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Far-field synoptic wind effects extraction from sea-level oscillations: The Venice lagoon case study

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ABSTRACT

We analyze the sea-level oscillations at eight mareographic stations of the ISPRA network located in the Venetian lagoon considering four years from 2008 to 2011. The aim is to study the *acqua alta* phenomenon (i.e. the average increase in flooding levels higher than 79 cm), on different time scales by using a nonlinear method (Independent Component Analysis). We show that it is possible to extract from the water-level oscillations, on the time scale of the year, a long period component, which has a high correlation with the wind recordings (>0.8). Three tidal constituents are extracted by ICA including astronomical and meteorological effects. In particular, a long period component, peaked at two months, is ascribed to the wind effect on synoptic scale; indeed it shows a high correlation with the wind stress signal. According to the ICA model, that component is linearly superimposed on the extracted astronomical tides. These results allow us to estimate the tide super-elevation due to the wind stress at each station and so to improve the forecasting model of *acqua alta*, e.g., by introducing the proper wind effect correction at each station.

1. Introduction

The Venice lagoon is a complex basin in the northeast of Italy. It is an enclosed bay connected with the Adriatic Sea through three inlets: Lido, Malamocco and Chioggia (see Fig. 1). The sea-level is normally in the range [-50:79] cm with respect to the mareographic zero at Punta della Salute as indicated by Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM) at the URL, http://www.comune.venezia.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/1748, whereas it reaches up to 194 cm during anomalies (e.g., November 4, 1966) (see, e.g. Massalin et al., 2007). The phenomenon of ocean tide anomalies, typically occurring during the annual cycle of the tides, with a few events in the summer, is a classic theme of the coastal basins literature (see,e.g., Kjerfve, 1994). Coastal lagoons are very complex systems from a hydrodynamic point of view, in which nonlinearity plays a relevant role. Namely, the sea-level and the circulation in the Venice lagoon are mainly ruled by 1) the exchanges with the Adriatic Sea; 2) the general weather conditions and 3) the complex bathymetry. Relative to this last point, the bathymetry is considered very relevant among the causes that determine the flow properties of shallow systems (see, Dias and Lopes, 2006). In the specific case of the Venice lagoon, the bathymetry changes over the time (see, e.g. Molinaroli et al., 2009) due to natural and anthropogenic effects (see, e.g., Sarretta et al., 2010; Madricardo et al., 2017). This information is used in constraining finite elements hydrodynamic models to assure their reality (see, e.g., Umgiesser et al., 2004). The phenomenon of *acqua alta*, the average increase in flooding levels (higher than 79 cm as indicated by ICPSM), has been studied in detail and also continuously monitored within this area also due to the importance of the artistic heritage of the city of Venice. A relevant factor in producing such episodes is certainly played by the winds blowing over the Adriatic Sea, especially the North-East Bora, up to 140 km/h, which induces an additional increase of the sea-level at the south-western end (Raicich, 2015).

Indeed, starting from the seminal work of Orlić et al. (1994), Raicich (2015) discusses in detail how the principal winds of the Adriatic Sea, i.e. the Scirocco and Bora winds act as forcing mechanism for the Adriatic area. In more general terms, sea-level oscillations are expected to be a suitable combination of two main factors, i.e. astronomical tides and meteorological contributions, whose local effects have to be identified in order to improve the forecasting model of *acqua alta*.

A dense network of stations equipped to measure several physical parameters including the sea-level oscillations, the wind velocity and the atmospheric pressure, is managed by the "Istituto Superiore per la Protezione e la Ricerca Ambientale-ISPRA" (Massalin et al., 2007). The stations have been recording for a long time providing a huge quantity of high-quality data. The main tidal constituents are generally identified by using the standard linear approach of the harmonic analysis (see, e.g., Melchior, 1978). Accordingly, cotidal maps and lines of equal

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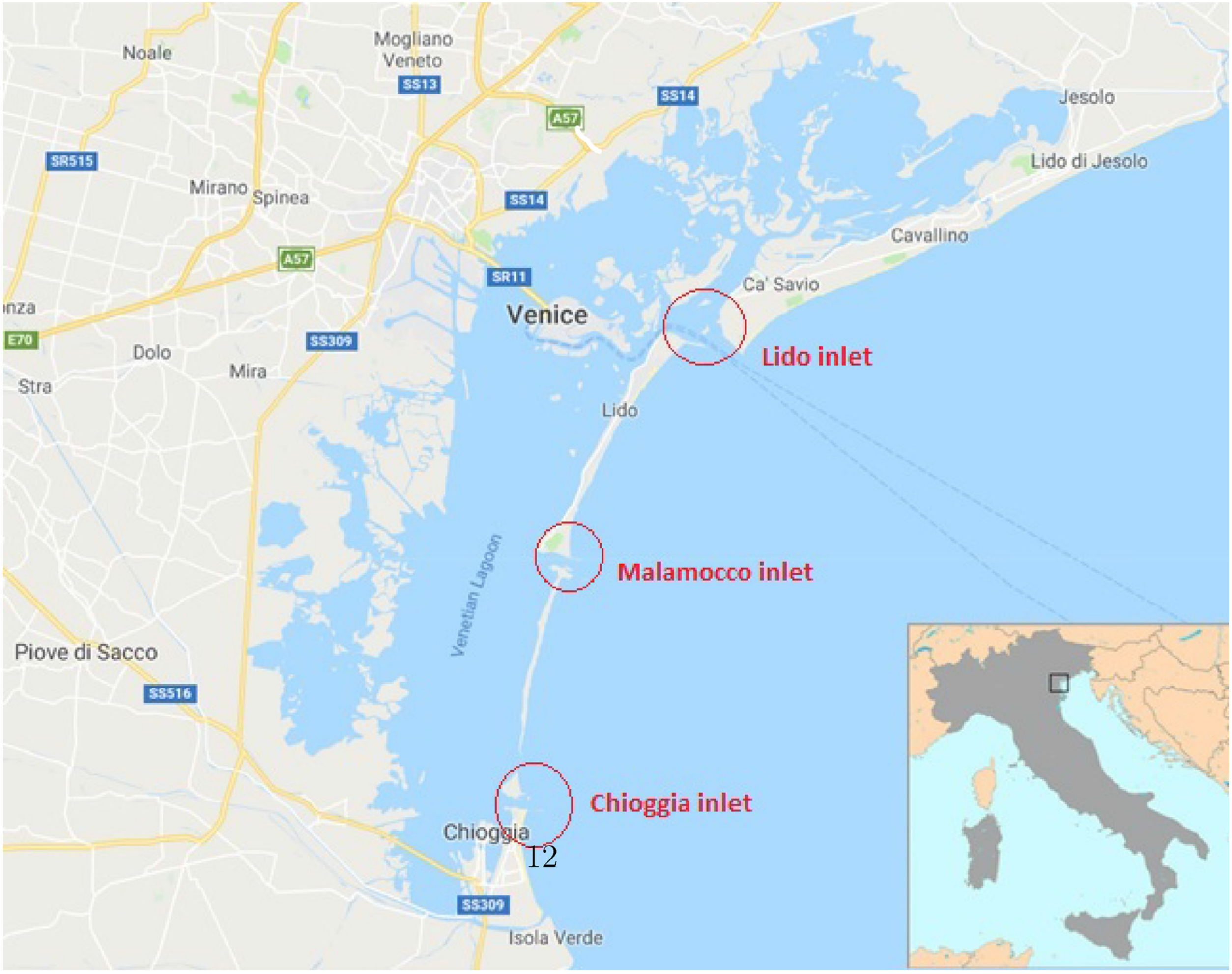

Fig. 1. Map of Venice lagoon, with the three inlets, Lido, Malamocco and Chioggia.

phase have been better and better reproduced starting from the seminal paper of Polli (1959) to more recent ones (see, e.g., Umgiesser, 1997; Lovato et al., 2010; Poulain, 2013) regarding both the Adriatic Sea and the Venice lagoon.

Nevertheless, a general model which takes into account all previous contributions from astronomical and meteorological effects and their coupling with the local complex basin structure is not completely refined, requiring further studies on this specific topic. In line with these thoughts, this work is devoted to the study of sea-level oscillations on different time scales with a particular focus on the synoptic ones, in order to extract meteorological effects directly from the experimental data with no *a priori* assumptions.

2. Data set

We analyzed the relative sea-level (RSL) data collected over four years 2008–2011, with a sampling period equal to 10 min, at eight tide gauges (Malamocco, Lido (North-inlet), Marghera, Burano, Grassabò, Valle Averto, Punta della Salute and Chioggia Vigo). Lido and Chioggia Vigo stations are also equipped with barometers and anemometers with the same sampling regime. Here, as an example, we show the results obtained from investigating the RSL oscillations (relative to the mareographic zero at Punta della Salute) collected during the year 2008 (year notable for the absence of gaps in the data). In Fig. 2a, the anomalies (exceptional flood events) are compared with the wind speed and the atmospheric pressure: by visual investigation, the *acqua alta* episodes mainly occur in connection with periods of low pressure and strong winds (often Bora as indicated in Fig. 2b). Fig. 3a shows the tidal signal during the year 2008: three major semi-diurnals (M_2, S_2, N_2) and two major diurnal constituents (K_1, O_1) are always identified by the spectral analysis (Fig. 3b). Moreover, a strong low-frequency contribution and some higher frequencies are evident too. In this work, we are interested in studying this evidenced low-frequency contribution and its origins, which are probably ascribable to meteorological effects.

3. Low frequency analysis

The sea level variation is mainly affected by astronomical tides and meteorological contributions over subdaily-to-synoptic time scales (relatively to the Mediterranean Sea, see Buzzi, 2010). Specifically, wind stress and atmospheric pressure can induce long-period perturbations (3–15 days) into RSL (Truccolo and Franco, 2000).

3.1. Standard spectral analysis

To evidence the presence of meteorological tides and the relative periodicities in the Venice lagoon, a low-frequency zoom of the spectrogram of one year long sea oscillations is reported in Fig. 4 at two specific stations Malamocco and Valle Averto. It can be seen that these tides have their main frequencies in the range [5 days-20 days] and affect the RSL oscillations during the spring and autumn period, when the anomalies typically occur. Wind and pressure are independently measured and modeled to account for their effects on sea level (see, e.g., Truccolo and Franco, 2000; Tosoni and Canestrelli, 2010).