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Tidal dynamics in the inter-connected Mediterranean, Marmara, Black and Azov seas

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ABSTRACT

In this study we investigated the tidal dynamics in a system of inter-connected land-locked basins formed by the Mediterranean, the Marmara, the Black and the Azov seas (MMBA system). Through the application of an unstructured grid hydrodynamic model to a unique domain representing the whole MMBA system, we simulated the tidal propagation and transformation inside each basin and in the straits connecting them. The model performance was evaluated against amplitudes and phases of major tidal constituents from 77 tidal gauges. The numerical results provided a description of the characteristics of the principal semi-diurnal, diurnal and long-term tides over the entire system. Even if the narrow straits act as a barrier for the tidal sea surface oscillations, our numerical results demonstrated that the along-strait interface slope produces water fluxes between the adjacent basins of the same order of magnitude of the climatological transports estimated by several authors. The long-term tidal modulations of the water exchange between the Mediterranean and the Black seas resulted to be non negligible and may partially explain the monthly and fortnightly flow variability observed in the Dardanelles and Bosphorus straits.

1. Introduction

The Mediterranean Sea - the largest semi-enclosed sea in the world - and the Black Sea - the largest brackish sea in the world - represent an exceptionally complex system of semi-enclosed connected basins that have been the subject of intensive oceanographic and biogeochemical research (Rohling et al., 2015; Özsoy and Ünlüata, 1997; Stanev, 2005). Even if they are generally considered as separated water bodies, they are part of a chain of adjoining regional seas - the Mediterranean Sea, the Marmara Sea, the Black Sea and the Azov Sea (hereinafter referred to as MMBA system) - connected by narrow straits (Fig. 1).

The Mediterranean Sea opens to the Atlantic Ocean only through the Strait of Gibraltar, a channel 60 km long and 20 km wide, characterised by a complex system of contractions and sills (Fig. 2a). The Mediterranean and the Black seas actively exchange waters through the Turkish Straits System (TSS, Fig. 2c), which consists of the Dardanelles Strait (75 km long, 1.2–7 km wide, 55 m deep on average), the Sea of Marmara (250 km long and 70 km wide, up to 1200 m deep) and the Bosphorus Strait (35 km long, 0.7–3.5 km wide, 30–110 m deep). The shallow Azov Sea (340 km long, 135 km wide, 1–14 m deep) is connected to the Black Sea through the Kerch Strait (Fig. 2b), which is about 45 km long, from 0.7 to 4.5 km wide and very shallow (3–12 m deep).

Straits have an extremely important role in forming the hydrographic and ecological conditions in semi-enclosed seas (Astraldi et al., 1999). This is particularly true for the TSS, which connects two water basins subjected to very different hydrological and climatic conditions. Over the Mediterranean Sea, evaporation exceeds the sum of precipitation and river discharge (Mariotti et al., 2002). On the other side, river runoff and precipitation over the Black Sea - together with the Sea of Azov - exceed evaporation, resulting in a net outflow through the Bosphorus Strait (Stanev and Lu, 2013). Usually, Black Sea Waters (BSW) spread in the surficial layers of the Aegean Sea (Mavropoulou et al., 2016 and references therein), while Mediterranean Sea Waters (MSW) extend into the deep Black Sea as a salt wedge identified by higher salinity, temperature and density (Yüce, 1996). Therefore, BSW strongly influence Aegean Sea biogeochemistry (Nieblas et al., 2014; Petihakis et al., 2014; Cossarini et al., 2015), while MSW plume and its cascading at the shelf break create an active way for the ventilation of the Black Sea anoxic waters at intermediate depth (Özsoy et al., 2001; Stanev et al., 2001).

In the micro-tidal Mediterranean Sea the tides are generated by the

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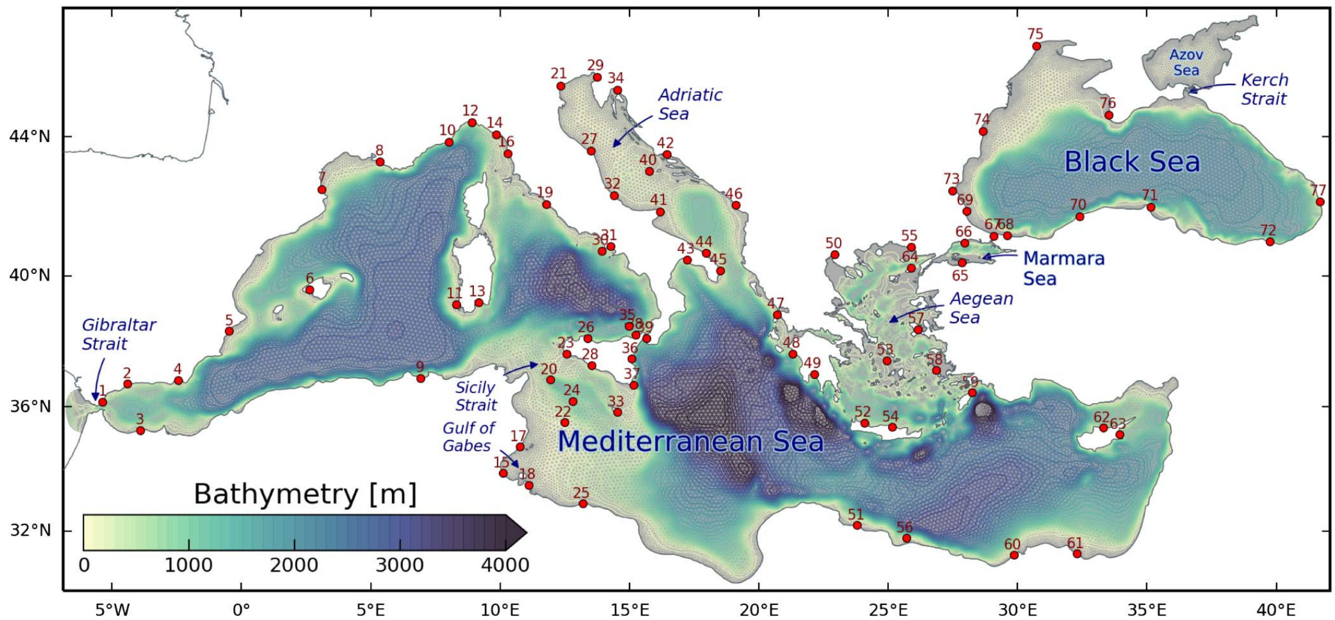

Fig. 1. Bathymetry of the Mediterranean, Marmara, Black and Azov seas with the unstructured grid superimposed. The red dots mark the location of tide gauges used in the model validation (see section 2.3 for more details). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sum of the direct action of the equilibrium tide and the incoming Atlantic tidal waves. The resulting tidal waves interact with the sea bottom producing significant tidal oscillations only in certain areas, namely, the North Adriatic Sea, the Gulf of Gabes, and the North Aegean Sea (Tsimplis et al., 1995). On the contrary, the Black Sea is considered a non-tidal basin with amplitude of major tidal constituents of few centimeters (Dotsenko et al., 2016), and amplification of semi-diurnal tides only in the north-western part (Medvedev et al., 2016).

Tides in the Mediterranean Sea are responsible for the amplitude modulation of water transport with the Atlantic Ocean, through the Gibraltar Strait, and between internal sub-basins, and has non negligible effects on the general circulation structure (Guarnieri et al., 2013; Sannino et al., 2015; Cucco et al., 2016). However, even if there are evidences that the Turkish Strait System acts as a barrier of tidal sea surface height fluctuations (Yüce, 1996; Alpar and Yüce, 1998), there is still a lack of knowledge regarding the impact of tides in modulating the water exchange between the Mediterranean and the Black seas. In literature there are some evidences of fluctuations of water currents in the Dardanelles and Bosphorus straits at diurnal and semi-diurnal tidal frequencies (Yüce, 1996; Jarosz et al., 2011b, 2012; Book et al., 2010), but they were not analysed in details.

To correctly reproduce the exchange of water and energy between adjacent seas, there is the need to jointly describe the general circulation at the basin scale and the processes in the straits, detectable at very fine spatial and temporal scales. Several numerical studies have been carried out in the past considering only one compartment of the MMBA system. Generally, numerical models of the Mediterranean Sea, the Aegean Sea and the Black Sea neglected or applied a parametrization of the Dardanelles and Bosphorus fluxes (Beckers et al., 2002; Beuvier et al., 2010; Sannino et al., 2015; Hamon et al., 2016; Tzali et al., 2010; Androulidakis et al., 2012; Kopasakis et al., 2012; Mavropoulou et al., 2016; Kokkos and Sylaios, 2016; Staneva et al., 2001; Bajo et al., 2014; Korotenko, 2015). Similarly, the numerical models of the TSS until recently were mostly focused to the Dardanelles Strait (Kanarska and Maderich, 2008), the Marmara Sea (Chiggiato et al., 2012; Book et al., 2014) or the Bosphorus Strait (Özsoy et al., 2001; Oğuz, 2005; Ilıcak et al., 2009; Sözer and Özsoy, 2017) in separate basin or strait model domains. Recently Sannino et al. (2017) applied a high-resolution model to simulate the TSS system as a whole, by considering the Marmara Sea, the Dardanelles and the Bosphorus straits, and part of the Aegean and the Black seas.

Numerical models of inter-connected basins using nesting techniques or unstructured grid models can be used to realise a seamless transition between different spatial scales (Zhang et al., 2016; Ferrarin et al., 2016; Stanev et al., 2017). Only few studies reported applications of models in order to reproduce the Black Sea connected to the TSS (Blain et al., 2009; Maderich et al., 2015; Stanev et al., 2017).

The aims of the research reported here were to (i) apply and validate the barotropic SHYFEM hydrodynamic model to an unstructured grid representing the MMBA system as a whole (Section 2.3), (ii) provide an overview of the tidal characteristic over the MMBA system (Section 3.1), and (iii) peer into the tidal transformation and tidal driven water exchanges at the straits connecting the different water basins (Section 3.2).

2. Materials and methods

2.1. Numerical model description

The numerical experiments consisted in simulating the tidal propagation and generation in MMBA system using the 3D finite element hydrodynamic model SHYFEM (Umgiesser et al., 2014). The open source model SHYFEM is freely available on the web pages http://www.ismar.cnr.it/shyfem and https://github.com/SHYFEM-model. The model has been already applied to simulate hydrodynamics in the Mediterranean Sea (Ferrarin et al., 2013), in the Adriatic Sea (McKiver et al., 2016; Ferrarin et al., 2016; Ferrarin et al., 2017), in the Black Sea (Bajo et al., 2014) and in several coastal systems (Umgiesser et al., 2014 and references therein).

The model uses a semi-implicit algorithm for integration over time, which has the advantage of being unconditionally stable with respect to gravity waves. The Coriolis term and pressure gradient in the momentum equation, and the divergence terms in the continuity equation are treated semi-implicitly. Bottom friction and vertical eddy viscosity are treated fully implicitly for stability reasons, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly.

Smagorinsky's formulation (Blumberg and Mellor, 1987; Smagorinsky, 1963) is used to parameterise the horizontal eddy viscosity. For the computation of the vertical viscosities, a turbulence