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Meteorologically-driven circulation and flushing times of the Bay of Algeciras, Strait of Gibraltar

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A R T I C L E   I N F O

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A B S T R A C T

A primitive-equation model has been used to investigate the meteorologically-driven circulation of the Bay of Algeciras. It is shown that the mean circulation of Atlantic Water (AW) is characterized by an anticyclonic cell, while Mediterranean Water (MW) follows a preferred cyclonic pathway. Meteorological forcing distorts substantially the AW mean circulation pattern, and only modulates that of the MW. Winds drive a vertical circulation cell in the Atlantic layer consistent with Ekman dynamics, whereas the horizontal circulation pattern is markedly dependent on the swift Atlantic jet entering the Mediterranean and changes from clearly anticyclonic to cyclonic as the jet separates or approaches the strait's northern shoreline. This occurs through atmospheric pressure-driven acceleration/deceleration of the jet, in agreement with internal hydraulics theory predictions. It is also found that the renewal of AW is largely modulated by tides, with meteorological forcing playing a secondary role. The opposite applies to the renewal of MW.

1. Introduction

The Bay of Algeciras is located at the north-eastern end of the Strait of Gibraltar (Fig. 1). Covering an area of about 9×11 km, and with maximum depth of nearly 400 m, features by far the mildest surface currents of the strait. This circumstance has made this spot the preferred location in the zone for the settlement of harbors from early civilizations (Bernal Casasola et al., 2003). Today, the bay holds two important ports in both Algeciras and Gibraltar, and also numerous industrial plants distributed all along its shoreline. Marine pollution is therefore a realistic risk and a major problem in the area. A potential accident such as a significant oil spill will damage not only the remarkable ecology of the area, but also its economy and that of its surrounding regions, mainly depending on tourism.

Because of these factors the understanding of the bay's circulatory system is of particular concern, which has recently motivated a number of investigations. For instance, Álvarez et al. (2011) report on the existence of high-frequency motions related to the intrusion of an internal tidal bore coming from the main sill of the strait. Periñaez (2012) studied the dispersal of different types of pollutants, while recently Sammartino et al. (2014) described in detail both the barotropic and baroclinic tidal circulation of the bay in a combined numerical and experimental study.

Even if the major source of variability in the region are tides (García Lafuente et al., 2000), subinertial motions acting at typical time scales of 2–4 days can be also significant (see for instance Candela et al., 1989; García Lafuente et al., 2002). Broadly speaking, they are driven by local wind forcing, and more important, by fluctuations of atmospheric pressure in the far field (particularly over the western Mediterranean). Winds primarily affect the first tens of meters of the water column, while changes in atmospheric pressure lead to surface pressure gradients that drive barotropic flows through the Strait of Gibraltar. The associated volume transport can reach 1 Sv or more, and modulate substantially the exchange flow. An important effect of meteorologically forced flows is then expected on the bay circulation.

The aim of this paper is twofold. Firstly, to investigate the subinertial variability of the Algeciras Bay circulatory system; and second, to asses its flushing time under different meteorological and tidal scenarios. Regarding to this point, it should be noted that we use a more realistic approach than Periñaez (2012), who also aimed at providing typical flushing times of the bay on the basis of a barotropic tidal model. Note, however, that this is only a rough approximation as the actual (tidal and non-tidal) dynamics of the strait is markedly baroclinic (see, e.g., Sánchez-Garrido et al., 2011). Actually, Sammartino et al. (2014) show that Mediterranean

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and Atlantic Waters (MW and AW, respectively) in the bay, separated by a relatively pronounced pycnocline at around 90 m depth, present nearly counter-phase tidal motion.

This paper is organized as follows. Section 2 briefly describes the numerical model used in this work and its validation. Section 3 presents the model results, whereas Section 4 includes a short summary and some concluding remarks.

2. Numerical model

2.1. Model description

The Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al., 1997; Marshall et al., 1997) has been used in this work. We make use of the model simulation described in Sánchez-Garrido et al. (2013) and Sammartino et al. (2014), who developed a regional circulation model of the Strait of Gibraltar and adjacent sub-basins on the basis of the MITgcm source code. The model is a component of an operational oceanography system, and its detailed description can be found in the above referred papers; here we only give a brief outline of the model features and set up.

The model domain covers the Gulf of Cádiz and the Alboran Sea (from 9°W to 1°E), and has been discretized with an orthogonal curvilinear grid of variable horizontal resolution. It is maximum within the Strait of Gibraltar where Δx, $\Delta y \sim 300$—500 m. With this configuration the Bay of Algeciras contains 28×25 grid points. Towards the model open boundaries the resolution gradually decreases to 8–10 km. In the vertical, the model has 46 unevenly distributed z-levels. The resolution is maximum at the surface, $\Delta z = 5$ m, and exponentially decays towards the sea floor. The bottom topography is represented as partial vertical cells.

The model is laterally forced by daily-mean temperature, salinity and velocity fields extracted from a larger-scale circulation model of the Mediterranean (Oddo et al., 2009). Together with this slowly-varying forcing, tidal and meteorically-driven barotropic velocities are prescribed across the open boundaries. Tidal velocities are extracted from the results of the model described in Carrere and Lyard (2003), while the later velocity field, capturing the remote effect of atmospheric forcing in the model (essentially

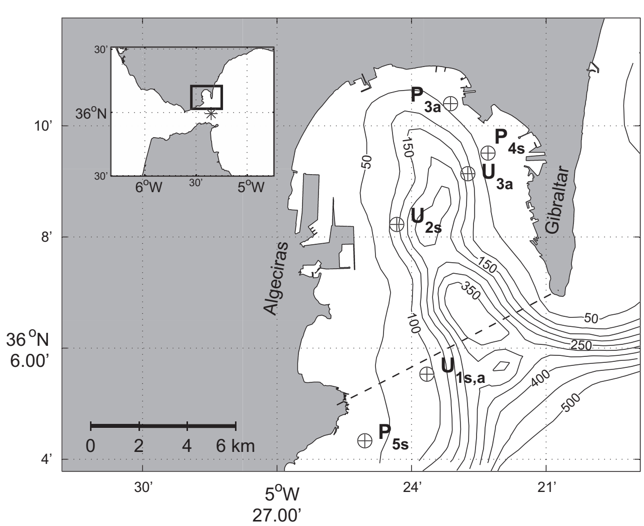

Fig. 1. Bathymetric chart of the Bay of Algeciras. The locations of the mooring lines deployed during the experiment are indicated and their respective names labelled. Subscripts indicate the season of the year when they were deployed: Spring(s) and Autumn (a). The asterisk mark in the inset indicates the location of the wind velocity time series referred in the text. Dashed line: bay mouth cross-section.

the inclusion of a barotropic flow through the strait varying at subinertial time scales), is obtained from the outputs of a storm surge operational system (Álvarez Fanjul et al., 2001). At the free surface the model is driven by high-resolution (1/20° in space, and 3 h in time) atmospheric forcing fields provided by the Spanish Meteorological Agency. Winds stress, shortwave, and longwave radiative forcing are applied to the ocean surface. Latent and sensible heat fluxes are interactively calculated by the model using standard bulk formulas.

2.2. Model validation

The ability of the model to simulate a realistic variability of the exchange flow through the Strait of Gibraltar and the circulation of the Alboran Sea has been proven in Sánchez-Garrido et al. (2013). Regarding the Bay of Algeciras, Sammartino et al. (2014) found a very satisfactory agreement between model and field measurements at tidal scale, thus here we only focus on the subinertial time scale.

A set of moorings lines were deployed in the bay during Spring and Autumn 2011 (Fig. 1; see Sammartino et al., 2014 for detailed description of the experiments). In total 6 mooring lines were deployed, three of them at shallow depths (P3, P4, and P5; ~25 m), and the rest (U1, U2, and U3) at around 100 m depth (subscripts "*s*" and "*a*" refer to Spring and Autumn respectively; same notation as in Sammartino et al., 2014). The low-frequency[1] temperature and salinity time series recoded near the sea floor are depicted in Fig. 2, together with the modelled time series. Overall, there is a very satisfactory agreement between model and observations. There are some discrepancies in the mean value of the time series, especially in salinity recorded at U1 (Fig. 2b), where the mean observed salinity exceeds in 0.33 units the modelled mean value. The difference is partially attributable to fine features of the bottom topography not represented by the model as the deepest model grid point at this location is some meters shallower than the depth of the CT probe. However, the model captures very well the amplitude and periodicity of the fluctuations of all the observed signals. The cross-correlation coefficient between observed and modelled variables ranges between $r = 0.78$ for salinity at U3, and $r = 0.95$ for temperature at T5, which are quite high values. It is also interesting to note the ability of the model for capturing the important fluctuations of temperature at shallow depths (Fig. 2a), driven by episodes of intense air-sea heat fluxes (not shown).

Fig. 3 shows the velocity over the two deepest stations of Spring (U1 and U2). Over U1 the zonal component (Fig. 3a) is predominantly negative over the whole water column and reaches peak values of around -20 cm s^{-1} near the surface, where the signal appears substantially modulated and some sporadic events of velocity inversion occur. The meridional component (Fig. 3c) is of the same order but exhibits a noisier pattern. Its sign is mainly positive, which implies a quasi-permanent net flow towards the bay. Velocities over U2 are smaller, of the order of 5 cm s^{-1} (Fig. 3e and g), and have a strongest dependence with depth, especially the zonal component that inverts sign at around 40 m and 80 m depth. It is positive near the surface and the bottom, and negative at mid-depths. It is interesting to note the prevalence of opposite sign of the near-surface velocities at U1 and U2, westwards and eastwards respectively, which suggests a dominant cyclonic circulation within the bay. As in U1, the meridional component has a more irregular pattern than the zonal velocity. The profiles are usually fairly homogeneous throughout the whole water column, alternating periods of northwards and southwards flow. The whole

[1] Low frequencies are meant here and throughout the rest of the paper as subinertial frequencies. The low-frequency signals are obtained by applying a low-pass Gaussian filter with cut off frequency of 0.5 days^{-1} to the original time series.