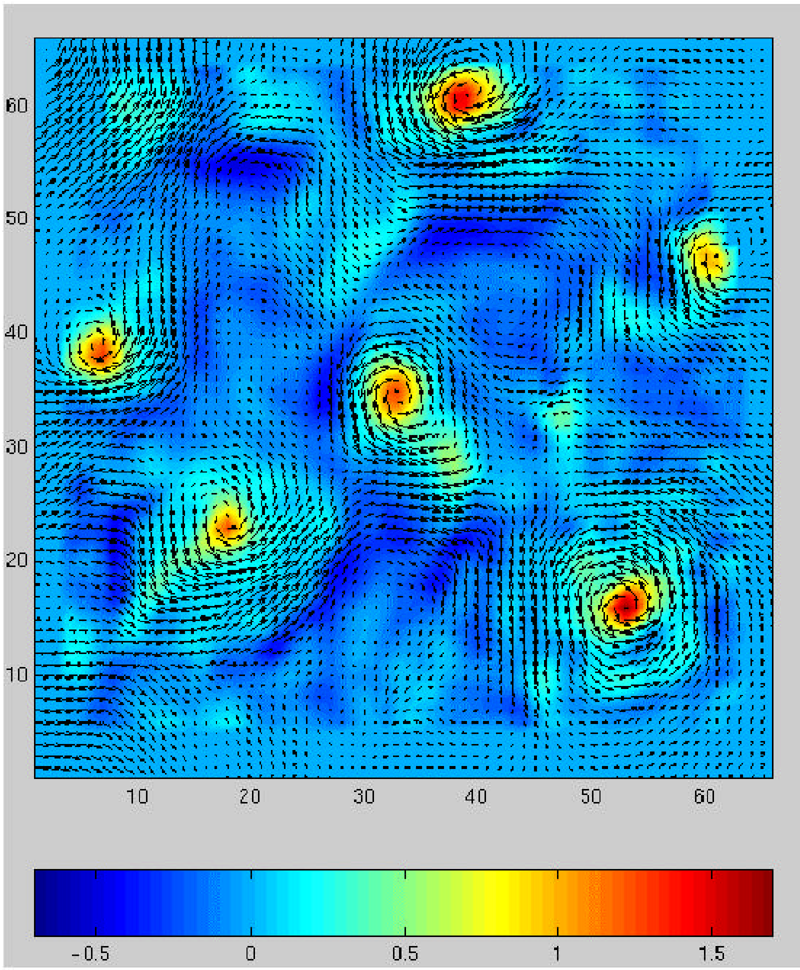


Figure 3