Modeling the Effects of Anisotropic Turbulence and Dispersive Waves on Oceanic Circulation and their Incorporation in Navy Ocean Models

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LONG-TERM GOALS

Our long-term goals are to advance the understanding and modeling capabilities of the dynamics and mixing in oceanic and atmospheric turbulent flows on small and large scales. The main emphasis is put on the development of analytical tools and their transition to practical applications useful for Navy operations.

OBJECTIVES

Our objectives encompass three areas: improving understanding of geophysical turbulent flows affected by anisotropy and waves using analytical tools; improving understanding of the physics of transition between 2D and 3D turbulence and the mechanisms of zonation, and improving performance of practically used ocean models by supplying them with advanced schemes for subgridscale parameterization.

APPROACH

Our analytical research relies upon the quasi-normal scale elimination (QNSE) theory of turbulence developed by our team, primarily by Dr. Sukoriansky. This is a spectral theory that enables one to obtain anisotropic eddy viscosities and eddy diffusivities in complicated flows affected by various external factors such as stable stratification or system rotation. We use numerical simulations to substantiate and validate our theoretical results and generate information not available from the analytical tools.

WORK COMPLETED

We have applied the QNSE theory to flows with system rotation. This is still an ongoing effort but we have already obtained important results, see below. We have also performed a large number of simulations of barotropic vorticity equation on the surface of rotating sphere which showed that large-scale flows with a beta-effect develop inverse energy cascade that facilitates energy transfer from eddies to mean flows. We have analyzed energy exchange between eddies and the mean flow and quantified this exchange in terms of the zonostrophy index. We compared our results with data collecetd by space stations and satellites.

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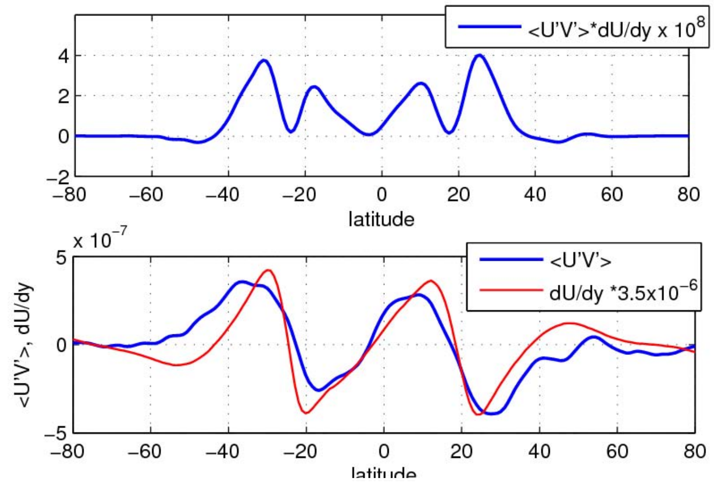
RESULTS

The most striking finding of the application of the QNSE theory to rotating turbulence is that the horizontal eddy viscosity on large horizontal scales gradually decreases and goes to zero. This result exposes flow two-dimensionalization under the action of strong rotation on scales on which the Rossby number, Ro, is smaller than 1. In principle, it is expected that due to the two-dimensionalization, the Laplacian eddy viscosity will become negative on scales larger than the forcing scale and where Ro < 1 thus reflecting the inverse energy cascade characteristic of two-dimensional turbulence. As far as we know, no analytical theory so far was able to capture such transition in turbulence with rotation. In the framework of the QNSE theory, this result suggests that the scale elimination procedure should account not only for $O(k^2)$ terms which contribute to the Laplacian viscosity but also for $O(k^4)$ terms which give rise to a biharmonic viscosity. The biharmonic viscosity has been used in many models of oceanic and atmospheric circulations but neither its origin nor the value of the biharmonic viscosity coefficient or its scale dependence have been thouroughly investigated. Our research offers an opportunity and a venue for such an investigation.

Generally, one may question the utility of computational schemes with negative eddy viscosity. To address this important query, we used direct numerical simulations of 2D barotropic turbulence on the surface of a rotating sphere. Our purpose was to investigate the impact of the inverse energy cascade on large-scale flows where not only rotation but also beta-effect are important. The flow was in the regime of zonostrophic turbulence for which the zonostrophy index, $R_\beta \geq 2.5$ (see Galperin, Sukoriansky and Dikovskaya, 2008, 2010). In these simulations, we had $R_\beta = 2.32$. We have calculated the production of turbulence energy given by W = <uv> dU/dy, where u and v are fluctuations of the zonal and meridional velocities, respectively, U is the mean zonal velocity, and the angular brackets, < >, denote an averaging over the entire surface of a planet. A positive value of W indicates that the kinetic energy is transferred from smaller to larger scales, i.e., from eddies to a zonal flow (Salyk et al., 2006). A figure below shows that in our simulations, W>0 almost for all latitudes thus indicating that the inverse cascade is strong and global. In addition, the correlation between <uv> and dU/dy is strong, about 0.79, such that the Reynolds stress and the lateral shear appear to be almost linearly related. Obviously, a straightforward division of <uv> by dU/dy would yield negative viscosity. However, as discussed above and in our earlier papers (e.g., Sukoriansky et al. 1996, 1999; Sukoriansky and Galperin, 2005), in the case of 2D turbulence, one needs to use a stabilized negative viscosity (SNV) formulation that combines *negative Laplacian* and *dissipative biharmonic* viscosities. In SNV, both viscosity coefficients are flow dependent and so the relationship between <uv> and dU/dy is not straightforward and requires further research which can be expected to have important implications for understanding of jet flows in the oceans and the atmosphere.

We compared our results with the data collected by the Cassini space station during its encounter with Jupiter (Salyk et al., 2006) where the zonostrophy index is large. Both the turbulence energy production, W, and the correlation between <uv> and dU/dy obtained in our simulations are in very good agreement with the observations. The comparisons are ongoing and we are exploring flows with large, small and intermediate values of the zonostrophy index such that we expect that this effort will further clarify the dynamics of large-scale turbulence with a beta-effect, the structure of planetary circulations and the physics and transport properties of the oceanic jet flows. It is instructive to note that since our first publication on oceanic zonal jets, e.g., Galperin et al. (2004), the research in this area has been constantly expanding and today, these jets are considered to be a fundamental part of ocean dynamics significantly affecting all transport properties (e.g., Maximenko et al., 2009).

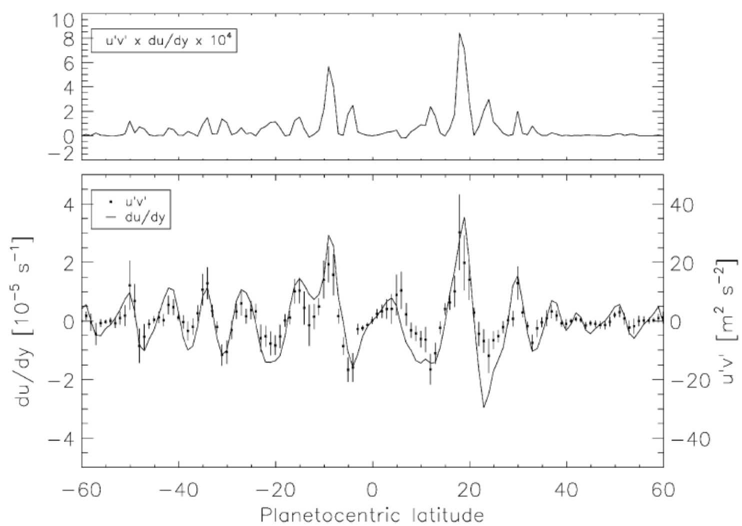
Negative viscosity in zonostrophic turbulence



n_ϕ=16, n_{Rh}=6.9, R_ϕ=2.32.

Simulations are in good agreement with the Cassini data for Jupiter; the correlation coefficient is 0.79.

Transport of momentum on Jupiter



Zonal velocity data for Jupiter collected by the Cassini mission (Salyk et al., Icarus, 2006). There is a distinct positive correlation between the Reynolds stress and the zonal velocity shear, their correlation coefficient being 0.86. The product $\overline{u'v'}\,\mathrm{d}\bar{u}/\mathrm{d}y$ ***averaged over the surface yields the power per unit mass transferred from eddies to zonal mean flow and points to a "negative viscosity" mechanism.***

IMPACT/APPLICATIONS

We expect that our research will improve modeling of oceanic flows via further improvement of the subgridscale mixing schemes and deepening of our understanding of the dynamics and transport properties of turbulent flows with strong anisotropy and different types of dispersive waves.

RELATED PROJECTS

US Army Research Office, Agreement Number W911NF-09-1-0018: Further implementation and refinement of the QNSE model of turbulence.

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HONORS/AWARDS/PRIZES

2009 USF Outstanding Research Achievement Award – for the discovery of zonons