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The effect of lagoons on Adriatic Sea tidal dynamics

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ABSTRACT

In this study the effects that lagoons exert on the barotropic tidal dynamics of a regional sea, the Adriatic Sea, were numerically explored. This semi-enclosed basin is one of the places with the highest tidal range in the Mediterranean Sea and is characterised by the presence of several lagoons in its northern part. The tidal dynamics of a system comprising the whole Adriatic Sea and the lagoons of Venice, Marano-Grado and Po Delta were investigated using an unstructured hydrodynamic model. Numerical experiments with and without lagoons reveal that even if the considered shallow water bodies represent only the 0.5 and 0.002% of the Adriatic Sea surface and volume, respectively, they significantly affect the entire Northern Adriatic Sea tidal dynamics by enhancing tidal range (by 5%) and currents (by 10%). The inclusion of lagoons in the computation improved the model performance by 25% in reproducing tidal constituents in the Adriatic Sea. The back-effect of the lagoons on the open-sea tide is due to the waves radiating from the co-oscillating lagoons into the adjacent sea. This is the first time these processes are shown to be relevant for the Adriatic Sea, thus enhancing the understanding of the tidal dynamics in this regional sea. These findings may also apply to other coastal seas with connections to lagoons, bays and estuaries.

1. Introduction

Coastal systems like estuaries, lagoons and wetlands comprise some of the most valuable ecosystems on the planet with crucial ecological, historical, economical and social relevance (Pérez-Ruzafa et al., 2011; Wolanski and Elliott, 2015). Whereas the ecological contribution coastal basins make to offshore is widely recognised - since they provide nursery grounds for aquatic species of immense ecological, cultural and economic importance (Elliott et al., 2007) - their role on the open-sea hydrodynamics is still poorly investigated.

The need for predicting changes in the tidal regime caused by coastal developments and perturbations has led to increased numerical modeling of tides on regional seas. Pelling et al. (2013) and Song et al. (2013) demonstrated that reclamation of tidal flat and coastline or bathymetry changes could modify the distribution of tidal energy entering the system extending the local effect over a much larger range, thus generating far-field effects. Cazenave et al. (2016) showed that wind turbine monopiles alter the shelf-wide tidal amplitude with increases at sensitive coasts. More attention has been paid to the evaluation of the effects of tidal power plants on the tidal regime, indicating that tidal energy extraction has an impact on the sea elevations and circulation in the whole adjacent shelf sea (Choi et al., 2010; Duff, 1979; Greenberg, 1979; Hasegawa et al., 2011; Nekrasov and Romanenkov, 2010). Additionally, numerical models have been used to investigate the back-effect of shelf and coastal areas on the open-ocean tidal dynamics. According to Arbic et al. (2009) and Skiba et al. (2013) resonant shelf systems affect tidal elevation amplitudes and phases in both the adjacent open-sea and global ocean.

The aim of the research reported here is to evaluate the back-effect coastal basins exert on the barotropic tidal dynamics of the adjacent regional sea. The study area is the Adriatic Sea, a semi-enclosed regional basin with one the highest tidal range and sea level extremes in the Mediterranean Sea (Marcos et al., 2009; Tsimplis et al., 1995). Several shallow coastal transitional waters are present in the northern part of the Adriatic Sea, the main of which are the Marano-Grado Lagoon, the Venice Lagoon and the system of lagoons of the Po Delta.

Using a 3D unstructured hydrodynamic model the tidal propagation in the whole Adriatic Sea and its northern lagoons was simulated. Several numerical experiments were carried out to investigate the barotropic tidal dynamics in the Adriatic Sea coupled and uncoupled to the lagoons. A physical explanation of the far-field effect lagoons exert on the open-sea dynamics is provided after the presentation of the numerical results. The physical processes driving these dynamics have been studied for idealised settings; this is the first study to quantify them and show that they are relevant within the Adriatic Sea.

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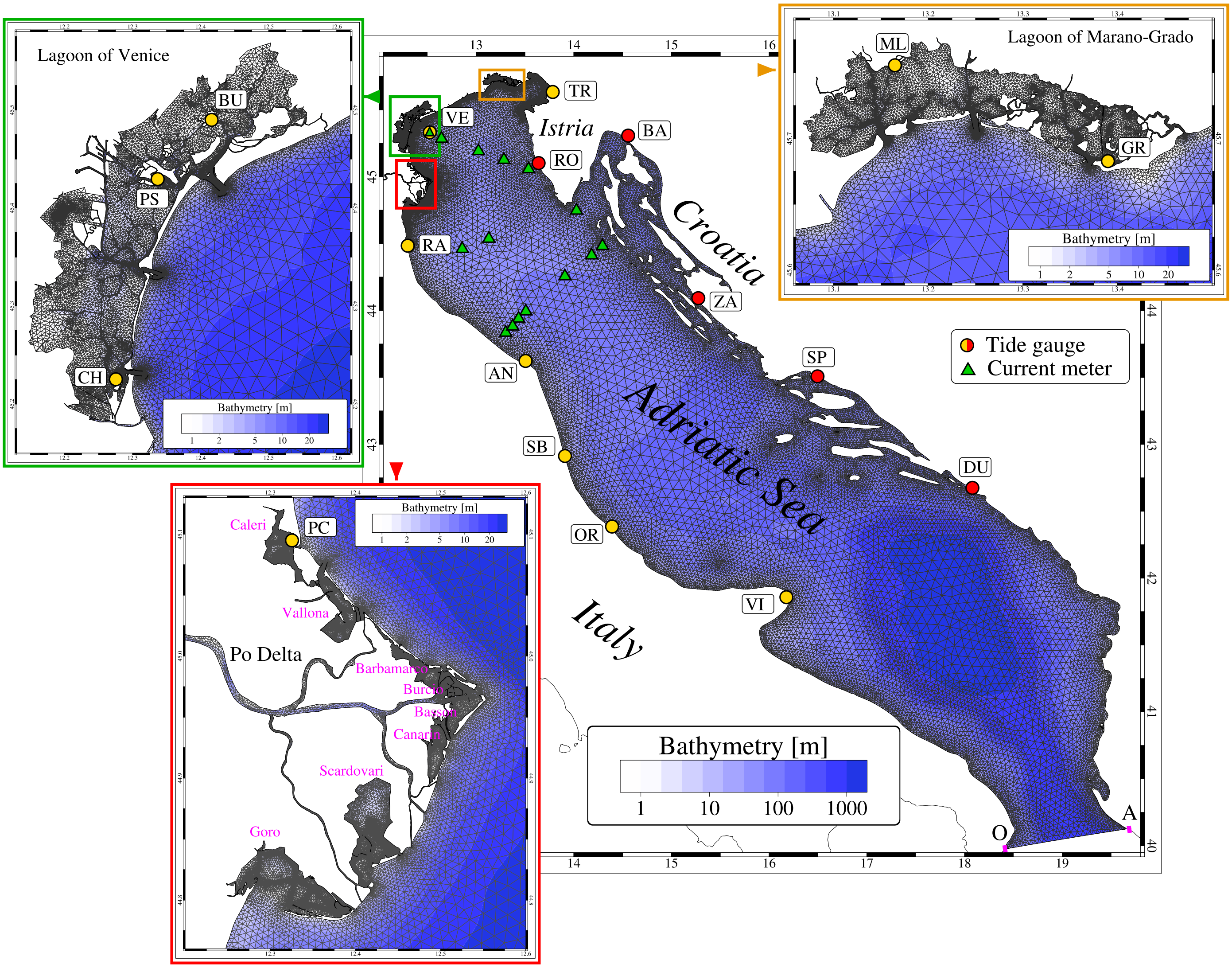

Fig. 1. Bathymetry of the Adriatic Sea and the Marano-Grado, Venice and Po Delta lagoons interpolated on the finite element numerical grid (superimposed). Circles mark the location of tide gauges. Triangles mark the location of the current meters. The purple OA line indicates the Otranto Strait boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Tides in the Adriatic Sea and in its lagoons

The Adriatic Sea is an 800-km-long, 150-km-wide elongated semi-enclosed basin interacting with the Mediterranean Sea through the Otranto Strait in the southern part (Fig. 1). The Adriatic Sea could be formally subdivided based on its bathymetry in a relative shallow Northern Adriatic (north of the 100 m-isobath), the mid-Adriatic Pit (Jabuka Pit, 270 m deep) and the deep Southern Adriatic Pit (with depths exceeding 1000 m; Artegiani et al., 1997).

Fluctuations of Adriatic Sea level and currents at tidal frequencies are among the most important of the entire Mediterranean Sea (Poulain, 2013). However, the circulation of the Adriatic Sea is strongly influenced by wind and heat forcing at the surface, which produce deep-water masses in the northern and southern Adriatic and forces the circulation to be seasonal, and by river runoff (concentrated along the western basin area), which is an important component of the buoyancy budget in the overall basin (Artegiani et al., 1997; Orlić et al., 1992).

The Adriatic tidal regime has been interpreted as co-oscillations with the Mediterranean Sea, forced through the strait of Otranto, and amplified by resonance phenomena along its longitudinal direction from south to north (Cushman-Roisin et al., 2001 and references therein). Only seven tidal constituents, four semidiurnal (M_2, S_2, N_2 and K_2) and three diurnal (K_1, O_1 and P_1), give a contribute significantly to the evolution of sea surface elevation in the Adriatic Sea (Book et al., 2009). According to Lovato et al. (2010), the tidal form factor (the ratio of the amplitudes of the major diurnal and semi-diurnal tidal constituents, $F = (K_1 + O_1)/(M_2 + S_2)$) reveals that the mixed mainly semidiurnal tidal regime ($F < 1$) prevails in the Adriatic Sea, although the tide maintains a diurnal character ($F > 3$) in proximity of the semi-diurnal amphidromic points in the middle Adriatic Sea.

Tides in the Adriatic Sea have been investigated experimentally, theoretically and numerically. However, to our knowledge none of the previously published studies investigated the potential effects of lagoons on Adriatic Sea circulation. Polli (1960) first described the tidal dynamics in the Northern Adriatic Sea based on water level measurements by providing cotidal-corange chart for the M_2 constituent. More recently studies of the tides in the Adriatic Sea have included sea levels from tide gauges (see Cushman-Roisin et al., 2001 and Capuano et al., 2011 for a review), as well as current velocity from current meters (Book et al., 2009 and Martin et al., 2009 and reference therein), HF radars (Chavanne et al., 2007; Mihanović et al., 2011) and surface drifters (Poulain, 2013; 2001).

The model of Taylor (1922) has been used by many authors to explain the semidiurnal tide in the Adriatic as a superposition of an