Superparameterization of Oceanic Boundary Layer Transport

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LONG-TERM GOALS

To achieve deeper understanding of physical processes in turbulent planetary boundary layers and apply it to the development of more physically accurate modeling of coherent vortices to assess the oceanic boundary layer parameterizations used in high-resolution ocean models, specifically with respect to their impact on synoptic model predictions.

OBJECTIVES

One of the most difficult processes which limit our ability to generate realistic, high-resolution simulations of the ocean state is intermittent nature of oceanic turbulence related to the presence of coherent structures at wide range of scales when simple parameterizations based on eddy diffusion concepts do not necessarily provide the correct answer. The coherent vortices have life-times in excess of the appropriate eddy turnover time. This clearly contradicts the notion underlying the dimensional analysis of the turbulent cascade. It is necessary first to understand the transport of momentum and heat due to coherent vortices in order to properly parameterize it in ocean circulation models. That is a main goal of our study.

APPROACH

An interactive approach of data analysis and modeling is pursued. The data analysis provides a detailed description of the currents in the boundary layer, and guides the model development; the model on the other hand is intended to isolate and elucidate essential physics governing the flow behavior, thus aiding the interpretation of the observational data.

WORK COMPLETED

The boundary layer model developed by Ginis et al. (2004) and designed to explicitly simulate coherent roll vortices and their interaction with the mean flow has been generalized to include the Coriolis force. Transport properties of roll vortices were calculated and compared with the results of LES simulations. New physical mechanisms important for synoptic prediction of baroclinic eddies over steep topography and in sheared background flow were investigated (Sutyrin 2006a, Carton and Sutyrin 2006). An effective quasi-Lagrangian approach was developed for analysis of ageostrophic pulsations of stratified lens-like eddies (Sutyrin 2006b, c).

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RESULTS

a) *Transport properties of roll vortices in the boundary layer.*

We used the boundary layer model developed by Ginis et al. (2004) which is designed to explicitly simulate roll vortices and their interaction with the mean flow. Since this model has been originally designed for the boundary layer in non-rotating fluid, it was modified to include the Coriolis force for planetary boundary layer simulations. We use a simplified geometry, as shown in Fig. 1**,** in which the y-axis is directed along the background flow, x-axis is perpendicular to it, and z-axis is in the vertical direction. That model assumes that a) the roll vortices extended along the direction of the background wind; b) the spatial scale of the roll vortices along x-axis and in the vertical is much smaller that the spatial scale along y-axis. These differences in the characteristic spatial scales allow for splitting the full 3-D system of equations into two subsystems for the mean flow variables and for the deviations, correspondingly. Concerning the spatial structure of the rolls shown in Fig. 1, note that we do not assume that the lengths of roll vortices are of the same scale as the distance between the convective cross-sections, any subgrid scale parameterization (it is the main concept of the parameterizability) is based on the assumption that the statistical characteristics of subgrid scale motions (in our case, the roll vortices) are fully determined by the large scale environment (the resolved scales). The statistical properties of subgrid scale motions are dependent on the spatial scales of the mean flow. In each cross-section the roll vortices have the properties corresponding to the large-scale forcing within the area of the cross-section.

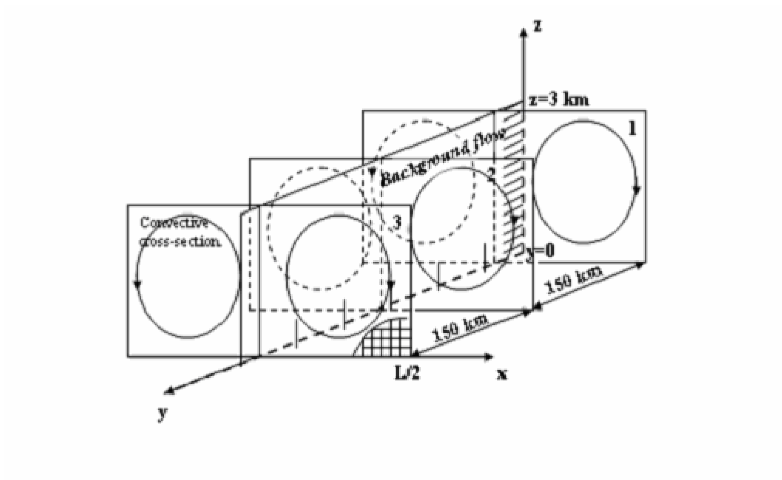

Fig. 1 Schematic of the planetary boundary layer model for explicit simulations of roll vortices used in this study.

The model is calibrated using the available data on the structure of the planetary boundary layer. We presently conduct numerical experiments to study formation, orientation and scale selection of roll vortices in a prescribed synoptic field and to assess existing parameterization methods.

b) Modeling baroclinic vortices interacting with a tall seamount

Our intermediate equations (IE) model (Sutyrin et al. 2003) was generalized to allow for intersection of the layer interface with the bathymetry and applied to study the interaction of surface-intensified anticyclones with the realistic shelves and tall seamounts. In a two-layer model with a rigid-lid the layer depths are

$$h_1 = D_1 + \eta, \qquad h_2 = D(x,y) - h_1, \tag{1}$$

where *D(x,y)* is the ocean depth, $D_1 = D(x,y)$ over the shallow shelf or the seamount top if $h_2 = 0$, otherwise $D_1 = const$ is the average depth of the upper layer. The interface displacement, *η,* and the geopotential, p_i (the pressure divided by density), are related by the hydrostatic equation:

$$g'\nabla\eta = \nabla(p_1 - p_2), \tag{2}$$

where *g′* is the reduced gravity. The evolution of p_i is modeled using our IE model (Sutyrin et al. 2003), where the velocity is expressed by ∇p_i expanding in the Rossby number. This approach is valid for finite variations of the layer depths and allows for calculating variable interface position at the sloping bottom from (1)-(2)

$$h_2 \equiv D(x,y) - D_1 - \frac{p_1 - p_2}{g'} = 0 \, . \tag{3}$$

The physical mechanism that has the most significant effect on the vortex evolution is the advection by a topographic anticyclonic circulation formed after replacement of water over the top of the seamount due to approaching vortex flow (Sutyrin 2006a). For a narrow seamount top effects of secondary cyclonic circulation are weak. Two distinguished types of trajectories were identified in this case. The vortex drifts either predominantly westward north to the top of the seamount or along a curved trajectory to the south of the seamount. This kind of criticality of the vortex evolution is explained by existence of a separatrix in a simple kinematic model for the beta-drift affected by the topographic anticyclonic circulation. For larger radius of penetration of the seamount top in the upper layer the topographic anticyclone becomes stronger and may cause substantial deformations of the approaching vortex core with loss of the material from the vortex periphery that leads to anomalous transport and diffusion (Fig. 2). These effects can be seen in the most relevant oceanographic observations of Agulhas rings where 6 out of 13 identified splitting events occurred in the direct vicinity of the Vema Seamount which rises from the deep ocean floor to within 50 m below the seasurface.

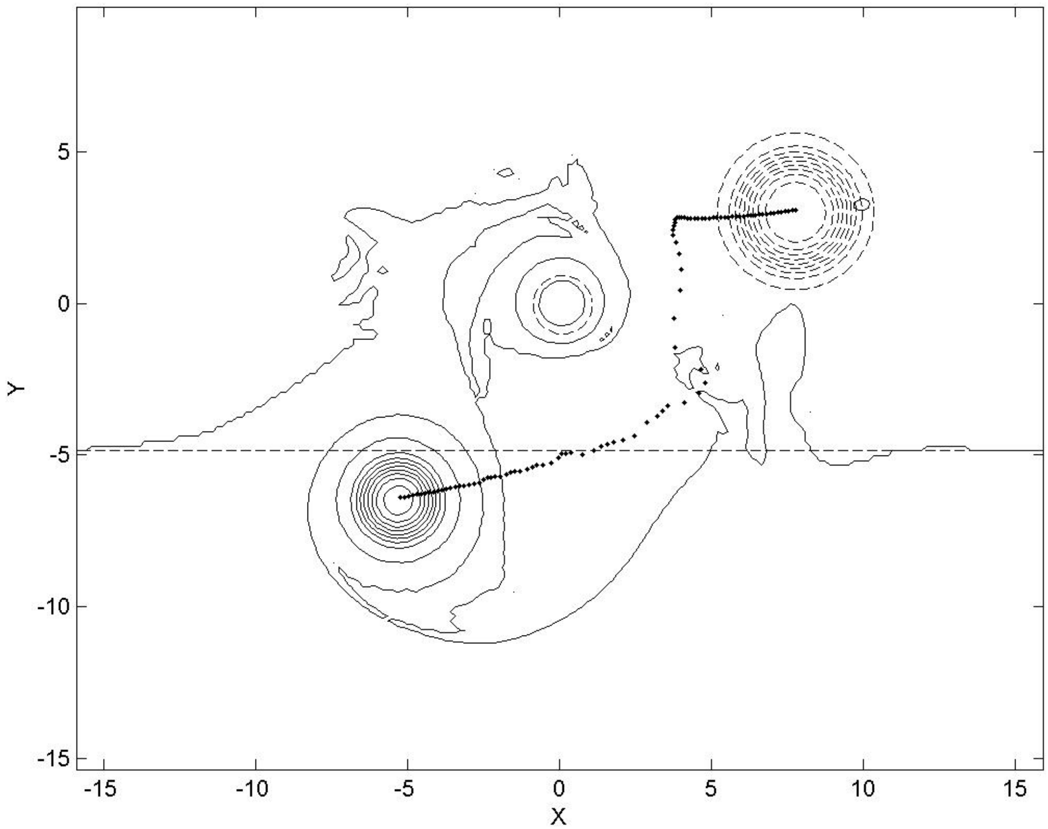

Fig. 2 The distribution of the potential vorticity at t = 5 days (dashed lines) and t = 200 days superimposed by the anticyclone trajectory (dots denote the positions of vortex geopotential maximum each 2 days). Note residual topographic circulation over the seamount top at the origin of coordinates which detrained the material from the vortex periphery due to strong vortex deformation in the vicinity of the seamount top.

c) The effects of sheared flow on an intense baroclinic vortex

The motion of a localized vortex on the beta-plane in the presence of a horizontally and vertically sheared flow is analyzed by an asymptotic theory and numerical simulations (Sutyrin and Carton 2006). Vortex drift due to the background potential vorticity gradient dominates the advective effect of the vertically sheared flow on the vortex. The horizontally sheared flow modifies the vortex drift due to nonlinear interaction of the azimuthal modes one and two (Fig. 3). These effects can explain observed propagation of warm-core rings in regions of the Northeastern Atlantic Ocean far from topographic obstacles where satellite data are available with a good space and time resolution.

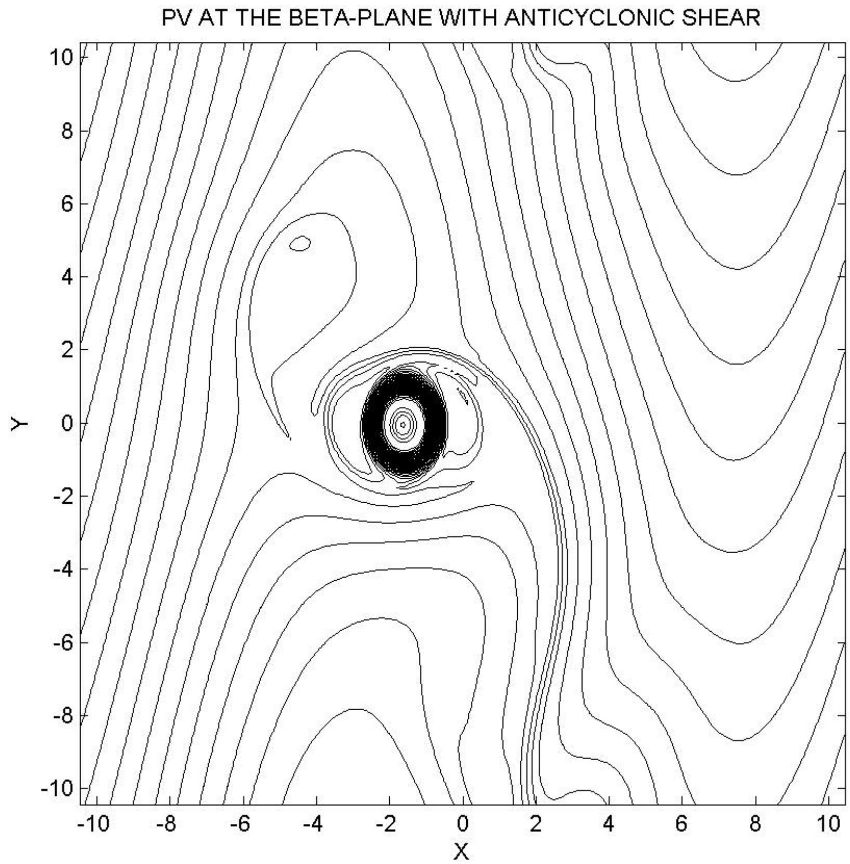

Fig. 3 The distribution of the potential vorticity in the cyclonic vortex on the beta-plane with anticyclonic shear after 100 days. Note substantial elliptical deformations of the vortex core.

d) Ageostrophic pulsations of lens-like stratified axisymmetric vortices

Exact analytic nonlinear solutions for finite-area lens-like anticyclonic vortices pulsating with inertial frequency (pulsons) were recently described in a self-similar form (Sutyrin 2006b). All pulson solutions have linear profile of radial velocity which is not affected by horizontal friction. An initial value problem was considered using Lagrangian variables for stratified axisymmetric flows in isopycnal coordinates (Sutyrin 2006c). If the initial radial velocity deviates from the linear profile, inertia-gravity waves propagate towards the edge of the vortex and form shocks calculated by a simple numerical model. After shocks dissipate, the solution tends to the non-stationary self-similar pulson solution with linear radial velocity. The ability of lens-like vortices to support inertial pulsations may be relevant to observed dominance of near-inertial oscillations in the oceanic gravity wave band. In particular, properties of inertia-gravity waves and enhanced mixing observed inside the core of warm-core Gulf Stream ring (Kunze et al. 1995) can be explained by existence of inertial pulsations in such lens-like anticyclonic vortices.

IMPACT/APPLICATION

A new way to assess the effects of planetary boundary layer parameterization based on explicit simulation roll vortices and their interaction with the mean flow (superparameterization) should provide more realistic modeling of oceanic variability. The means by which we have analyzed ageostrophic pulsations and evolution of baroclinic eddies over topography and in sheared flows in this study are novel and useful for future investigations.

RELATED PROJECTS

New knowledge about the behavior of roll vortices in strong wind conditions gained from this study is being incorporated into a coupled hurricane-ocean model under NOAA and NSF projects by Isaac Ginis. The explicit simulation of coherent vortical structures is used by Prof. J.C. McWilliams for parameterization of Langmuir circulations in the upper ocean.

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