VORTEX ASSYMETRY IN ISLAND WAKES

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Several aspects of the vortex asymmetry leeward of islands were studied with laboratory experiments conducted at the LEGI-Coriolis in Grenoble (France). A total of sixty-seven experiments were conducted and the impact of rotation and stratification on small-scale inertial instabilities was considered. The experimental setup mimics the upper thermocline layer on the top of a deep barotropic ocean. Symmetric, asymmetric and multiple islands arrangements were considered during the experiments. Preliminary results suggest that small-scale inertial instability could affect the dynamics of anticyclonic vortices in the far-field wake but also in the near-field wake one or two diameter behind the island. The stabilizing impact of the stratification may lead to stable anticyclones even for finite relative vorticity (ξ/f<-1). Moreover, asymmetrical island or archipelago geometry may also induce significant asymmetries in the wake.

1. INTRODUCTION

The role of oceanic islands wakes in the biological enrichment and the retention of surface pollutants is an area of growing interest. The geostrophic balance of cyclonic eddies induce a vertical advection of the deep chlorophyll maxima or the enhancement of biological productivity due to the deep nutrient upwelling (Hasegawa *et al.*, 2004, 2009). On the other hand, intense anticyclonic vortices may be the source of three-dimensional inertial instabilities, which enhance the horizontal transport and the vertical mixing of passive tracers in the island wake (Dong *et al.*, 2007; Teinturier *et al.*, 2010). Motivated by this oceanographic context, laboratory and numerical experiments were carried out to study the impact of the vertical stratification and the rotation on the asymmetry between cyclonic and anticyclonic vortices formed in the island wake.

As far as the oceanic wake of the Madeira Archipelago is concerned, various cyclonic eddies were detected among the satellite observations (Caldeira et al., 2002**)** but so far, no clear signature of anticyclonic eddy shedding was shown. Furthermore, realistic mesoscale simulations have shown that intense cyclonic eddies are preferentially formed on the westward side of Madeira. This cyclone-anticyclone asymmetry among the wake vortices may have several origins.

Inertial and/or elliptical instabilities may strongly destabilize intense anticyclonic eddies (Tabouriech, 1996; Afanasyev, 2002; Stegner, 2005). Indeed, three dimensional perturbations growth in a localized region, at the edge of the anticyclonic vortices, if the vortex Rossby number Ro=ξ/f<-1 is negative enough, where ξ is the relative vorticity and f=2Ω_0 the Coriolis parameter. For a columnar vortex, the vertical wavelength of the most unstable mode is mainly controlled by the vortex Rossby number Ro, the Reynolds number Re and the relative stratification parameter N/f (Kloosterziel *et al.* 2007). If the incoming oceanic flow is strong enough or if the island diameter is very small, then eddies that will form in the wake will have large vorticity values. In such case, the selective destabilization of anticyclonic eddies, which occurs in a specific range of parameters (Ro, Re, N/f), may favor the emergence of coherent cyclones in the oceanic island wake.

Another source of asymmetry between opposite sign eddies in the wake could be due to the island shape itself even for a pure two-dimensional flow which is not affected by the rotation and the stratification. For an asymmetrical island the detached boundary layers of the near wake may differ in width and amplitude. In such case, the vortices, which are formed further down in the wake, will differ in size (radius) and intensity (core vorticity).

After a description of the experimental setup and the data acquisition, we present our first results on the three-dimensional destabilization of surface vortices generated in the wake of a cylindrical island. Then, we present some preliminary results on the wake asymmetry induced by an asymmetrical island or archipelago.

2. EXPERIMENTAL SETUP

In order to study the impact of rotation and stratification on small-scale instabilities of wake vortices we conducted sixty-seven experiments on the 13-m-diameter rotating platform at the LEGI-Coriolis in Grenoble (France). The turntable had an anti-clockwise rotation (as the planetary rotation) which was kept constant Ω_0=0.069rad.s^{-1} corresponding to a Coriolis parameter $f=2\Omega_0$=0.139rad.s^{-1}. A linear salt stratification was set in the upper layer (h=7cm), which mimics the oceanic thermocline, on the top of a thick barotropic layer (H=50cm), which resembles the deep ocean condition. Strong and weak stratifications were considered corresponding to Brunt Vaisala frequencies $1<N<3$ s−1. In order to reproduce the dynamic of a surface current interacting with an isolated and steep island (or archipelago) island-like obstacles were towed only in the upper layer. Similar setups are described in Perret et al. (2008) and Teinturier *et al*. (2010). We assume that the motion of the obstacle transfers momentum mainly in the upper stratified layer and that the dynamic is governed by the first baroclinic mode. This will be generally the case if the lower layer is deep enough, namely when $h \ll H$. The towing speed U_0 was varied from 1cm/s to 8cm/s and the corresponding horizontal Reynolds number $Re= U_0D/\nu$ varied from 2500 to 50000, where D is the effective island diameter (D ~ 25-75cm).

The upper layer was seeded with particles of density equal to the mid level of the upper stratification. These buoyant particles were illuminated from bellow with submerged lights. The particles motion were captured by three to four full-frame cameras: two wide-angle cameras captured the global wake dynamics, one zoomed camera followed the evolution of a single eddy and one camera attached to the carriage captured the detached boundary layers (BL) with a high spatial resolution.

3. STABILITY OF INTENSE VORTICES GENERATED BY SYMETRICAL ISLANDS

Unlike the previous experimental investigations on inertial island wake instabilities (Teinturier *et al*., 2010) we focus our effort on quantitative PIV measurements of the wake flow. If three-dimensional perturbations induced by the inertial instability may strongly affect the dispersion of passive dye tracers (Fig.5 & Fig.6 in Teinturier *et al*., 2010) such small-scale patterns can hardly be detected by standard 2D PIV measurements. Hence, the signature of the inertial instability should be extracted from the mesoscale evolution of individual eddies.

We characterize an individual eddy by its maximum azimuthal velocity V_m, its typical radius R_m corresponding to $V(R_m)=V_m$ and its maximum core vorticity ξ_m. According to the linear stability analysis of Rankin vortices in a rotating and stratified shallow layer (Lazar *et al.* 2010), we use four dimensionless parameters which govern the eddy stability, namely: the eddy Rossby number $Ro=V_m/(\Omega_0 R_m)$, the vertical Reynolds number $Re=V_m h/\nu$, the aspect ratio parameter $\delta=h/R_d$ and the stratification parameter $S=N/f$, where h and N are respectively the thickness and the Brunt-vaisala frequency of the stratified upper layer. For circular vortices, the linearly unstable region is located at the edge of the eddy (Kloosterziel *et al*., 2007; Teinturier *et al.* 2010, Lazar *et al*. 2010) just outside the maximum velocity. Therefore, if the non-linear evolution is not too strong, the perturbations will weakly affect the core of the eddy. In such case, unlike the in the tall column vortices (Stegner *et al.* 2005) individual anticyclones that have large core vorticity values ($\xi_m/f<-1$) may survive for a long time (Fig.1(b)) due to the combined effect of the stratification ($S \gg 1$) and the shallow-water constraint ($\delta \ll 1$). The three dimensional unstable perturbations will then affect mainly the maximum velocity V_m rather than the core vorticity ξ_m. A clear asymmetry can be observed between cyclonic (Fig.1 (c)) and anticyclonic (Fig.1 (d)) velocity profiles, which can be seen as the signature of inertial instability. The stabilizing effect of the stratification is shown in Fig.1 (d) from $S=N/f=7$ to S=20.

Because the stratification and the shallow water constraint tend to weaken the inertial destabilisation of anticyclones, the unstable regions of the wake flow will be the detached anticyclonic boundary layer in the near wake, just behind the islands.

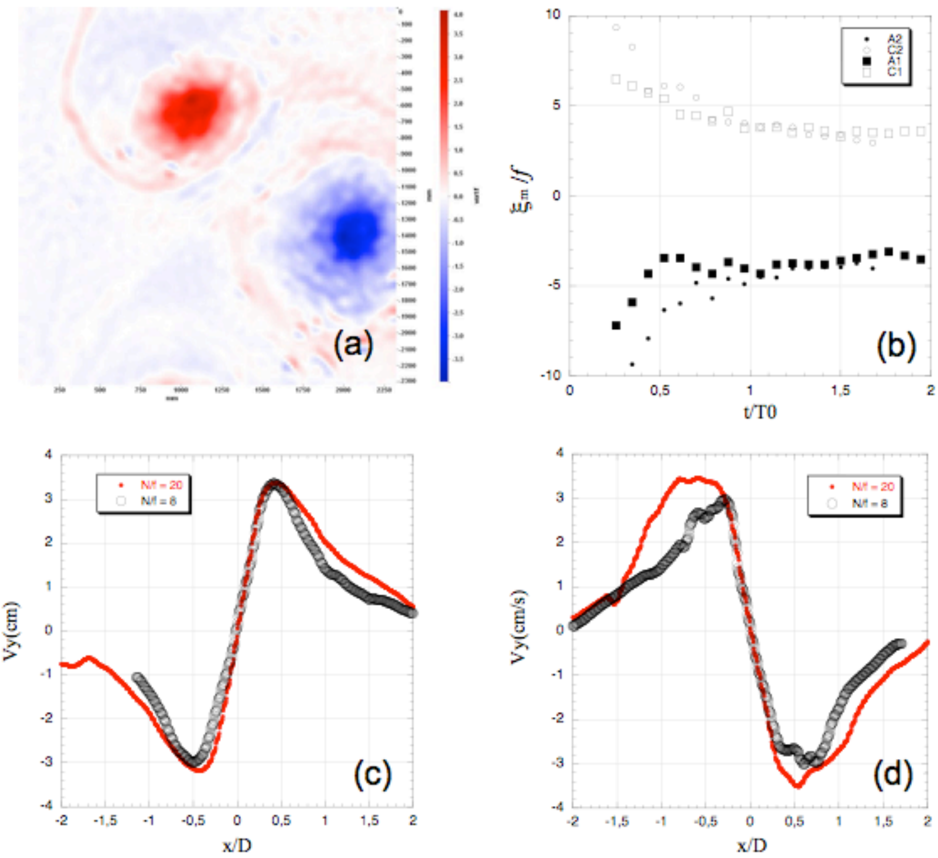

Figure 1 Relative vorticity of cyclonic (red) and anticyclonic (blue) eddies (a); core vorticity evolution (b); cyclonic (c) and anticyclonic (d) velocity profiles corresponding to the parameters: Re~1700, Ro ~ 2, d=0.25 and S= 8 and S=20.

4. WAKE ASYMETRY INDUCED BY SHAPE AND/OR MULTIPLE ISLANDS

To study the effect of island asymmetry, both symmetric (Fig. 2a-b; cylinder & ellipse) and asymmetric obstacles (tilted ellipse and multiple ellipses) were considered with the similar stratification 14<S=N/f<20,and the same Re~10000 (towing velocity). Preliminary analysis suggests that the pitching of the ellipse enhances (near-field) vortex asymmetry. In the multiple island cases there are also near-field differences (Fig. 2c-d). In the multiple islands case study the anticyclonic side (Fig. 2 c-d) produce independent wakes, which interfere with the anticyclonic shedding. Nevertheless, archipelago/asymmetric cases also induce the formation of coherent vortices (far-field) further leeward, when compared to the symmetric cases, i.e. wider boundary layer width.

It is hypothesized that the contribution of strong positive vortices in the near-field of the anticyclonic side (Fig. 2 c-d) as well as the presence of a small nearby island (e.g. Desertas) might play a significant role. Therefore it is likely that the lack of detection of anticyclones leeward of Madeira is not only caused by the limited remote sensing detection capability but also due to perhaps small near-wake instabilities.

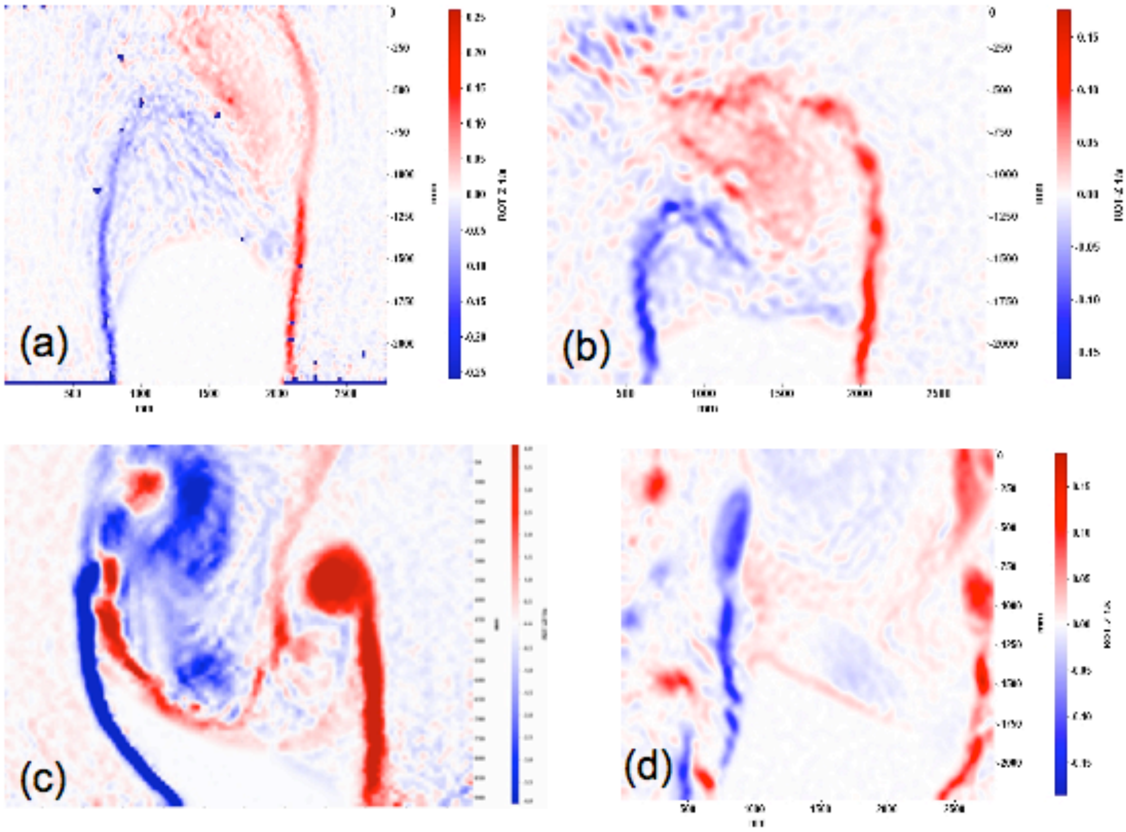

Figure 2 Vorticity field of various boundary layer (near-field) corresponding to different island/archipelago geometries: (a) Cylinder; (b) Ellipse; (c) Two-ellipses; (d) Madeira Archipelago.

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