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On the contributions of atmospheric pressure and wind to daily sea level in the northern Adriatic Sea

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ABSTRACT

Daily sea level variability in the Adriatic Sea is studied from different data sets using Empirical Orthogonal Functions, in connection with atmospheric pressure and wind stress. The first mode explains 56–69% of total variance and consists of uniform sea level variability all over the basin, correlated with atmospheric pressure through the inverse barometer effect. The second mode explains 13–16% of variance and accounts for an along-basin sea level gradient, which is correlated with the meridional wind stress component. The first two Principal Components are used as proxies to pressure- and wind-induced components of storm surges in the northern Adriatic. The analysis of the frequency of the most intense events in the 1957–2005 period shows that the wind contribution to storm surges has decreased, while no significant trends are found in the contribution of atmospheric pressure.

1. Introduction

Sea level variations represent a major issue in the context of current studies on climatic change. Their potentially harmful impact on human life and activities in several coastal regions of the world depends on the general mean sea level rise, but can be locally enhanced by an increased frequency of extreme events. Relative sea level changes, i.e. those observed relative to a ground-based benchmark, result from variations of several factors acting on different time scales, such as waves, tides, atmospheric forcing, ocean currents, mass and heat changes of the ocean, geophysical processes affecting the land level and the geoid, as discussed by Plag (2006) and Jevrejeva et al. (2008).

In the Adriatic Sea the northern region is very sensitive to sea level changes since most of the coastal areas is low and subject to floods. The sea level time series of the Adriatic stations exhibit different long-term trends that may strongly depend on local factors, such as the vertical motion of the tide gauge related to local geology and tectonic movements (Zerbini et al., 1996; Bergant et al., 2005). In addition to natural subsidence, the northwestern Adriatic coast, including the Venice Lagoon and the area around Marina di Ravenna, has been affected by anthropogenic subsidence connected with the extraction of underground water and gas, particularly during the 1930–1970 period (Carbognin et al., 2004).

On seasonal and longer time scales sea level variability is modulated by changes in the thermohaline structure of the basin, affecting the water density and volume, induced by changes in the hydrological balance and the atmospheric forcing, and the ocean circulation through the Otranto Strait, which connects the basin with the rest of the Mediterranean Sea. On the synoptic time scales atmospheric pressure and wind are the most effective forcing terms. The main wind regimes are characterized by Bora and Sirocco. Bora blows from the North-East to East sector across the basin, generally in connection with anticyclones over central or eastern Europe. Sirocco blows from South-East and is usually associated to cyclones over the western Mediterranean. Its flow is channelled by the orography that surrounds the basin, namely the Apennines along the Italian peninsula and the Dynaric Alps along the Dalmatian coast, and it is a major factor responsible for storm surges in the northern Adriatic. A comprehensive review of the Adriatic oceanography and air–sea interactions can be found in Cushman-Roisin et al. (2001).

Several authors dealt with the interactions and relationships between sea level and atmospheric pressure and wind in the Adriatic Sea. Longer than daily time scales have been analysed, for instance, by Lascaratos and Gačić (1990), Raicich and Crisciani (1999), Pasarić et al. (2000), Beretta et al. (2005) and Bergant et al. (2005). Also events that develop on daily and sub-daily time scales have been studied, namely storm surges and seiches (e.g. Buljan and Zore-Armanda, 1976; Raicich et al., 1999; Raicich, 2003; Pirazzoli and Tomasin, 2008) and meteorological tsunamis (Vilibić et al., 2004).

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The response of sea level to the atmospheric pressure and wind forcing on time scales relevant to storm surges can be modelled by means of depth-integrated equations of motions (e.g. Bowden, 1983). Neglecting Earth's curvature, in a reference system where x is positive eastwards and y northwards, the responses to atmospheric pressure (p_a) only and meridional wind stress (τ_y) only (similarly for zonal wind stress τ_x) can be written in finite form as

$$\Delta\eta = -\frac{1}{g\rho}\Delta p_a \qquad (1)$$

$$\frac{\Delta\eta}{\Delta y} = \frac{\tau_y}{g\rho(\eta+h)} \qquad (2)$$

respectively, where h is water depth, η is sea surface elevation, ρ is water density and g is gravity acceleration. In the Adriatic Sea $|\eta|$ is rarely greater than 1 m and the minimum depth (sufficiently far from the coast) is about 20 m, in the northern basin, therefore $(\eta+h)\approx h$ in Eq. (2). Under this approximation, linear relationships exist between sea level and atmospheric pressure anomalies (the inverse barometer effect) and between sea level gradient and wind stress, respectively.

In this work we study the time variability of Adriatic sea level using daily means, aiming at recognizing the contributions of atmospheric pressure and wind to storm surges in the northern basin, which determine only part of the basin dynamics. Nevertheless, the statistical analysis, performed on the basis of Eqs. (1) and (2), is able to extract significant signals related to the atmospheric forcing.

Data and methods are described in Section 2. Section 3 presents and discusses the results of the analysis of spatial and temporal variability of daily mean sea level and of the statistical analysis of extreme events. Conclusive remarks are proposed in Section 4.

2. Data and methods

Data for the following variables are analysed in this work: sea level, surface atmospheric pressure (henceforth simply pressure) and wind stress.

Hourly sea level data have been measured at the Italian and Croatian stations listed in Table 1 and shown in Fig. 1. Data are available through the web sites of ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy) at http://www.apat.gov.it and ESEAS (European Sea-level Service) at http://www.eseas.org and from the archives of CNR-ISMAR (Istituto di Scienze Marine, Trieste, Italy).

Table 1
Sea-level stations (from North to South), period covered, percentages of missing daily data in the October–March period and data source.

Station	Period	Missing data %	Source
Trieste	1939–2008	0	CNR-ISMAR
Venice	1940–2008	1	ISPRA
Rovinj	1955–2005	1	ESEAS
Marina di Ravenna	1971–2008	9	ISPRA
Zadar	1994–2005	7	ESEAS
Ancona	1999–2007	21	ISPRA
Split	1956–2005	< 1	ESEAS
Dubrovnik	1956–2005	2	ESEAS
Ortona	1999–2007	16	ISPRA
Vieste	1999–2007	23	ISPRA
Bari	1999–2007	14	ISPRA
Otranto	1999–2007	13	ISPRA

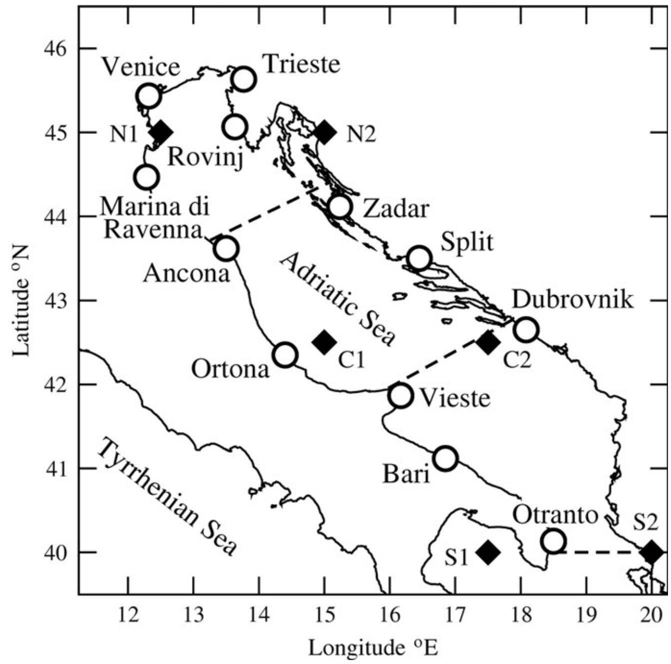

Fig. 1. The area of interest with the sea level stations (white circles) and the NCEP reanalysis grid points (black diamonds). The dashed lines allow identifying the northern, central and southern areas.

Since this study concerns the daily time scale, the sea level time series are preliminarily filtered removing the fluctuations on time scales longer than two months. They include the effects of low frequency atmospheric forcing (Pasarić et al., 2000), the seasonal changes of the water column properties and the long-term trend connected to vertical ground movements. Data gaps up to three hours in the filtered sea level (henceforth denoted simply as sea level) time series are interpolated linearly. Each time series is cross-checked using those of nearby stations in order to identify and confirm, correct or remove suspect values. Daily sea level means, centred on 12 UTC, are obtained by applying Doodson's X0 filter to the hourly data (IOC, 1985), in this way removing the astronomic tide constituents with periods up to the diurnal.

Most of the storm surges in the northern Adriatic occur in autumn and winter. We identify the significant storm surges as the 5% highest daily sea level means. It turns out that in the northern Adriatic, namely at the Trieste, Venice, Rovinj and Marina di Ravenna stations, between 97% and 98% of the events occur from October to March. Therefore, only sea level data in these months will be analysed. The data availability is summarized in Table 1 in terms of period and missing data percentage.

Surface pressure data come from the NCEP 6-hourly reanalyses on a $2.5^\circ \times 2.5^\circ$ grid, available from the Earth System Research Laboratory, NOAA, at http://www.cdc.noaa.gov (Kalnay et al., 1996). Only the grid cells that significantly overlap with the Adriatic Sea are considered (Fig. 1, black diamonds). If, in a given grid point, $p_n(h)$ is the pressure for day n and time h (h=00, 06, 12 and 18 UTC), then the mean daily value P_n, centred on 12 UTC is given by

$$P_n = [0.5p_n(00)+p_n(06)+p_n(12)+p_n(18)+0.5p_{n+1}(00)]/4$$

Two wind stress data sets are taken into account. The first (τ_N) is derived from the NCEP reanalyses mentioned above. Six-hourly zonal and meridional τ_N components are obtained from the respective wind components and daily averages are then computed in the same way as for pressure. The second (τ_Q) is derived from SeaWinds-on-QuikSCAT (henceforth QuikSCAT)