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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 global long-term goal is making further progress in understanding of the mixing processes in the ocean on large and small scales. To achieve this goal, we develop theories of anisotropic turbulence and dispersive waves in different environments, test them, compare them with data and implement them in ocean models. In this project, the goals were to extend the QNSE theory of turbulence to flows with solid body rotation, conduct a comprehensive study of the spectral characteristics of such flows, to develop a theory of the combined effect of rotation and stable stratification which may shed new light upon the Garrett-Munk spectrum, and to test these theories in oceanic models.

OBJECTIVES

The objectives of this project were outlined in the proposed following tasks:

1. Development of the analytical model for stable stratification for the case of weak stratification
2. Completion of the development of the QNSE theory for rotating flows and consideration of the limits of weak and strong rotation
3. Development of a theory of scalar diffusion in turbulence with rotation
4. Development of a theory turbulence that includes both rotation and stable stratification
5. Implementation and testing of the QNSE-based turbulence models in models of ocean circulation
6. Dissemination of results in scientific papers, conferences and meetings.

APPROACH

We use the QNSE theory to derive expressions for the effective, horizontal and vertical, viscosities and diffusivities in flows with stable stratification and/or a solid body rotation. We have also performed computer simulations with an idealized circulation model of quasi-two-dimensional turbulence on the surface of a rotating sphere in order to study turbulence anisotropization and diffusion modification under the action of a beta-effect. Key individuals in this effort, along with the PI, are Professor Sukoriansky and Dr. Dikovskaya from the Ben-Gurion University of the Negev, Beer-Sheva, Israel.

WORK COMPLETED

We considered a limit of weak stable stratification and developed an analytical theory of transition from turbulence to internal wave dominated turbulence. Unlike previous theories, QNSE fully accounts for turbulence anistropization and effect of waves and allows one to develop quantitative criteria for turbulence-wave transition.

We applied the QNSE algorithm to a flow with solid body rotation and calculated effective viscosities and diffuisivities in the directions parallel and orthogonal to the axis of rotation.

We extended our studies to quasi-2D flows with a beta-effect and found out that when a small-scale forcing is present, Rossby waves are excited on large scales. The most energetic Rossby waves excite secondary waves, which we termed *zonons*.

Our studies of the flows with rotation indicate that it may be difficult to extend them to the case of strong rotation but the progress can be achieved if rotation is inroduced using a small parameter expansion over the flow with stable stratification. This is an ongoing effort.

PI has been a member of a team on Martian planetary boundary layer at the International Space Science Institute and was responsible for reviewing turbulence models currently used for modeling boundary layers in atmospheric and ocean circulations. His review became a part of the paper recently published in the Reviews of Geophysics.

Results of our research have been published and reported in a variety of conferences and other forums.

RESULTS

We derived the first of its kind analytical theory of transition from neutral to stably stratified turbulence. The theory shows how turbulence interacts with internal waves and how wave characteristics can be related to the viscous dissipation, ε.

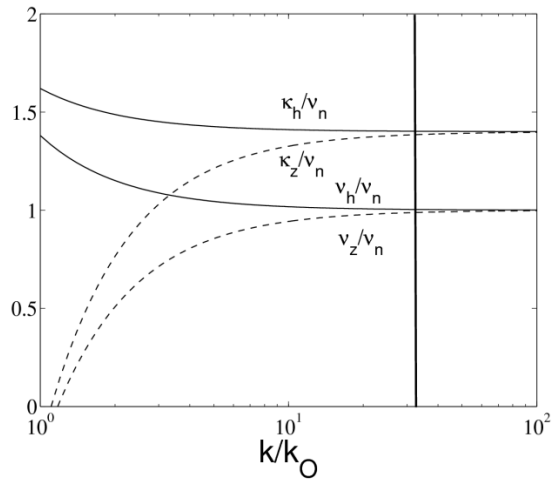

Figure 1: Normalised horizontal and vertical eddy viscosities (ν_h, ν_z) and diffusivities (κ_h, κ_z) as functions of k/k_O. Thick vertical solid line shows the threshold of internal wave suppression by turbulence. For normalization we use ν_n, effective viscosity for neutral stratification, and the Ozmidov wave number, $k_O=(N^3/\varepsilon)^{1/2}$, where N is the Brunt-Vaisala frequency. The theory is only valid for relatively large k/k_O; for $k/k_O < 5$, full solution needs to be considered.

Analogous results were obtained for flows with a solid body rotation. In this case, the theory shows that the effective horizontal viscosity decreases which is consistent with the developing inverse energy cascade while the vertical viscosity increases relative to the horizontal viscosity.

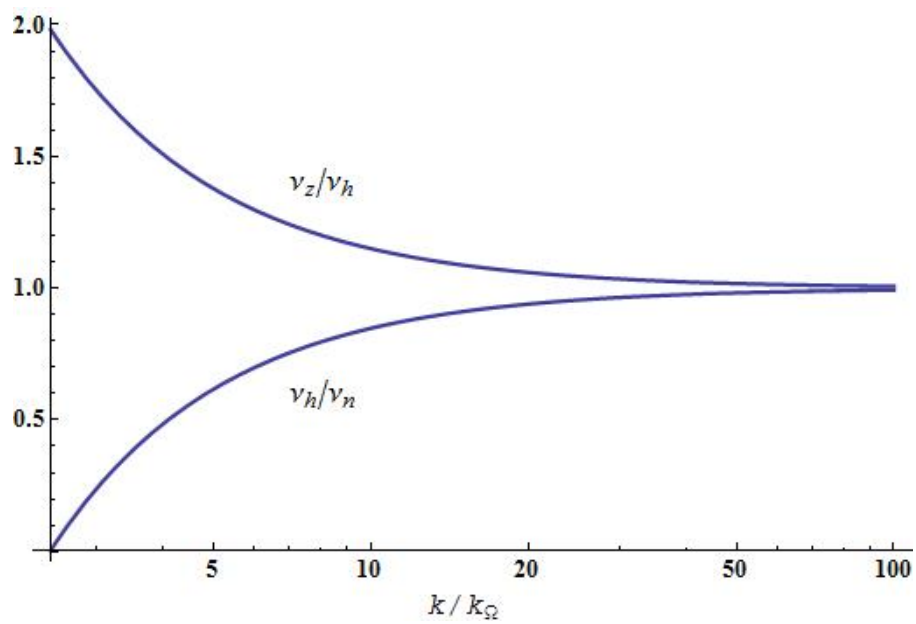

Figure 2: Normalised horizontal and vertical eddy viscosities (ν_h, ν_z) and diffusivities (κ_h, κ_z) as functions of k/k_Ω, where k_Ω is the rotational analogue of the Ozmidov wave number, $k_\Omega=(\Omega^3/\varepsilon)^{1/2}$, where Ω is the angular velocity of the solid body rotation.

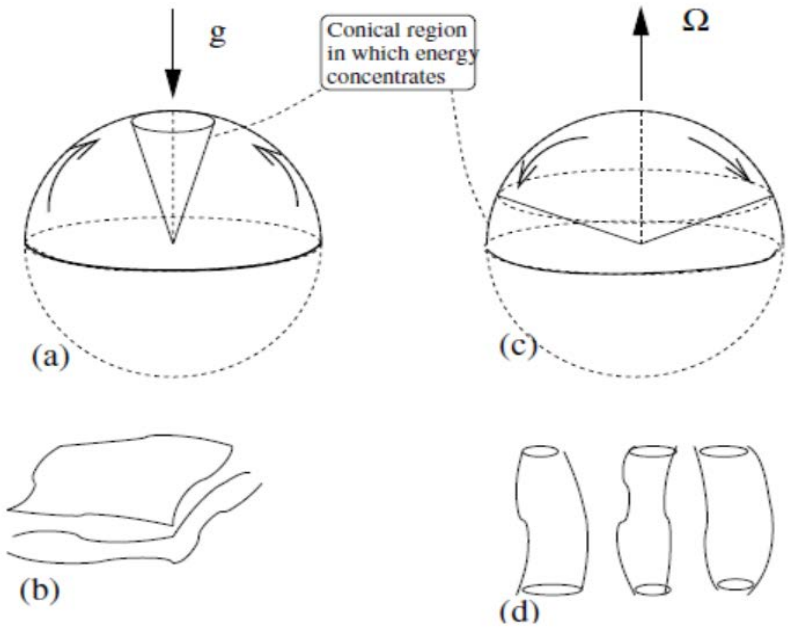

Figure 3: Angular energy drain for (a) stably stratified, (c) rotating turbulence, (b), (d) – shape in physical space (from C. Cambon, "Strongly Anisotropic Turbulence, Statistical Theory and DNS")

Anisotropic spectra of stably stratified and rotating turbulence produced within the QNSE formalism confirm results from Cambon shown in Fig. 3, namely that in flows with stable stratification the energy concentrates in horizontal layers ("pancakes") while in flows with rotation, the energy concentrates in vertically extent cylindrical structures ("cigars"). The diffusion coefficients, not shown here, do not show singularities and remain positive even on large scales. This behavior confirms our previous results that the wave-dominated scales do not contribute to scalar diffusion.

Simulations on a beta-plane show that zonons form non-dispersive, wetsward propagating wave packets that resemble non-dispersive eddies detected in the upper ocean using satellite altimetry. At the present, we are studying the physics of the zonons in an attempt to find our whether or not they satisfy the Korteweg- de Vries equation, i.e., whether or not they are the manifestation of the Rossby solitary waves.

In summary, this research yields significant new understanding of the fundamental mixing processes in the ocean and provides quantitative results (eddy viscosities and eddy diffusivities) that can be implemented in ocean circulation models.

IMPACT/APPLICATIONS

Subgridscale parameterizations have traditionally been one of the difficult subjects in numerical modeling of oceanic circulation and the progress being made in this ongoing research will help to further improve circulation models.

TRANSITIONS

The QNSE model of stably stratified turbulence has been implemented in the state-of-the-art atmospheric model WRF. We are working on the implementation of the QNSE model in HYCOM used at NRL - Stennis Space Center in collaboration with Dr. Jim Richman.

RELATED PROJECTS

PI received a grant from the International Space Science Institute in Bern, Switzerland to put together a study team which will survey the state-of-the-art in our understanding of the zonal jets and eddies in planetary, oceanic and laboratory environments.

PUBLICATIONS

Galperin, B. & S. Sukoriansky, 2010 Geophysical flows with anisotropic turbulence and dispersive waves: flows with stable stratification. *Ocean Dyn*., **60**, 1319–1337. (doi:10.1007/s10236-010-0325-z)

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