# LABORATORY SIMULATION OF ZONATION IN ROTATING FLOWS

Espa Stefania[1] & Di Nitto Gabriella [1]
[1]*Department of Civil, Construction and Environmental Engineering, Sapienza Università di Roma, via Eudossiana 18, 00184, Rome, Italy*

*Abstract* A rotating turbulent flow subjected to a $\beta$-effect has been considered in a laboratory setting. Several experiments have been performed in a rotating tank in which a shallow layer of saline solution has been forced by means of the Lorentz force. The parabolic free-surface of the rotating fluid has been used to simulate the $\beta$-effect. We investigated the emergence and the evolution of zonal jet-like structures due to the anisotropization of the upscale energy transfer typically observed in geophysical turbulence. The flow has been characterized in terms of the zonal velocity, the degree of anisotropy, the jet scale and the energy spectra.

The large-scale circulations of the planetary atmospheres and of the terrestrial oceans can be considered quasi-two-dimensional. The planetary rotation, the topographical constraints and the fluid stratification contribute in determining this peculiar feature. Moreover, the large-scale flows are affected by the latitudinal variation of the Coriolis parameter, the so-called $\beta$-effect [1]. This variation can induce flow anisotropy and the self-organization into jet-like structures along the zonal (i.e. East-West) direction [2-4]. Zonal jets have been observed in the atmospheres of the gas giant planets [5-6] and, more recently, in the Earth oceans [7, 8]. In the last 30-40 years, the physical phenomena leading to the formation and maintenance of the zonal jets have been intensely debated in the literature. According to one of the most important theories, the process of zonation is attributed to the anisotropic inverse energy cascade [9]. In two-dimensional turbulence the presence of the $\beta$-effect can lead to the anisotropization of the inverse energy cascade in small-scale forced, large-scale damped, barotropic flows [9]. In this context four possible flow regimes have been identified and classified in terms of a single non-dimensional parameter, $R_\beta$, known as zonostrophy index. Among these regimes, a universal behavior is found in the range $R_\beta > 2.5$ termed as *zonostrophic regime*. The main characteristics of this regime are a strongly anisotropic kinetic energy spectrum and the presence of a slowly changing system of alternating zonal jets spanning the entire flow domain [10-11]. The regime of zonostrophic turbulence has been identified as one of the basic mechanisms of generation and maintenance of planetary and oceanic zonal jets [6, 12].

We study, experimentally, the appearance of zonal jets in turbulent, rotating, shallow water fluid, in forced regime. The experimental setup consists of a square tank placed on a rotating table, 1m in diameter, whose imposed rotation is in counter-clockwise direction in order to simulate flows in the Northern hemisphere. The latitudinal variation of the Coriolis parameter has been simulated by the parabolic free-surface of the rotating fluid. The initial distribution of vorticity has been generated via the Lorentz force in an electromagnetic cell. Flow measurements have been performed using an image analysis technique in order to characterize the flow in terms of the mean azimuthal velocity, the degree of anisotropy, the distribution of energy and the jet scale. Spectral analysis has also been performed. In previous works we investigated the emergence of the jets both in decaying and forced regimes [13, 14]. In this work we consider a wider range of variation of the experimental parameters in the forced regime. In particular, we investigated the characteristics of the zonal jet-like structures varying the strength of the $\beta$-effect and of the forcing intensity. For this aim, the experiments have been performed changing the tank rotation rate and the amplitude of the forcing. Moreover, we investigated the response of the flow at the variation of the forcing configuration. Several experiments have been performed changing both the magnets size and their disposition.
As a result, the flow shows a clear tendency to self-organize into zonal structures. These bands are quite stationary when a stronger $\beta$-effect and a weaker/medium forcing intensity are considered (Fig. 1). We evaluated the length scale of the zonal structures in all the experiments. It has been observed that increasing $\Omega$ or decreasing the total energy of the system, the radial width of the jets tends to decrease. As far as the relation between the jet-scale and the $\beta$-strength (or the energy level) is concerned [4], these results provide an experimental validation of the theoretical predictions by Vallis and Maltrud.

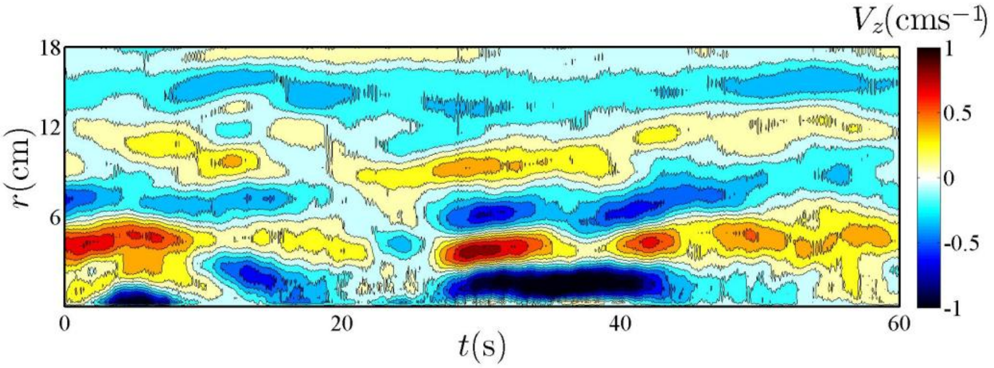


**Figure 1.** Azimuth-time contour plots of the azimuthal mean flow.

## References


[1] J. Pedlosky. Geophysical Fluid Dynamics (Springer-Verlag, New York Inc., 1987).

[2] P. Rhines. Waves and turbulence on a beta-plane. *J. Fluid. Mech* **69**: 417–443, 1975.

[3] G. P. Williams. Planetary circulations: 1. Barotropic representation of Jovian and terrestrial turbulence. *J. Atmos. Scie* **35**: 1399–1426, 1978.

[4] G. Vallis and M. Maltrud. Generation of mean flows and jets on a beta plane and over topography. *J. Phys. Oceanogr.* **23**: 1346–1362, 1993.

[5] K. Kondratyev and G. Hunt. Weather and Climate on Planets. (Pergamon, New York, 1982).

[6] B. Galperin, S. Sukoriansky and H.-P. Huang. Universal n−5 spectrum of zonal flows on giant planets. *Phys. of Fluids* **13**: 1545–1548, 2001.

[7] H. Nakano and H. Hasumi. A series of zonal jets embedded in the broad zonal flows in the Pacific obtained in eddy-permitting ocean general circulation models. *J. Phys. Oceanogr.* **35**: 474–488, 2005.

[8] N. A. Maximenko, B. Bang and H. Sasaki. Observational evidence of alternating zonal jets in the world ocean. *Geophys. Res. Lett.* **32**, L12607, 2005.

[9] S. Sukoriansky, N. Dikovskaya and B. Galperin. On the "arrest" of the inverse energy cascade and the Rhines scale. *J. Atmos. Sci.* **64**, 3312-3327, 2007.

[10] B. Galperin, S. Sukoriansky, N. Dikovskaya, P. L. Read, Y. H. Yamazaki and R. Wordsworth. Anisotropic turbulence and zonal jets in rotating flows with a β-effect. *Nonlinear proc. in Geo.* **13**, 83, 2006.

[11] S. Sukoriansky and B. Galperin. Anisotropic turbulence and internal waves in stably stratified flows (QNSE theory). *Phys. Scr.* **T132**, 014036, 2008.

[12] B. Galperin, H. Nakano, H. P. Huang and S. Sukoriansky. The ubiquitous zonal jets in the atmospheres of giant planets and Earth's oceans. *Geophys. Res. Lett.* **31**, L13303, 2004.

[13] S. Espa, G. F. Carnevale, A. Cenedese, M. Mariani. Quasi two-dimensional decaying turbulence subject to the beta effect. *J. of Turbulence* **9**: 1-18, 2008.

[14] S. Espa, G. Di Nitto, A. Cenedese. The emergence of zonal jets in forced rotating shallow water turbulence: A laboratory study. *Europh. Letters* **92**: 34006, 2010.