Ocean Modelling 104 (2016) 84–98

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Virtual Special Issue
Coastal ocean modelling

Modeling circulation patterns induced by spatial cross-shore wind variability in a small-size coastal embayment

Pablo Cerralbo[a,*], Manuel Espino[b], Manel Grifoll[b]

[a] *Maritime Engineering Laboratory at Polytechnic University of Catalonia (LIM/UPC), c./Escar, 6, 08039 Barcelona, Spain*
[b] *Maritime Engineering Laboratory at Polytechnic University of Catalonia (LIM/UPC) and International Centre of Coastal Resources Research (CIIRC), c./Jordi Girona, 1-3, 08034 Barcelona, Spain*

ARTICLE INFO

Article history:
Received 20 August 2015
Revised 4 May 2016
Accepted 31 May 2016
Available online 2 June 2016

Keywords:
Wind-driven circulation
Modeling
Bay dynamics
Coastal waters
ROMS, NW Mediterranean Sea
Alfacs Bay
40.5º–40.7ºN
0.5º–0.8ºE

ABSTRACT

This contribution shows the importance of the cross-shore spatial wind variability in the water circulation in a small-sized micro-tidal bay. The hydrodynamic wind response at Alfacs Bay (Ebro River delta, NW Mediterranean Sea) is investigated with a numerical model (ROMS) supported by in situ observations. The wind variability observed in meteorological measurements is characterized with meteorological model (WRF) outputs. From the hydrodynamic simulations of the bay, the water circulation response is affected by the cross-shore wind variability, leading to water current structures not observed in the homogeneous-wind case. If the wind heterogeneity response is considered, the water exchange in the longitudinal direction increases significantly, reducing the water exchange time by around 20%. Wind resolutions half the size of the bay (in our case around 9 km) inhibit cross-shore wind variability, which significantly affects the resultant circulation pattern. The characteristic response is also investigated using idealized test cases. These results show how the wind curl contributes to the hydrodynamic response in shallow areas and promotes the exchange between the bay and the open sea. Negative wind curl is related to the formation of an anti-cyclonic gyre at the bay's mouth. Our results highlight the importance of considering appropriate wind resolution even in small-scale domains (such as bays or harbors) to characterize the hydrodynamics, with relevant implications in the water exchange time and the consequent water quality and ecological parameters.

1. Introduction

Tides, winds and freshwater inputs are the main factors determining the hydrodynamics in coastal areas such estuaries and semi-enclosed bays. In micro-tidal and low-freshwater-discharge environments the winds become the main driving mechanisms. The response in bay dynamics to wind forcing has been investigated in detail from different approaches. For instance, Csanady (1973) investigated the current response to a wind in a non-rotating basin, in which the forced response is a surface distortion due to the setup accompanied by a forced flow pattern due to bathymetry variability. Basically, a stable situation shows that in areas shallower than mean water depth the transport is with the wind direction, while it is against the wind direction in deeper areas. Gravitational estuarine circulation is also influenced by winds: intensified with a down-estuary wind, and weakened or even reversed with an up-estuary wind (Valle-Levinson and Blanco, 2004). Furthermore, interaction between wind and gravitational circulation is able to generate substantial transverse circulation in estuaries with a triangular section (Wong, 1994), and the influence of winds on exchange flows in narrow areas is demonstrated in Narváez and Valle-Levinson (2008). Recently, application of 3D numerical models has allowed the physical mechanisms involving wind-driven circulation in coastal areas to be investigated: for instance, asymmetries in the ebb-flood cycle due to wind forcing in surface layers (deCastro et al., 2003), circulation patterns and water exchange processes (Schoen et al., 2014), and wind model resolution in circulation and wave model behavior (Signell et al., 2005; Klaić et al., 2011; Schaeffer et al., 2011).

Contributions focused on regional and oceanic scales have demonstrated that wind variability due to topographic constraints not only influences the local circulation but also affects mesoscale

---

* Corresponding author.
E-mail address: pablo.cerralbo@upc.edu, pablocerralbo@gmail.com (P. Cerralbo).

http://dx.doi.org/10.1016/j.ocemod.2016.05.011
1463-5003/

structures (Chavanne et al., 2002; Jiang et al., 2009). Espino et al. (1998) compares the wind curl with mesoscale circulation in NW Mediterranean Sea, and a theoretical approach to wind curl effects on coastal areas such as the Benguela Current was described by Junker et al. (2015). Zampato et al. (2007) studied the sensitivity of sea level prediction in the Adriatic Sea to different atmospheric model resolution, showing how the finest-resolution models improve the representation of most energetic events. At smaller scales, Rueda et al. (2009) studied the uncertainty of 3D hydrodynamic models associated with the spatially and temporally varying wind fields in a lake, demonstrating that the better results were obtained using the maximum of available observational data to interpolate the spatial wind fields (reproducing the maximum spatial wind variability). Herrera et al. (2005) studied wind variability on the coast of Spain, emphasizing the wind channeling effects of the Ria de Vigo estuary through a comparison of various meteorological stations. Cerralbo et al. (2012) applied a numerical model in the same estuary and observed that a meteorological model ($\approx$4 km resolution) was not able to reproduce all the spatial variability, thus leading to remarkable errors in current modeling. However, only few studies on spatial wind variability have been carried out on bays and estuary dynamics, mainly due to the lack of meteorological observations and the coarse resolution of meteorological models (on the order of a few kilometers). Klaić et al. (2011) compares the hydrodynamic patterns resulting from the application of different-resolution atmospheric models in the mid-Adriatic, revealing the appearance of new hydrodynamic structures using the finest-resolution models. An interesting example is found in Podsetchine and Schernewski (1999), based on a lake and showing how wind variability on short spatial scales affects the hydrodynamic response. On the other hand, Grifoll et al. (2012) investigated the influence of wind variability in harbors whose layout strongly conditioned the preferential directions for the water motion, thus reducing the effects of the spatial wind variability.

The wind variability affects the water exchange between the sheltered waters and the open sea. In this sense, an integrated parameter of water exchange between the bay and the open sea may be also useful to assess the influence of the spatial wind variability on the hydrodynamics. Water exchange time is a physical variable determining how the ecological status of a coastal embayment or estuary is affected by human-induced stresses. For example, short water exchange times indicate that there is insufficient time for the dissolved oxygen to be depleted (i.e. Tweed Estuary, UK) (Wolanski, 2007). On the other hand, longer times in a restricted coastal area will, potentially, allow an increasing buildup of inputs from land and lead to seasonal or even permanent O_2 depletion in bottom layers and consequently ecological problems (Jickells, 1998).

With the purpose of gaining knowledge of the effects of wind variability in semi-enclosed areas on water circulation, Alfacs Bay (located on the Ebro River delta, Fig. 1) was chosen as the study site, where a set of meteo-oceanographic data were available. The main objectives of this contribution are to characterize the hydrodynamic response of the bay under spatial wind variability conditions, as well as to investigate their influence on the water exchange between the bay and the open sea, estimating the water exchange times. The skill assessment of the numerical model is carried out with water current observations obtained during field campaigns in Alfacs Bay. The analysis and discussion of the results are also supported by numerical experiments in idealized domains made in order to investigate the physical mechanism responsible for the hydrodynamic response to the spatial wind variability. Even the results are particularized by the physical characteristics of Alfacs Bay; the new insights provided may be exported to similar domains in terms of hydrodynamic response to heterogeneous wind fields. The paper is organized as follows: the study area, observations and numerical model are described in Section 2. Numerical modeling skill assessment and the results of the numerical experiments are presented on Section 3. In Section 4, we discuss the wind variability effects on the hydrodynamic response and contextualize our results in the state of the art. In Section 5, we conclude by highlighting our main findings.

2. Methods

2.1. Study area

Alfacs Bay is defined as a bar-build estuary (Pritchard, 1952) formed by the interaction of Ebro River sediment and currents (Fig. 1). The bay is around 16 km in length by 4 km wide, with an average depth of around 4 m. The connection with the open sea is 2.5 km, with a central channel of 6.5 m and shallow shoals of around 1–2 m on both sides. The bay is surrounded by rice fields to the north, which spill around 10 $m^3 s^{-1}$ of freshwater loaded with nutrients 9–10 months per year into the bay (April-December), and a sand beach closing it on the east side. Monstià Serra, with maximum altitudes of around 700 m, closes the bay on the western side (Fig. 1).

The bay has been defined as a salt-wedge estuary (Camp and Delgado, 1987) with almost stable stratification all year. The highest tidal range during spring tides is around 0.2 m, and the hydrodynamic fluctuations are controlled by the wind modulated by the seiche activity (Cerralbo et al., 2014). The most intense regional winds in the area are from the north and northwest (Bolaños et al., 2009), establishing a wind jet due to the orographic effects in the Ebro River valley. As an example, 36 h time-averaged wind fields (modeled) during a northwesterly event during winter 2014 are shown in Fig. 2. In general, the water column used to be stratified due to the freshwater discharge, but well-mixed conditions are more common during winter and mostly related to the hydrodynamic response to wind forcing (Llebot et al., 2013) and occasionally to seiches (Cerralbo et al., 2015a).

2.2. Observations

The bulk of the observational data correspond to two field campaigns: from July to mid-September 2013 and February to April 2014. The data set consisted of water currents from two 2 MHz acoustic Doppler current profiler (ADCPs) moored in the mouth (A1) and inner bay (A2) (Fig. 1) configured to record 10 min averaged data from 10 registers per minute and with 25 cm vertical cells. Both devices were equipped with pressure systems and a temperature sensor, and were mounted on the sea bottom at 6.5 m depth. Moreover, a chain of three temperature and salinity sensors (CTs) was moored in A2 at around 0.5, 2, and 4 m depth, recording minutely data. The sea level data were obtained from the “Catalan Meteo-oceanographic Observational Network” (described in detail in Bolaños et al., 2009) in Sant Carles de la Ràpita harbor (Fig. 1) and bottom pressure systems from the ADCPs. Atmospheric data (wind, atmospheric pressure, solar radiation and humidity) were obtained from a fixed land station: Alcanar (M-A) and M-Met (from Meteorological Service of Catalonia, http://www.meteocat.cat).

2.3. Description of numerical models and simulations

Numerical wind information was obtained from current implementations of the Weather Research and Forecasting model (WRF; Skamarock et al., 2008) applied at two spatial resolutions (9 km and 3 km) in Alfacs Bay (Fig. 2) and oriented to provide meteorological forecasts by the Meteocat agency. Information, configuration and validation details of the atmospheric models are summarized in Cerralbo et al. (2015b).