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Vertical Transport and Mixing Induced by Eddy Instability in the Ocean

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Abstract :

Eddy instability and interaction in the ocean play an important role for the vertical transport and mixing of tracers and momentum. We study the dynamics of oceanic eddies with a non-hydrostatic numerical model (HAROMOD). The simulations show a cyclone-anticyclone asymmetry. Centrifugal instability is shown to play an important part in the dynamics of strong anticyclonic eddies and the emergence of an asymmetric vorticity field. We emphasize the importance of the very small scales in the eddy dynamics and quantify the vertical transport and mixing. The importance of non-hydrostatic effects are evaluated. Finally, we discuss the impact of the eddy induced vertical transport on the large scale dynamics of the ocean

Key-words :

centrifugal instability, vertical velocity, oceanic eddies

1 Introduction

Observations laboratory experiments (M05) and numerical simulations (K07) show a clear asymmetry between the distribution of negative and positive relative vorticity ζ in quasi two-dimensional flow on a rotating plane. The most striking feature is the absence of vorticity with values lower than minus the Coriolis parameter f of the background rotation, whereas no such cut-off exists for positive values of the relative vorticity. The cut-off is usually explained by the fact that values of relative vorticity smaller than minus the Coriolis parameter can not be obtained by vortex stretching, which is easily verified by considering (shallow water) potential vorticity:

$$Q = \frac{\zeta + f}{H}, \quad (1)$$

a quantity that is conserved by every particle in the shallow water approximation. Indeed a change in thickness ($H > 0$) will not change the sign of Q , that is $\zeta > -f$. On the positive side stretching (increase of H) can produce arbitrary large values of relative vorticity.

Vortex stretching is, however, not the only mechanism of modifying the vorticity of a fluid particle; baroclinicity, dissipation, vortex-tilting and external forces (see (P86) chap. 2.4) are other candidates, which could well produce vorticities $\zeta < -f$.

We here consider another process which also leads to a cut-off at $-f$ for the relative vorticity, that is centrifugal instability. Anticyclones having a relative vorticity smaller than $-f$ are unstable by such instability which acts at a rather short time-scale and thus also leads to a cut-off at $-f$ for the relative vorticity. Although the two explanations, vortex-stretching versus centrifugal instability, both lead to a cut-off related to the horizontal dynamics (vertical component of the vorticity), their impact on the vertical transport is very different. If indeed centrifugal instability occurs it has a major impact on the vertical exchange of water masses as it leads to large vertical velocities as we will here demonstrate. Furthermore, the vertical velocities develop very rapidly in a thin filament along the line of instability (see section 3). Such kind of

structures might not be well described by a model based on the hydrostatic approximation. Our research is thus based on the non-hydrostatic model HAROMOD (see section 2).

In this communication we therefore clearly identify the instability of strong anti-cyclones as being of the centrifugal type and we determine the vertical velocities connected to this instability as a function of the stratification of the ocean. All parameters in the calculations are inspired by existing oceanic situations.

We emphasize, that in a quasi-geostrophic approach, which is valid only when the relative vorticity is small compared to rotation that is when the Rossby number $|Ro| \ll 1$ (where $Ro = \zeta/f$), there is a perfect symmetry between positive and negative relative vorticity.

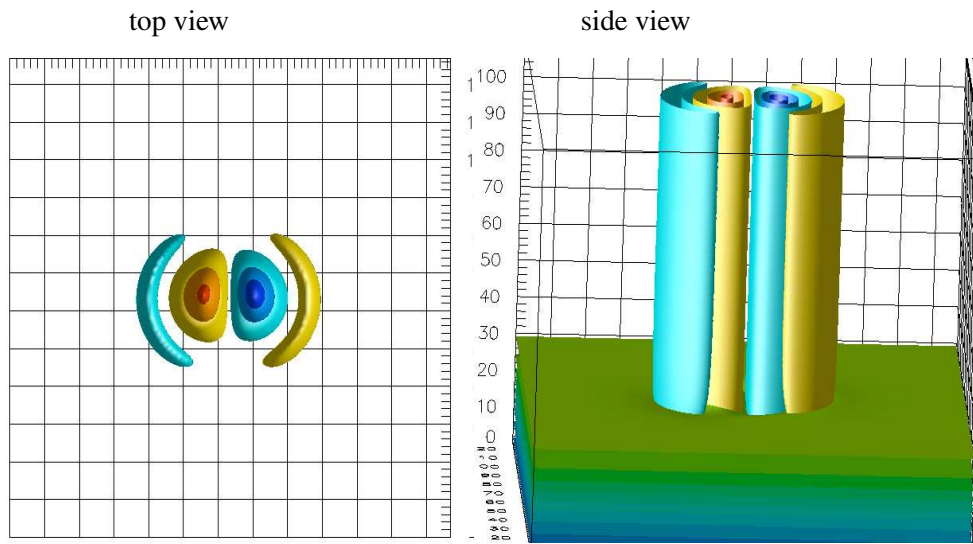


Figure 1: Configuration of an experiment with a dipole after the initial forcing ($t=2h$). Isosurfaces of vorticity are shown (red positive, blue negative), the right figure also shows the stratification near the ocean floor.

2 The Experiments

We consider the dynamics of pairs of vortices in a stratified ocean on the f -plane (constant rotation rate). The domain considered spans 100km in both horizontal directions with periodic boundary conditions. The depth is 1km and there is a rigid-lid free-slip boundary at the surface and a no-slip boundary at the bottom. The domain is strongly stratified by a temperature difference of 10K in the lower 200m of the ocean (see Fig. 1), to reduce the influence of bottom Ekman-pumping in the upper part of the ocean. An additional constant stratification from zero to up to $5 \times 10^{-3} \text{K m}^{-1}$, in the entire domain, is varied between different experiments to evaluate the role of stratification. In the first two hours a force is added that creates two eddies in the upper part of the ocean (see Fig. 1). After two hours (one sixth of the inertial period of 12 hours) the forcing stops and the two eddies evolve freely. We also vary the sign and distance between the eddies. When two like-sign eddies are close together they form a single elliptic eddy. The key physical parameters of the experiment are given in table 2. The geometrical shape of the forcing-function is given by:

$$F_0 = \exp\left(-((x-d)^2 + y^2)/(2l_H^2)\right) (-y, x, 0) (1 - \tanh((z-z_0)/l_z))$$

where the parameters are given in table 2 and the distance between the eddy centers d is varied.

L_x	L_y	L_z	\mathbf{f}	l_H	l_z
10^5 m	10^5 m	10^3 m	$1.45 \cdot 10^{-4} \text{ s}^{-1}$	$6.26 \cdot 10^3$ m	844 m

l_z/l_H	Ek	Ro	Re_{max}
.13	$3.4 \cdot 10^{-4}$	1.6	375

The mathematical model used are the three-dimensional Navier-Stokes equations in a rotating frame with one buoyant scalar (temperature).

The numerical model used is HAROMOD, a pseudo spectral model entirely based on Fourier expansion (see (W04), (W06) & (W07)). The domain has $256 \times 256 \times 112$ grid points.

3 Preliminary Results

Our simulations show that strong anticyclone ($\zeta < -f$) are unstable while cyclones are stable. This proves, that the instability is not of the barotropic type, which does not distinguish between the sense of rotation. The instability occurs at about 20 hours after the start of the experiment. The instability is clearly located above the stratified region which proves that is not connected to spontaneous emission of gravity waves.

We furthermore looked at the location where the instability originates and see that it happens at locations (see Fig. 2) where the relative vorticity changes sign as predicted by the Rayleigh stability criterion

$$(2v_\theta + fr)(\zeta + f) < 0, \quad (2)$$

put forward and verified in laboratory experiments by Kloosterziel and van Heist (K91) (see also (H92)). This indicates also that we are here not concerned with elliptic instability, which would show an instability originating from the eddy center.

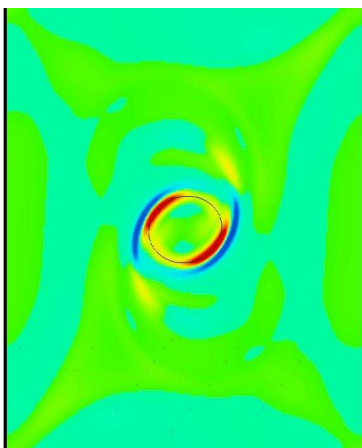


Figure 2: Vertical velocity at 200m depth (blue down, red up). The black-line shows where the Rayleigh stability criterion, predicts the appearance of instability.

4 Conclusions and Perspectives

We have thus clearly identified centrifugal instability as an important player for strong vortices in an oceanic context. We have also shown that such instability leads to strong vertical velocities, key to the biological activity in the ocean.

Further work will concern the evaluation of vertical velocities and mixing as a function of a constant stratification in the upper ocean.

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