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Surface water renewal and mixing mechanisms in a semi-enclosed microtidal domain. The Barcelona harbour case

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ABSTRACT

Water renewal and mixing are highly related to the evolution of the ecological status in harbour areas and are crucial for environmental harbour management. For the first time, these processes have been studied in the Barcelona harbour with a high resolution 3D hydrodynamic model. This harbour is representative of a semi-enclosed domain with a complex coastline in a micro-tidal environment (like most Mediterranean harbours). The tracking of numerical Lagrangian particles deployed in the flow was used to parameterize the surface water renewal mechanisms. The use of Finite Size Lyapunov Exponents has proven to be a relatively easy and efficient way to characterize the mixing patterns. The complex geometry of the harbour and the meteo-oceanographic forcings lead to intricate hydrodynamics that define spatial heterogeneity of water renewal and mixing. The most favourable conditions for enhancing surface water renewal and mixing have been identified in idealized scenarios and realistic simulations. In general, renewal is enhanced near the harbour mouths and strongly limited in the inner areas. However, under particular forcing conditions, the residence time can decrease even in the most sheltered areas. The presence of two mouths in the harbour seems to favour water renewal in comparison to harbours with only one mouth. Mixing is mainly induced by the action of wind forcing, while external shelf currents are much less efficient. The study of two realistic simulations suggests that harbour response to real forcing cannot be deduced from the combination of simple idealized scenarios. The time evolution of the forcings and the transient response of the system play a key role in defining the residence time patterns.

1. Introduction

The harbours impacts in the water ecological system can be significant on detrimental of other activities such as bathing or fishing (Borja et al., 2006). Examples of decreased ecological status due to harbour as a source of pollution are widely documented in the literature (e.g. Xu et al., 2004; Zhang et al., 2008). Ecological status and water quality evolution are highly related to water renewal. For example, water residence time is a fundamental concept for estimating the transport time scale in both geochemical and biological processes occurring in a water body (Monsen et al., 2002). In similar terms, Migon et al. (2007) demonstrated that dissolved and particulate geochemical concentrations are related to water renewal parameters in a semi-enclosed bay. Torretón et al. (2007) showed the pertinence of using flushing indices determined from hydrodynamic modelling to explain the distribution of planktonic and chemical variables in a coastal reef. Doering (1996) have also shown the relationship existing between water renewal indices and phytoplankton blooms.

The water renewal capacity of semi-enclosed domains is mainly controlled by the exchange flow between the outer and inner domains but also by the inner water circulation. In particular, in domains with complex geometry it is suggested to evaluate the spatial behaviour of water renewal rather than the integral values based on early definitions of residence time (e.g. Bowden, 1967; Dyer, 1973; Takeoka, 1984). Spatial heterogeneity of water renewal has been analysed in many different contexts. For instance, Cucco and Umgiesser (2006) computed the spatial distribution of residence time in the Venice Lagoon; Oliveira and Baptista (1997) elucidated the temporal and spatial variability of residence time in the Tagus Estuary; and Bilgili et al. (2005) investigated the water exchange between an estuary and open-sea and obtained a spatial distribution of residence time. Most of the studies that focus on water renewal processes rely on numerical modelling because there is no suitable data for those studies. In that sense, different numerical techniques and methodologies to parameterise the renewal have been proposed in the literature. For example, Meyers and Luther (2008),

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Bilgili et al. (2005), Oliveira and Baptista (1997) or Jouon et al. (2006) describe water renewal using Lagrangian Particle Tracking Methods (*LPTM*). On the other hand, Abdelrhman (2002), Cucco and Umgiesser (2006) or Ribbe et al. (2008) use a numerical Eulerian passive tracer to evaluate its dilution in the domains. In addition, Delhez et al. (2004) use complementary techniques, which reduce the computational time, to calculate the decreasing concentration of the Eulerian tracer computed from the solution to an adjoint problem. In summary, water renewal analysis has been applied to a wide range of domains using different numerical techniques.

A complementary concept to water renewal is the mixing process. Mixing has a crucial role in physical, chemical and biological dynamics in coastal areas (d'Ovidio et al., 2004). In particular, in harbour domains, mixing can enhance the decay of the concentration of spilled substances, reducing the impact of polluted waters. Also, considering the harbour as a source of pollution for open sea waters, the impact on the outer region will depend on the dilution (i.e. mixing capacity) of the polluted waters exiting the harbour. Turbulent mixing is determined by hydrodynamics, so the proper hydrodynamic modelling of the harbour domain could help in understanding its real impact on the evolution of water quality. For that, the spatial resolution needed to simulate harbour domains should be high because a detailed description of the geometry is required.

Previous studies have analysed water renewal in the Barcelona harbour under simplified perspectives, using either box models or stationary 3D modelling in a single scenario (e.g. Grifoll et al., 2006; Sánchez-Arcilla, 2002). However, they concluded that a more complex configuration would be required to properly describe the water renewal processes. The purpose of this contribution is to describe the surface water renewal and mixing mechanisms in the Barcelona harbour under different hydrodynamic conditions using realistic 3D modelling. Although quantitative results of water renewal and mixing are obtained for the Barcelona harbour (a micro-tidal harbour located in the North Western Mediterranean Sea), the basic processes described here could be applied to other similar environments. Semi-enclosed domains with a complex coastline and which are affected by similar environmental conditions (low tidal range, highly variable wind forcing and currents in the nearby shelf area) would behave similarly. In general, most Mediterranean harbours have those characteristics. Moreover, the Barcelona harbour has two entrances, so discussion about the implications of having two entrances instead of a single one may also apply to other semi-enclosed domains with two entrances.

This contribution is organized as follows. In Section 2 (methods), we present the study area, the numerical model, the verification procedure, the numerical experiments and the methods for estimating residence time and mixing. In Section 3, we present the results of the experiments. First, we pay attention to the circulation, residence time and mixing in several idealized scenarios. Then, we present results from a realistic configuration. In Section 4, the results are discussed and, finally, the conclusions of the contribution are drawn in Section 5.

2. Methods

2.1. Study area

Barcelona harbour is located in the NW Mediterranean Sea. At present, the size of the harbour is approximately 10 km long and 2 km wide, with a longitudinal axis rotated at about 30° with respect to the north. Depths in the harbour range from 8 to 20 m. The inharbour water domains are connected to the open sea through two mouths (Fig. 1): North and South Mouths. The main driving mechanisms are wind and shelf currents (Grifoll et al., 2011). From in-situ observations it has been determined that there is a clear north to south circulation pattern in winter, which is reversed (south to north) in summer with averaged velocities of about 4 cm/s. However, it must be noted that current variability is significant (standard deviation of ADCP time-series is about 7 cm/s). This variability is controlled and restricted mainly by the harbour layout, in particular in the northern part, where basins and breakwater controls and restricts the flow. Tides have a low impact on the inner harbour circulation (maximum astronomical tide is 0.44 m according to annual reports of harbour authorities [Puertos del Estado; www.puertos.es]). Atmospheric (heat and salt) fluxes only affect the vertical stratification and have a secondary role in harbour water circulation. Finally, it has been demonstrated that inner freshwater sources (i.e. wastewater discharges) have a low impact on circulation (Grifoll et al., 2011).

2.2. Description of numerical model implementation

The analysis of field data summarized in the previous section has shown that the presence of barriers, breakwaters and docks leads to a complex flow in the harbour water domain. Furthermore, the high frequency of typical forcings (wind, water circulation outside the harbour, etc.) also contributes to the generation of high temporal and spatial variability in the inner harbour circulation, both in the horizontal and the vertical. The hydrodynamic model used in the present study is the Regional Ocean Modeling System (ROMS; Song and Haidvogel (1994), Shchepetkin and McWilliams (2005)).

The implementation of ROMS in the Barcelona harbour consists of a structured, equally-spaced mesh of 226 grid points in the along-shore direction and 108 grid points in the cross-shore direction with a grid resolution of 43 m (see Fig. 1). This grid resolution is the minimum required to solve the harbour geometry (i.e. the model solves the narrowest channel with at least 5 grid points) and is a good compromise between quality and computational cost. We have performed some sensitivity experiments increasing the grid resolution up to 20 m but results do not change significantly because the spatial resolution of the forcings is much lower. Five sigma (terrain following) layers are used to discretize the vertical direction. Therefore, the chosen resolution and computational domain are a good compromise between the computational cost and the numerical requirements of our problem. We use a Flather radiation condition in the lateral open boundary conditions for the 2D variables while an Orlanksy-type radiation condition is used for 3D variables (Marchesiello et al., 2001). The horizontal eddy viscosity is determined by the Smagorinsky turbulent closure model and the vertical viscosity through a K-profile parameterization (Large et al., 1994). The same model implementation has been used by Grifoll et al. (2011) to describe the circulation patterns in the Barcelona harbour. In that contribution, the model outputs were validated against current measurements showing a good agreement in terms of intensity and patterns of variability.

2.3. Numerical experiment description

The strategy chosen is to simulate the hydrodynamics in the harbour under the most typical forcing conditions in order to establish the most likely cases for renewal and mixing. As a first step, the model is implemented in idealized scenarios designed to understand the physical process and to highlight the impact of the different forcing conditions on the hydrodynamics, renewal and mixing. Then, as a second step, a realistic configuration is used to determine the behaviour of the harbour under real conditions.

The idealized runs are designed based on the analysis of measurements of wind and external currents, which are the main forcing factors in the Barcelona harbour. Data on the external currents are extracted from a currentmetre moored in front of the Barcelona harbour (see Fig. 1 for its location). The current rose for 2009 is shown in Fig. 2. The circulation outside the Barcelona harbour is mainly parallel to the coast, so two prevailing current directions are considered: northeastward and south-westwards. These directions define two computational experiments in which the model is only forced by external currents of 15 cm/s towards the NE and SW directions (experiment SC1