Dynamics of Large-Scale Vortices in the Near Shore

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ABSTRACT

In spite of the ubiquity of long shore flows, rip currents and also tidal jets in the near shore, large-scale vortices associated with these phenomena remain poorly understood. In particular, little is known about the effect of the vertical confinement on vortex dynamics. To understand this phenomenon we present in this paper a new laboratory experiment on pulsed jets (assimilated to a rip current) in a shallow water layer. In this study we analyze the evolution of three-dimensional turbulence generated by a pulsed jet in a homogeneous shallow water layer. We show that the jet evolution depends mostly on one dimensionless parameter (where Q the injected momentum flux, H the water depth and the injection duration). C characterizes the vertical confinement. When C is weak, the jet spreading is free. The generated turbulence remains fully three-dimensional. When C is large (C>2), we observe a damping of the vertical motion and the formation of a large horizontal dipolar structure. We also identify inside the global 2D dipolar structure, local three dimensional vortices. We have developed a theoretical model in good agreement with these measurements.

ADDITIONAL INDEX WORDS: Vortex dynamics, turbulence, shallow water, nearshore.

INTRODUCTION

Flows near shore are forced by a combination of wave breaking, winds, and topographic effects. Exchanges between the surf-zone and water farther offshore are thought to occur mainly via large-scale horizontal vortices. There is an increasing number of observations of these vortices in the near shore. For instance, observations of shear waves associated with the presence of alongshore currents have been reported from field experiments at Duck, North Carolina. Rip currents are also a common feature of the near shore. These currents are narrow, seaward-directed currents that extend from the inner surf zone out through the line of breaking wave. In general, as HALLER et al. (2001) describe them, rip currents return the water carried landward by waves and under certain conditions of near shore slope and wave activity, they are the primary agent for the seaward transport of water and sediment. They are also thought to influence the movement and the form of the sand near shore. Rip currents are usually narrow (extending 10-20 m in the long shore direction) and generally span the entire water column. SMITH et al. (1995) have observed that as the seaward directed jet expands laterally, a mushroom-shaped structure (vortex pair) develops at the head, with counterrotating eddies that may or may not be of equal size. This vortex may detach and carry a patch of surf zone offshore. An example of rip currents is illustrated in figure 1.

A classification of 2-D coherent structures in large scale structures in shallow flow is presented by JIRKA (2001). He proposed three types of generation mechanisms: topographic forcing, internal transverse shear and secondary instabilities of the base flow. He noticed that the growth of the 2-D coherent structures and the internal turbulent kinetic distribution among different scales is governed by principles of "2-D turbulence" theory.

In this paper, we present a new experiment laboratory on pulsed jets, assimilated to rip current, in a shallow water layer. We limit herein our attention to predominantly one directional shallow flow which is free of Coriolis force influences and tidal effects. By shallow flow we mean a flow bounded by a no-slip bottom and a free surface in which the vortex structures size is much smaller than the wavelength of surface waves.

EXPERIMENTAL SETUP

Experiments have been performed on the Coriolis turntable of the LEGI (Grenoble, France). In this circular turntable, 13m in diameter, we have built a rectangular channel (8m×3m). In this channel, we inject a small amount of fluid through a horizontal cylindrical nozzle immersed in water at rest. During our experiments, three parameters are modified: the depth from 0.21 to 0.35m, the discharge (product of the injection speed by the nozzle section) from 2.5e-4 to 7.5e-4 m s⁻¹ and the injection duration from 1 to 20s. The injected fluid is taken outside the channel and is strictly the same than the receiving fluid. The discharge is held constant during the injection duration.

Flow Visualizations

In order to obtain qualitative informations on the flow, plioilite particles (size 300µm, density 1023.6 kg.m⁻³) are added to the whole fluid and illuminating by a laser sheet (argon laser).
Then, the streamlines are visualized by particles streaks.

**Particle Image Velocimetry**

PIV is a non-intrusive velocity measurement technique that provides instantaneous velocity field. It consists in analyzing the displacements of particles added to the flow.

The light sheet illumination is provided by an argon laser with power 8W (model “coherent innova 70-4 A”). It emits an horizontal laser sheet which can be quickly moved to cover three horizontal slices, the lower one at 5cm above the bottom, the middle one at half-depth and the upper one 3cm below the free surface. A CCD camera (SM1DM60) with a 1024 x 1024 resolution is used. It captures frames with an adjustable frequency until 60Hz. The observed area is relatively large (2.5×2.5m²). Frames sequences are recorded from the injection until the flow goes out the observation area. Typical duration of recording is about 300s.

The step following the frame grabbing is the correlation process, performed by CIV (Correlation Image Velocimetry). CIV is an advanced Imaging Velocimetry implementation of Direct-Cross Correlation PIV that relies on generalized pattern matching by direct cross-correlation of pattern boxes between image pairs. For a complete review on CIV features, the reader is referred to Fincham et al. (1997) and Fincham et al. (2000).

The seeding of the flow is of great importance for the quality of PIV measurements. The particles need to accurately follow the local flow. It means that the particles should have a density very close to that of the fluid and a small size to avoid perturbations. The seeding density (particle concentration) is governed by the need to have roughly 0.05 particles per pixels. This density should be homogeneous in the whole observed region. In our measurements, we have used piolite particles, with a size about 300μm and a density of 1023.6 kg.m⁻³. Salt has been added to the water to match the particle density.

**INFLUENCE OF VERTICAL CONFINEMENT ON THE DYNAMIC BEHAVIOR**

In previous experiments, at small scales, Souss et al. (2003) showed that the jet evolution depends mainly on one dimensionless parameter C, which characterizes the vertical confinement, that they defined by \( C = [\frac{Q}{(H \cdot \text{HQC})}]_{\text{Re}} \) (Q the injected momentum flux, H the water depth and tinj the injection duration), whereas the Reynolds number has only a weak influence. In few words, when C is weak (\( C < 1 \)), the evolution is a typical three-dimensional turbulence decay, as you can see in figure 3, while when C is great (\( C > 2 \)) the “shallow water behaviour” is systematically observed. This behaviour is characterized by a progressive damping of the vertical motion and formation of large horizontal dipoles. An example of the horizontal structure is presented on figure 2. These experiments were performed at small scale (\( Re < 1800 \)).

The objective of the present experimental study is to confirm these results at larger scale so that they could be extended to the observed phenomena in nature and in particular to rip currents as their form resembles a two-dimensional starting jet (Smith et al., 1995).

In order to evaluate the influence of C on the flow, we computed the correlation product between the velocity fields on three horizontal slices (upper, middle and lower). The correlation product is computed as follows:

\[
\text{corr} = \frac{1}{nb_{\text{points}}} \sum_{i,j} \frac{u_i u_j + v_i v_j}{\sqrt{u_i^2 + v_i^2} \sqrt{u_j^2 + v_j^2}}
\]

where (\( u_i, v_i \)) and (\( u_j, v_j \)) are the velocity components given at each point of the PIV mesh grid on two different slices, i and j describe the mesh grid constituted by nb_{points}.

Corr is equal to 1 when the velocity fields are totally identical. We compute then the arithmetical average between the values obtained for the upper and middle slices and for the middle and lower slices. The maximum of this average during the flow evolution is called Mcorr. Its evolution is studied depending on the dimensionless time \( t^* = \frac{t}{t_{\text{inj}}} \). The acquisition starts at \( t_{\text{inj}} = 0 \) and finish when the flow goes out the acquisition area (\( t_{\text{end}} = 140 \) for the longest experiments). The evolution of Mcorr versus the confinement number C for two different Reynolds number is plotted in Figure 4. As at small scale, we note a direct influence of C on Mcorr while Re has no significant role. When C is small, the confinement is too weak to generate large horizontal vortices. From \( C = 2 \), Mcorr remains superior to 0.8, the flow is structured over the depth. The corresponding velocity fields indicate that it consists mainly of dipoles. Most of the pulsed jets generated with \( C < 2 \) do not develop a structured flow but we have observed appearance of dipoles for \( C = 1, 7 \).

These results are consistent with the experiments carried out at small scale. The same influence of the confinement number C has been found on one hand for \( 1000 < Re < 1800 \) and on the other hand for \( 50,000 < Re < 75,000 \). When \( C < 1 \), the confinement does...
not influence the jet expansion. A transition occurs when $1 < C < 2$ where the confinement starts to acts on the jet evolution but the flow is not systematically structured. When $C > 2$, the “shallow water behaviour” systematically appears. The flow gets organized in large horizontal dipole. The influence of the Reynolds number on vortex dynamics is negligible.

GLOBAL AND LOCAL FLOW IN A SHALLOW WATER層

At small scales, we have observed the presence of vertical motion in the dipoles in a shallow water layer. We have identified in particular the presence of vertical circulation in the front of the dipolar structure. This circulation in front of the dipole has been also observed at larger scales, as you can see both in figure 5 and in figure 6. Figure 5 shows a turbulent dipole generated with $C=3.2$ and $Re=50,000$ at $t^*=33.7$. Figure 6 shows visualizations with fluoresceine for a turbulent dipole generated with $C=4.8$, and $Re=50,000$ at $t^*=45$.

At larger scale, we illustrate in figure 5 small-scale turbulence inside the global large horizontal dipolar structure. In particular, we observe that small shear zones associated to small three dimensional vortex structures remained in the global dipole.

These local three dimensional effects and global large horizontal dipoles are typical features of the vortex dynamics in a shallow water layer. They have not been observed in stratified or rotating fluids.

THEORETICAL MODEL

Hypothesis

We propose a model of the dipole evolution. Our model aims to describe the evolution of a dipole in linear translation, of speed $U$ and radius $a$. We assume that the boundary layer is stable and that the frontal circulation of the dipole is only responsible of small-scale turbulence production. The momentum $P$ (divided by $\rho$) and the kinetic energy $E$ (divided by $\rho$) are respectively estimated by:

$$P \approx U a^2 H, \quad E \approx U^2 a^2 H\quad (1)$$

Energy Dissipation

The kinetic energy dissipations can be written:

$$\frac{dE}{dt} = \frac{dUP}{dt} = P \frac{dU}{dt} + U \frac{dP}{dt}\quad (2)$$

- Estimation of $P \frac{dU}{dt}$

This term is associated to turbulence production occurs in the frontal circulation, characterized by its thickness $H$ and its “active” volume evaluated by $aH^2$. The energy dissipation rate in the circulation can be then written as the product of the volumic dissipation by the “active” volume:

$$P \frac{dU}{dt} \approx - \frac{U^3}{H^2} aH^2 \approx - U^3 aH \approx - \frac{EU}{a}\quad (3)$$

We can note that the advection time at the scale $a$ is about $a/U$. It is of the same order than the 2D organisation time. The equation (1) leads to $a \approx \frac{P^{1/2}U^{1/2}}{H^{1/2}}$. Then (3) becomes:

$$P \frac{dU}{dt} \approx -U^{5/2} P^{1/2} H^{3/2}\quad (4)$$

- Estimation of $U \frac{dP}{dt}$

This term is nil if the momentum is constant. A remarkable property of the 2D dipoles is to transport momentum as a solid body does. Dipoles in shallow water possess significant vertical motion and it is of great interest to know if they possess nevertheless this transport property.
If \( P \) is not constant, we consider that its dissipation is caused by the bottom friction. This dissipation can be estimated by:

\[
\frac{dP}{dt} \approx \nu \int \frac{\partial v}{\partial z} dr^2 \tag{4}
\]

Where \( \delta \) is the boundary layer thickness. Equation (4) becomes:

\[
\frac{dP}{dt} \approx \nu \frac{U a^2}{\delta} \tag{5}
\]

The boundary layer equilibrium leads to:

\[
\delta = \sqrt{\nu \frac{H}{U}}
\]

Then (5) can be written:

\[
\frac{dP}{dt} \approx -\nu \frac{1}{2} U^{3/2} H^{-1/2} \tag{6}
\]

Which leads to:

\[
U \frac{dP}{dt} \approx -\nu \frac{1}{2} U^{5/2} H^{-1/2} \tag{7}
\]

We have the following expression for the total kinetic energy dissipation:

\[
\frac{dE}{dt} \approx -U^{5/2} P^{1/2} H^{3/2} - \nu^{1/2} U^{5/2} H^{-1/2} a^2
\]

With the typical values \( U=0.02 \) m/s and \( H=0.3 \) m one can estimate the contribution of both terms. The first one is about \( 2 \times 10^{-6} \) while the second one is about \( 10^{-7} \). In first approximation, the second term contribution associated to \( U \frac{dP}{dt} \) can be neglected. This assumption is strictly verified if the momentum is conserved.

The kinetic energy is estimated by:

\[
\frac{dE}{dt} \approx P \frac{dU}{dt} \approx -U^{5/2} P^{1/2} H^{3/2}
\]

**Velocity Evolution**

From the previous expression (6), evolution laws for \( U \) and \( a \) can be deduced:

\[
U \approx \left( \frac{P}{H} \right)^{1/3} (t - t_0)^{-2/3}
\]

**THEORETICAL / EXPERIMENTAL COMPARISON**

In the previous theoretical model, we assumed that the momentum is conserved. The first step of the model validation is to confirm experimentally this hypothesis.

Four nearly symmetric dipoles in linear translation have been generated with \( C=4.8, \) \( Re=50,000 \) at \( t^*=45 \), middle slide.

![Figure 6. Visualizations with fluoresceine for a turbulent dipole generated with \( C=4.8, \) \( Re=50,000 \) at \( t^*=45 \), middle slide.](image)

![Figure 8. Comparison between model prediction and measured velocity for \( C=1.7 \) (average on the three slides).](image)

![Figure 7. Compared evolution of reduced momentum and reduced kinetic energy on the middle slide, \( Re=50,000 \).](image)

![Figure 9. Comparison between model prediction and measured velocity for \( C=2.2 \) (average on the three slides).](image)
studied. From the three horizontal slices, the velocity fields \((u,v)\) are obtained all along the dipole evolution. The momentum and the kinetic energy are computed as follows:

\[
P = \sum_S udS + \sum_S vdS
\]

and

\[
E = \frac{1}{2} \sum_S (u^2 + v^2) dS
\]

where \(S\) is the PIV mesh grid surface and \(dS\) the surface element. Average values are computed between the three slices. By dividing \(P\) and \(E\) by their respective maxima, the reduced momentum \(P^*\) and the reduced kinetic energy \(E^*\) are obtained.

Figure 7 shows the compared evolution of \(P^*\) and \(E^*\) for two cases \(C=4.8\) and \(C=8\). The instant \(t=0\) corresponds to the beginning of the PIV analysis. First observations show that the momentum is less dissipated than the kinetic energy. The momentum can be considered constant at the beginning of the analysis but then some oscillations appear.

Despite oscillations, the momentum dissipation remains moderate compared to kinetic energy dissipation. From these results, we can assume, that the more the dipole is confined (when \(C\) is great), the less the momentum is dissipated.

The model predicts the following evolution law of the typical speed \(U(t) = A(t - t_i)^{-\frac{1}{2}}\) where \(t_i\) is defined by \(U(t_i) = U_0\) with \(U_0\), the initial speed and \(A\) is a constant. On figures (8) to (10), comparisons between model predictions and experimental results are presented. The constant \(A\) takes respectively the following values: 1, 0.6, 0.7, 0.7 and 1. For more detailed, the lecturers have to be referred to Sous et al (2003).

We find a good agreement between the prediction model and the experimental results for the different number \(C\) studied.

CONCLUSIONS

In spite of the ubiquity of large scale vortices in the near shore, especially rip currents, tidal jets, these dynamic features remain poorly understood. In particular, little is known about the effect of the vertical confinement on vortex dynamics. To understand this phenomenon, we present a new laboratory experiment on pulsed jet (assimilated to rip currents), in a shallow water layer.

We show that the vortex dynamic depends on a dimensionless number, coming from a dimensional analysis and which characterizes the vertical confinement. We have called this number \(C\). When \(C\) is weak \((C<1)\), the vortex dynamic evolution is a typical three-dimensional turbulence decay, while when \(C\) is great \((C>2)\) large horizontal dipolar structures appear similar to those observed by Smith et al. (1995) governed by principles of 2D turbulence theory.

We focus then on a confined case, and show by qualitative results that the global flow is, as mentioned before, organized in a dipolar structure. This global dipolar structure can transport what has been trapped inside the structure, for example sediments or pollutants.

Inside this global structure, locally three dimensional vortices remain. This model could be helpful in developing a physical parameterization which can take into account these 3D local effects and that could be integrated in coastal hydrodynamic 2DH depth-integrated current models.

We present finally a theoretical model based on the momentum conservation. This hypothesis has been validated with our experimental results. The model predicts the following evolution law of the typical speed \(U(t) = A(t - t_i)^{-\frac{3}{2}}\) and is in good agreement with the experimental results. In spite of the presence of 3D turbulent effects, the global vortex dynamic is mainly governed by principles of 2D turbulence theory. This theoretical model could be the base of a physical parametrization useful for coastal hydrodynamic models.

LITERATURE CITED


