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Spatial and temporal variability of tidal flow in the Strait of Gibraltar

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ABSTRACT

Recent observations collected at different places in the Strait of Gibraltar are used to investigate the temporal and spatial variability of tidal currents in this region. The analysis of a five-year long time series of velocity observations at the Espartel sill (western end of the strait) shows that harmonic constants fluctuate seasonally exhibiting smaller amplitude in winter. This fact, along with an increased subinertial flow during the winter induces a marked decrease in the relative importance of the tide to the total flow compared to the summer. New computations of tidal transport at the key sections of Espartel and Camarinal, together with historical information reported for the Eastern Exit of the strait, have been analyzed jointly to highlight the internal along-strait divergence of the tidal transport in each layer and the transfer of the tidal signal from one layer to the other. This study covers the whole length of the strait, thus extending previous results reported for the central-eastern strait. Most of the topographically forced divergence is accounted for by large vertical displacements of the interface, although velocity observations collected on the continental shelf of the northern strait suggest that coastal recirculation plays some role in the volume conservation at tidal frequencies.

1. Introduction

The Strait of Gibraltar connects the Mediterranean Sea and the Atlantic Ocean through a rather complicated system of sills and narrows. It has a length of nearly 60 km and a mean width of 20 km. The shallowest depth, less than 300 m, is found in the main sill of Camarinal (CS) and its minimum width of around 14 km coincides with the contraction of Tarifa narrows (see Fig. 1). The excess of evaporation over precipitation and river run-off, together with the conservation of mass and salt in the Mediterranean basin drive the two-layer baroclinic exchange in the Strait of Gibraltar. This exchange has been traditionally described as an inverse estuarine circulation (Stommel and Farmer, 1953) with an upper flow Q_1 of 0.81 ± 0.06 Sv ($1\ \text{Sv} = 10^6\ \text{m}^3\ \text{s}^{-1}$) of fresh ($S_A \approx 36.2$) and warm Atlantic water spreading into the Mediterranean basin (Soto-Navarro et al., 2010), and a westward flow Q_2 of relatively cold and salty ($S_M \approx 38.4$) Mediterranean water. The mean flow through the Strait of Gibraltar is modified by various processes at different time scales. It shows seasonal (Garcia-Lafuente et al., 2002a; Garrett et al., 1990) and inter-annual variability, sub-inertial (O(10 days)) changes driven by winds and, mainly, by atmospheric pressure differences between the Atlantic Ocean and the Mediterranean Sea (Candela et al., 1989; Garcia-Lafuente et al., 2002b) and diurnal and semidiurnal variations due to strong tidal currents, which interact with the topography of the strait and have marked influence on the mean flow.

Tidal currents in the strait have been extensively studied by analyzing observations collected over the last decades, most of them in the strait contraction area. The first description of the complicated tidal pattern was reported by Lacombe and Richez (1982) using data from the early sixties, although it was the experimental effort of the Gibraltar experiment in the mid-eighties that allowed for the investigation of the tidal currents with much greater detail. Using sea level records from different coastal stations, García Lafuente et al. (1990) first described the structure of the barotropic tide (sea level oscillation) and showed that the amplitude of the prevailing semidiurnal constituents diminishes more than 50% from the western to the eastern end of the strait and has little cross-strait structure. Candela et al. (1990) confirmed this pattern and described the tidal velocity field in some locations of the strait, particularly in the Camarinal sill section (Fig. 1). These authors found that, at tidal frequencies, the along-strait pressure gradient is mainly balanced by the acceleration of the flow, while the cross-strait balance tends to be geostrophic. Ten years after a new experimental effort was carried out during the Canary Islands Azores Gibraltar Observations (CANIGO Project, 1996–98). Several moorings were deployed in the strait to monitor the exchange and address its seasonality. An upward-looking ADCP installed in CS provided observations to study the vertical structure of the tidal currents with a high vertical resolution (Tsimplis, 2000). García-Lafuente et al. (2000) analyzed in detail the tide in the eastern part of the strait and Baschek et al. (2001) estimated the transport in this section using a tidal inverse model.

All these works focused on the main sill of Camarinal and on the eastern strait due to their demonstrated role on the hydraulical control of the exchange flows (Armi and Farmer, 1985). There are, however,

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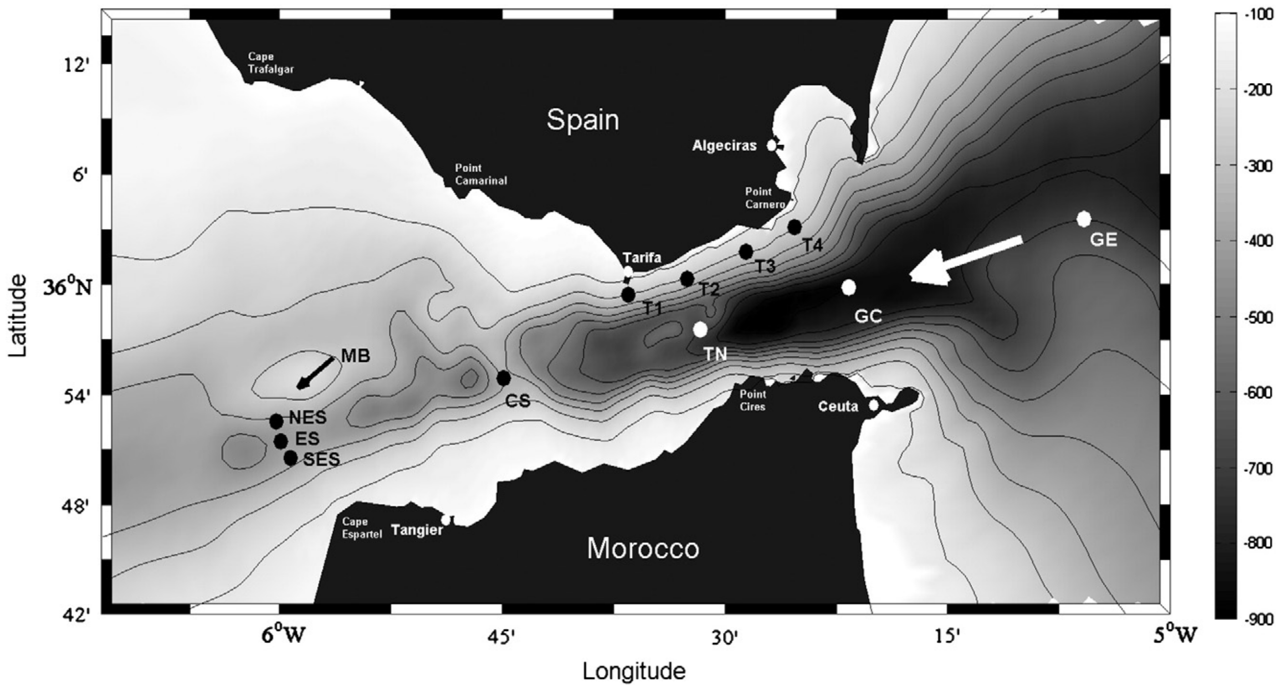

Fig. 1. Map of the Strait of Gibraltar showing the bathymetry (m) and the location of the stations. The topographic features shown are Espartel sill (ES), Camarinal sill (CS) and Tarifa narrows (TN). MB is the submarine ridge of Majuan Bank, which divides the Espartel section into two channels. NES and SES indicate the location of the auxiliary deployments in the main channel. GC and GE correspond to observing stations used in Sánchez-Román et al. (2009) that have been employed to construct the along-stream tidal maps. The white arrow indicates the direction of the flood tide.

other key places in the strait that deserved further attention. In late 2004, an oceanographic station was deployed at the sill of Espartel (ES, Fig. 1) west of CS with the aim of monitoring the Mediterranean outflow and its variability. This section, which has a complex topography due to the presence of the submarine ridge of Majuan Bank (Fig. 1) that divides the outflowing cross-section in two channels, represents the main gateway of the Mediterranean outflow. The observations at ES were already used by Sánchez-Román et al. (2008a) to describe the vertical structure of tidal currents in the main channel of this section, although a further investigation about the role played by this site in the tidal dynamics and associated transports in the strait is still lacking. These observations also indicate that the sill exerts hydraulic control over the outflow more than 96% of the time and the control is only lost for short periods of the ebb tide in the most energetic spring tides (Sánchez-Román, 2008b; Sannino et al., 2009), which makes ES suitable to monitor the Mediterranean outflow.

The present study has three main objectives, all of them aiming at providing a more complete description of tidal dynamics through the Strait of Gibraltar. The first objective is to investigate, for the first time, seasonal variability of tidal currents at the western strait by means of long velocity records available in ES. The second objective is to carry out a joint analysis of these data and other historical observations from other sites along the axis of the strait to depict a reliable pattern of the along-strait spatial variability of the tides in terms of the tidal transport. A first attempt to describe this pattern was made by García-Lafuente et al. (2000) using transports computed at the Eastern Exit of the strait and at CS. This work extends this analysis to the whole length of the strait by including the ES data in the western boundary of the area. The last objective of the paper is to investigate the cross-strait spatial variability of the flow at ES section and in the contraction area using recent observations with the aim of searching for dynamical connections between inshore and offshore tidal currents.

The paper is organized as follows: Section 2 describes the data and data processing. Section 3 addresses seasonality of tidal currents at ES. Section 4 discusses the along-strait spatial variability of tidal transports. Section 5 addresses the cross-strait spatial variability of the tidal currents and Section 6 discusses our results and summarizes the main findings.

2. Data and data processing

2.1. Datasets

The bulk of data come from the ES station (see Table 1 for details) in the main channel of the Espartel section. The station consists of an upward-looking moored ADCP at 345 m depth (15 m above seafloor) that resolves 40 bins, each 8-meter thick, and provides horizontal velocity at 40 levels every 30 min. This work analyzes the period from October 2004 to December 2009. Two auxiliary stations, equipped with up-looking ADCPs were deployed north (NES) and south (SES) of the ES station (Fig. 1) to describe the cross-structure of the outflow. It is important to remark that these stations were not deployed simultaneously (Table 1). Data collected by another ADCP at CS from January to April 2006 have been also used. The instrument profiled the horizontal velocity in 8 m bins between 44 and 260 m depth with a sampling interval of 30 min. Finally, data from four locations (T1 to T4 in Fig. 1) on the continental shelf break of the Spanish coast were collected by upward-looking ADCPs between May 2009 and April 2010 (see details in Table 1). The lines were placed along the 100 m isobath and the horizontal velocity was monitored in 2 m bins between the sea surface and 90 m depth with a sampling interval of 2 or 3 min (Table 1).

2.2. Data processing

2.2.1. Sequential harmonic analysis

The long record at ES has been used to investigate the time variability of harmonic constants. Classical harmonic analysis (Foreman, 1978; Pawlowicz et al., 2002) was performed to calculate tidal ellipses of the main diurnal (O_1 and K_1) and semidiurnal (M_2 and S_2) constituents. The dataset was divided in 3-month length sub-series and submitted to harmonic analysis to investigate the year-round variability of the harmonic constants. The sub-series overlapped 20 days to smooth