EXPERIMENTAL STUDY OF LAGRANGIAN MIXING IN WEAKLY DISSIPATIVE TIDAL CHANNELS

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INTRODUCTION

Estuaries are extremely dynamic environments, allowing wildlife to grow in a wide variety of ecosystems because of the interaction of masses of water with different characteristics. In particular, coastal bays and estuaries are characterized by flows driven by hydraulic unbalance such as baroclinic pressure gradients, river inflows and wind stresses, and tidal waves. Here, following a reductionist approach, we examine dispersion processes in a physical model of a tidal channel bounded by an inlet mouth, with tides as the dominant forcing. The presence of a tidal inlet can generate macro-vortices that during a tidal cycle may influence the momentum and mass transport on relatively large distances (Awaji et al. (1980), Awaji (1982), Branyon et al. (2022)). Moreover, tides tend to produce non-monotonic particle velocity correlation leading to possible particle looping trajectories that also reflect on a looping character of the Lagrangian integral time scales, differently from the classical statistically steady or homogeneous turbulence (Enrile et al. (2019)). Our goal is to examine the dispersion regimes by means of two-dimensional velocity measurements at the free surface reproduced in a large-scale physical model as a starting point for Lagrangian analysis. We show how the presence of a tidal inlet generates complex flow patterns depending on the character of the forcing tides. Furthermore, the mixed nature of tides may be crucial to dispersion processes, as it enhances the ability of the flow to transport mass in the direction of the main flow.

MATERIAL AND METHODS

The experiments were performed in a large-scale physical model. The facility consists of a flume of dimension 29 m long and about 2,5 m wide. In particular, it is divided in two main parts: a rectangular basin (20% of the total length) and a compound channel (80%), connected through a tidal barrier island, as shown in Figure 1.

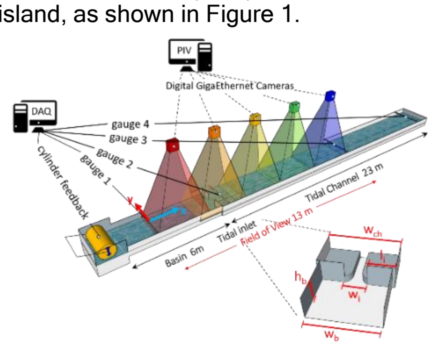

Figure 1 - Sketch of the experimental set up and measuring system.

Tidal regular volume waves with variable periods and amplitudes were generated by the oscillation of a cylinder. Both single and multi-harmonic tides have been studied, using a ~~tidal~~ law of the kind:

(eq.1) $$\eta(t) = \sum_i a_i \sin(\omega_i t + \phi_i)$$

where η is the surface elevation, a_i is the amplitude, ϕ_i the phase shift and $\omega_i = 2\pi/T_i$ the tidal angular frequency and T_i the corresponding period of the i^{th} tidal component.

The free surface elevation was monitored by four ultrasound gauges, whereas the Large Scale- PIV acquisitions by five high-resolution digital cameras.

Following Toffolon et al. (2006), we defined the governing parameter of the process based on *external* quantities, i.e., geometry of the domain and main characteristics of the tidal forcing. In particular, we designed the experiments preserving the friction parameter:

(eq.2) $$\chi = \frac{aT\sqrt{g}}{2\pi C^2 D_0^{\frac{3}{2}}},$$

where C is the conductance coefficient, D_0 the mean flow depth and g the gravitational acceleration. The measurements presented in the rest of the study can be considered representative of the behaviour of real weakly dissipative estuaries with an almost constant channel width, as shown in Figure 2. Note that γ is the convergence ratio, see Toffolon et al. (2006) for its definition.

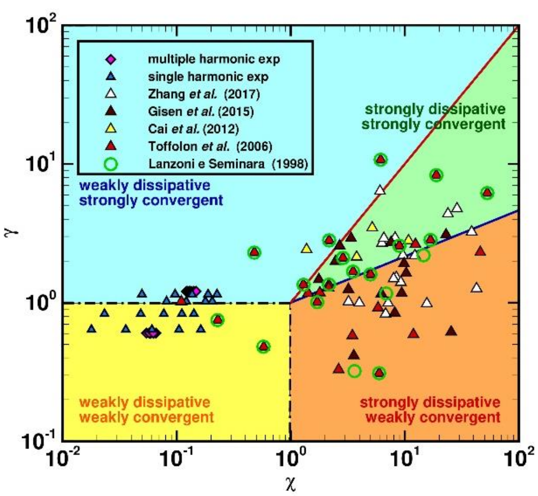

Figure 2 - χ, γ-plane classification of several natural estuaries together with the present experiments.

RESULTS

Large Scale- PIV measurements of the 2D free surface time dependent velocity fields provided a huge data set upon which a thorough Eulerian and Lagrangian analysis was performed. We found out that the interaction of the flow with the inlet mouth triggers the generation of flood-macrovortices, able to occupy the entire tidal flats. As pointed out by Shadden et al. (2005), the detection of large-scale coherent structures is still possible even despite the turbulent character of the flow. In this way, a deeper understanding of the flow dynamics can be performed also retaining the spatial inhomogeneities. LCS approach, firstly introduced by Haller and Yuan (2000), claims that coherent structures in a flow represent surfaces of large separations, i.e., they act as transport barriers, and allow for differentiating flow regions with complex dynamical behaviors. Then, in order to analyze the flow in a consistent mathematical way and identify the so-called tubular material surfaces, i.e., regions characterized by high coherence and vorticity, we calculate the Lagrangian Averaged Vorticity Deviation (LAVD), as defined by Haller et al. (2016):

(eq.3) $LAVD(t_1, t_0, \boldsymbol{x_0}) = \int_{t_0}^{t_1} |\boldsymbol{\omega}(\boldsymbol{x}(s, \boldsymbol{x_0}), s) - \bar{\boldsymbol{\omega}}|\, ds.$

In eq. 3, $\boldsymbol{x_0}, t_0, t_1$ are the initial position, the initial time instant, and the final one, respectively; $\boldsymbol{\omega}$ and $\bar{\boldsymbol{\omega}}$ are the local and the spatial mean vorticity along a particle trajectory. Haller et al. 2016 defined the LAVD-based vortices as an objective identifier and thus independent from the observer. As a result, a direct application on non-periodic flows is straightforward. Thus, by means of the Lagrangian Averaged Vorticity Deviation (LAVD), the flood-macrovortices appear as a results of small scales vortex shedding and thinning process that interacting each other, merge into larger structures (Figure 3) (De Leo et al. 2022).

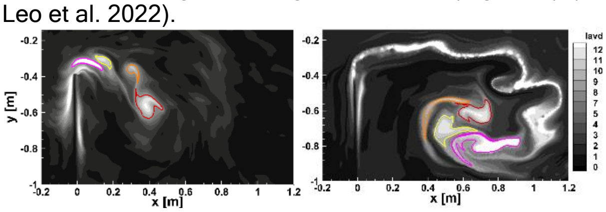

Figure 3 - Vortex interaction identified through LAVD, within half of the domain, focus on the inlet entrance.

One of the main goals of the present study is to assess the dispersion processes occurring in weakly dissipative tide dominated estuaries characterized by the presence of an inlet mouth and by a single main channel with lateral flats. Flood-macrovortices are invariably observed for all experimental parameters. They are clearly generated by interaction between the flow and the inlet mouth, and are able to occupy the entire tidal flats. Flood macro-vortices are the results of the vortex shedding at the inlet and a merging process that, ultimately, tends to form structures at the scale of the tidal flats width. Owed to the periodic character of the flow, in all cases, during the ebb phase, the macrovortices are flushed away towards the basin: this mechanism has been ascribed to the compound geometry. Performing a time average within a tidal period, it has been seen that a residual current occurs. The flood-macrovortices, the periodic flow and the surface residual current strongly influence the Lagrangian properties. In particular, in the absolute dispersion, after an initial ballistic regime (times smaller than a Lagrangian time), a looping-like behavior is recalled that, however, shows a linear trend (Brownian regime), Figure 4(a), see LaCasce (2008). The resulting dispersion coefficients, panel (b), show a constant trend for increasing values of the friction parameter.

The present experiments provide a deep understanding of the main dispersion processes occurring in weakly-dissipative tidal systems characterized by the presence of a tidal inlet.

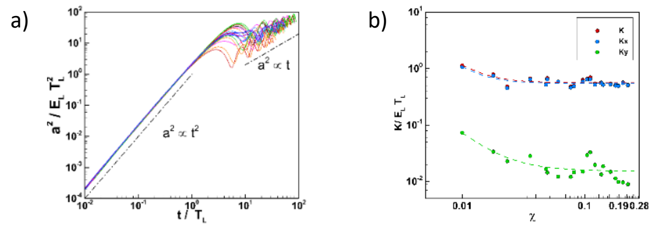

Figure 4 – a) Non dimensional absolute dispersion; b) Non dimensional dispersion coefficients as a function of χ.

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