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Flow variability in the Strait of Gibraltar: The Mediterranean adjustment to tidal forcing

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A B S T R A C T

The vertical structure of the flow variability through the Strait of Gibraltar is studied based on the Gibraltar Experiment and the Word Ocean Circulation Experiment data sets. An analysis of the leading modes of velocity and density variability at the Strait of Gibraltar showed an adjustment of the water masses exchanged through the Strait. Mediterranean mass variations resulting from the water exchanged by barotropic tidal oscillations generate changes of the baroclinic component of the flow that damp these mass variations. This adjustment explains the previously observed fortnightly variation of the shear. Moreover, the adjustment is found to operate for the subinertial time scale flow variability forced by the atmospheric pressure. An analytical model aimed at reproducing variations of the velocity with time and in the vertical is derived. The model includes a depth-varying parameterisation of friction and takes into account density gradient fluctuations across the Strait. The model reproduces the main features of the flow, in particular the shear and the interface depth variations with the tide phase.

1. Introduction

The flow variability at the Strait of Gibraltar is mainly forced by tide and by the atmospheric pressure. Tide induces large flow fluctuations, mainly semi-diurnal, with an important fortnightly modulation. The atmospheric pressure is the major forcing of the flow at the subinertial time scales. The resulting fluctuations are mainly barotropic but friction also plays a critical role in limiting the response and delaying the flow relative to the forcing (Candela et al., 1989, 1990; Candela, 1991). Some interactions are shown to operate between the tide-induced flow and that related to the atmospheric forcing (Lacombe and Richez, 1984; Mañanes et al., 1998; Phu, 2001). Tidal oscillations also induce a net water exchange "*the barotropic pumping*", a flow related to the lack of complete recycling of the water exchanged and to vertical variations of the interface (Hopkins, 1999).

Hydraulic control models of the flow through the Strait of Gibraltar were developed by Assaf and Hecht (1974), Farmer and Armi (1986) and Bormans and Garrett (1989). They showed the importance of considering realistic Strait configuration and flow parameterisation on the model's results. Friction forces at the lateral walls of the Strait are for example shown to have a significant effect on the flow (Bormans and Garrett, 1989; Garrett, 2004).

Analytical models were developed to simulate the variability of the flow through the Strait of Gibraltar and its relation to the atmospheric forcing. Garrett and Toulany (1982) first developed a model based on the assumption of a cross-strait geostrophic balance, including effects of acceleration and friction. The model was further examined and extended to the two-basin case and to travelling atmospheric pressure disturbances by Garrett (1983), Toulany and Garrett (1984) and Garrett and Majaess (1984). Candela et al. (1989) proposed an analytical model that reproduces the Mediterranean

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response to the atmospheric pressure variability at the subinertial time scales. The model successfully reproduced the main features of the transport through the Strait of Gibraltar, in particular a damping and a delay of the transport induced by friction. A linear friction term, $-\lambda Q$, proportional to the transport, Q, is used with λ as a friction coefficient. This parameterisation was applied not only to the Strait of Gibraltar but also to the Strait of Sicily (Candela et al., 1989, 1991). The model also successfully reproduced the Mediterranean basin altimetry sea level (Le Traon and Gauzelin, 1997). An attempt to improve the model was done by Malačič (1993), who introduced a frequency-dependent friction coefficient. Such a varying coefficient did not appreciably improve the model performance.

To validate their analytical model, Candela et al. (1989) analysed the vertical structure of the subinertial velocity variations at the Strait of Gibraltar. In addition to the barotropic mode (strongly connected to variations of the atmospheric pressure), they found a baroclinic mode with an important fortnightly modulation. In this mode the vertical shear is enhanced during neap tides and reduced during spring tides. Candela et al. (1989) suggested possible tidal origin to this mode. Bruno et al. (2000) studied the vertical structure of the flow at the Camarinal sill and its relation to velocity and density amplitude variations at the semi-diurnal frequencies. However a detailed analysis of the dependence of the baroclinic mode on flow characteristics and mass exchange through the Strait was not performed.

In this paper we study the vertical profile of the flow through the Strait of Gibraltar and its interaction with the tide based on two independent data sets. We focus on the effects of friction and density gradients on the baroclinic fluctuations of the flow. In the following section we present the data used and their preliminary processing. In Section 3 we show a decomposition of the observed flow at the Strait of Gibraltar into barotropic and baroclinic components. In Section 4 we derive from this decomposition a mass balance requirement at the Strait of Gibraltar. In Section 5 we present derivations of a model that aims to reproduce the flow components, in particular the baroclinic one. Model verification is also shown in this section.

2. Preliminary processing

Data used for the derivation of water exchange through the Strait of Gibraltar are based on two sets. The first one contains the widely used measurements carried out during the *Gibraltar Experiment* (October, 1985–October, 1986; Pillsbury et al., 1987; Candela et al., 1989; Bryden et al., 1994; Morozov et al., 2002). This set (hereafter referred to as *GE*) forms the main data set. The second set contains measurements performed in the Strait of Gibraltar during the *Word Ocean Circulation Experiment* in the 1990s (Astraldi et al., 1999; Candela, 2001). This data set (hereafter referred to as *WOCE*) covers almost continuously 2 years (November, 1994–September, 1996) and is used as an independent data set. We should notice that several other important measurements were made at the Strait of Gibraltar (e.g., CANIGO measurements in the Camarinal Sill performed in 1997–1998, Tsimplis and Bryden, 2000; moorings at the eastern entrance of the Strait in 1995–1996, García Lafuente et al., 2000). For the purpose of the present work, *GE* and *WOCE* data sets are considered representative of the mean flow through the Strait of Gibraltar and its variability at tidal and subinertial time scales.

During the *Gibraltar Experiment*, current meter moorings were deployed at nine locations in the Strait. Figs. 1 and 2 show the location of the moorings and the depth of the attached current meters that will be used in this study. The preliminary processing of the data is standard; it differs only slightly from those followed by Pillsbury et al. (1987) and Candela et al. (1989). The raw data are drift corrected, smoothed and sub-sampled to obtain hourly series of along-strait velocity component, temperature and salinity. Density series are then deduced using the UNESCO equation.

The period lasting from October 22, 1985 to April 21, 1986, corresponding to the common period of moorings C-1 and C-3, is the base period of this study. The period covered by current meters of the mooring C-2 (October 22, 1985–November 23, 1985) is much shorter. Only mean and *rms* of the data from this mooring are used. The data at the C-2 location are approximated by interpolating the data from the neighbouring moorings C-1 and C-3 and scaling them with the mean and the *rms* of data from mooring C-2. To overcome the absence of shallow instruments, data from the mooring C-8 (October 22, 1985–February 26, 1986), which include a current meter at a depth of 30 m (Figs. 1 and 2), are used. C-8 is used in spite of its different location as it showed a pronounced correlation in low-frequency along-strait currents with C-3 (Bryden et al., 1994). Hence data at 30 m depth are approximated by extrapolation of data values at the uppermost instruments of the mooring C-3 and scaling them with the mean and *rms* of the mooring C-8. Finally data are interpolated on 10 vertical positions corresponding to centres of 10 trapezoid layers (Fig. 2). The 10 layers considered in this study are of equal areas, each representing one tenth of the Strait of Gibraltar area A_G. This permits us to overcome the problem of using different weights when calculating vertical integrals.

As mentioned above the Strait configuration can significantly affect the calculation of the net water transport. Astraldi et al. (1999) reduced currents in the upper 100 m by 9% in order to obtain an estimation of the transport in agreement with the net evaporation over the Mediterranean Basin. Examples of the admitted values for the transport are 0.03 Sv (Harzallah et al., 1993), 0.04 Sv (Bryden and Kinder, 1991; Bryden et al., 1994; Candela, 2001), 0.05 Sv (Baschek et al., 2001) and 0.11 Sv (Tsimplis and Bryden, 2000). As the primary interest of this paper is to investigate the variability of the flow, we set $\overline{Q} = 0.042$ Sv as mean transport through the 10 layers of the trapezoid idealised Strait. We should notice that the results found in this paper remain almost unchanged if one chooses other admitted transport values. Based on the sign of the velocity, the mean inflow and outflow values