Coherent structures in rotating turbulent flow: laboratory and numerical experiments

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We compare our laboratory experiments and numerical simulations on the time evolution of coherent structures in a rapidly rotating cylindrical tank. The laboratory flow is produced by forcing water through sources and sinks near the bottom of a closed rotating cylindrical tank (40 cm diameter, 50 cm height) [1]. The flow evolves from strongly three-dimensional small-scale turbulence near the forcing to rotationally dominated large-scale quasi-two-dimensional flow near the top of the tank. Particle Image Velocimetry is used to obtain velocity and vorticity fields. Direct Numerical Simulations (DNS) are made for a rotating shallow-water flow using a pseudo-spectral method. No-slip boundary conditions are imposed on the cylindrical wall using a volume penalization method which considers both the fluid and the solid regions as porous media, whose permeability tends to zero in the solid and to infinity in the fluid [2]. A Brinkman force term is added to the momentum equation to model the effect of the no-slip boundary condition; this results in the production of vorticity at the wall. In both the laboratory and numerical experiments we observe that the turbulent flow develops intense localized coherent structures that persist for times long compared to the dissipation time scale. We analyze the flow throughout its evolution using either a discrete wavelet packet transform (DWPT) (order $N \log_2 N$ operations) or a discrete wavelet transform (DWT) (order N operations) [3, 4], and compare both methods. The basis functions of the DWT are a fixed set of dilations and translations of a "mother" wavelet with compact support. The basis functions of the DWPT are a generalized set of the DWT basis which include spatial modulation of the mother wavelet; the choice of the particular DWPT basis is adapted to the vorticity field analyzed. We separate the coherent flow from an incoherent remainder using a nonlinear thresholding of the DWPT and DWT coefficients [5]. The large-amplitude coefficients above a threshold are identified as "coherent", while the small-amplitude remaining coefficients are "incoherent". Coherent and incoherent vorticity fields are then reconstructed by the inverse transform of the respective coefficients. The respective velocity fields are reconstructed from the vorticity fields using Biot-Savart's integral relation. We find that the DWPT and the DWT yield similar results despite the adaptability of the DWPT basis; therefore the lower computational cost of the DWT makes it preferable. In both the experiment and numerical results, we find that less than 10% of the coefficients of each transform are required to produce coherent fields that retain 98% of the total enstrophy. The coherent flow also preserves the global properties of the total flow throughout its evolution such as broad PDFs, the enstrophy spectra, the long range temporal and spatial correlations, the coherence of the scatter-plot between vorticity and streamfunction, and transport of passive scalar particles. In contrast, the remaining incoherent flow has quasi-Gaussian PDFs, does not preserve the enstrophy spectra, has short range temporal and spatial correlations, does not show coherence of the scatter-plot between vorticity and streamfunction, and only contributes diffusively to the transport. This motivates the possibility of simulating turbulence using only a small number of "coherent" coefficients, resulting in significant computational savings.

References

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