Wind versus air pressure seiche triggering in the Middle Adriatic coastal waters

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Abstract

Strong air pressure and sea level oscillations, which occurred in the Middle Adriatic region during the storm passage on 21 August 2004, were recorded at a number of meteorological and tide gauge stations. Large sea levels measured were related to the Proudman and harbour resonances, being also observed during the past event on 27 June 2003. Both cases were characterized by a travelling air pressure disturbance, but a part of the oscillations in August 2004 case were a result of short-lasting strong winds which were absent during the event in June 2003. Occurrence of a strong 4-h fundamental oscillation of the whole region versus weak harbour seiches was a result of the shape of travelling air pressure disturbance: it looked like a box-function containing large energies in a low frequency domain, whereas the event in June 2003 was characterized by a cosine-like disturbance, redistributing the energy towards higher frequencies. Using a numerical model it is shown that the strength of 4-h oscillation is sensitive to the speed of travelling atmospheric disturbance and to its incoming direction. The largest amplitudes were modelled for a speed of 13 m/s, indicating that inner part of the region is possibly the best place for occurrence of the Proudman resonance.

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1. Introduction

Resonant coupling of atmospheric disturbances was occasionally studied in the Adriatic Sea, but only after the episodes when large sea level oscillations occurred causing flooding and damages in some bays and narrow straits (Hodžić, 1979/1980; Orlić, 1980; Vilibić and Mihanović, 2003; Vilibić et al., 2004). However, it is known that the coupling may occur more frequently; at least it was experienced in this way by local fishermen, who were frightened by sudden changes in the sea level characterised by no or low winds at that time. The phenomenon is known worldwide (Donn, 1959; Hibiya and Kajiura, 1982;
Rabinovich, 1993) particular by in some parts of the Mediterranean Sea such as Balearic Islands (Monserrat et al., 1991, 1998; Gomis et al., 1993; Rabinovich et al., 1999), Sicily (Candela et al., 1999) and Maltese Islands (Drago, 2004). Large sea level oscillations are mainly the result of two effects: (i) Proudman resonance (Proudman, 1929, 1953) which occurs in the shallow waters where the speed of air pressure disturbance is equal to the speed of long waves in the sea, resulting in multiplied barometric effect in the sea, and (ii) harbour resonance, being the result of energy transfer from the open sea waves to the harbour/bay normal modes, resulting in large sea level oscillations at the top of a basin. Besides, additional enhancement and resonance in the sea level oscillations may occur as a result of topographic constraints (Vilibić et al., 2004), edge waves (Liu et al., 2002) or coupling between two adjacent inlets (Liu et al., 2003).

A comprehensive study of the first two effects coupled in the shallow Middle Adriatic area were conducted by Vilibić et al. (2004) after floods and damages occurred during the passage of a gravity wave on 27 June 2003. Although the most affected area was not covered by measurements, some records showed the presence of a large high-frequency sea level oscillation in some bays, which were supported and verified by a numerical model and extended to the most affected bays and harbours. Only strong high-frequency air pressure changes were observed with very low winds (<5 m/s), thus the model was forced by a travelling air pressure disturbance only. Another episode with large sea levels occurred on 21 August 2004 and will be studied in this work. However, the major difference was the presence of strong short-lasting winds in front of air pressure changes. An additional difference, which clearly arose from the sea level data, was the occurrence of a large 4-h oscillation in the whole area rather than high-frequency oscillations in the affected bays and harbours. Thus, two questions arise: (i) does the short-lasting wind generate oscillations, and is the wind forcing more significant in comparison to the effect of a travelling air pressure disturbance; (ii) what is the reason for the different energy distributions in the two extreme episodes compared?

Both questions will be handled in this work by analysing available data, comparing them to the 2003 case, and by applying a barotropic nonlinear numerical model with wind and air pressure acting separately on the sea surface. Section 2 gives an overview of the available data and model performances. Sections 3 and 4 display atmospheric conditions and model simulations versus wind and air pressure forcing, being discussed and concluded in Section 5.

2. Data and methods

The area of the eastern Middle Adriatic Sea is a complex bay system open to the west with a number of along-bay islands and channels (Fig. 1). The depth decreases from 100 m at the entrance to about 15 m in the inner bay, being able to resonantly capture atmospheric gravity waves through Proudman resonance travelling at a speed of 12 to 30 m/s. The area has been covered by a number of tide gauge and meteorological stations (Fig. 1), handled by the Hydrographic Institute and the Meteorological and Hydrological Service of the Republic of Croatia. Air pressure was digitally measured at Palagruža (PA) and Makarska (MA) with 10-min time resolution and ±0.05 hPa accuracy. In addition, chart-recording barographs were operational at Komiza (KO), Hvar (HV), Split (SP) and Lastovo (LA). Wind speed and direction were recorded at PA, HV, SP, MA and Ploče (PL), averaged over 10 min intervals with an accuracy of ±0.5 m/s and ±5°, respectively. Sea levels were recorded at three stations in the investigated area (SP, Sućuraj—SU and PL; Dubrovnik-DU data will also be analysed) by digital tide gauges with a time resolution of 1 min and height accuracy of ±1 mm.

In order to quantify and extract long-term internal waves from the measurements several numerical methods were used. The energy distribution and coherence of sea level time series was estimated by applying a classical spectral analysis (Jenkins and Watts, 1968). Furthermore, a number of band- and high-pass filters (cutoffs at 1 and 7 h) were applied in order to separate 4-h seiches from the high-frequency oscillation, which were observed at some inner-harbour stations. The procedure was based on the works of Ormsby (1961) and Z. Pasaric (in preparation).

The modelling of these barotropic nonlinear processes was undertaken using a two-dimensional, nonlinear finite difference model 2DD developed by Black (1995). An explicit leapfrog solution is applied...
to solve the two-dimensional momentum and continuity equations, equipped with both wind and air pressure terms:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - f v = - g \frac{\partial \zeta}{\partial x} - \frac{g u (u^2 + v^2)^{1/2}}{C^2 (d + \zeta)} - \frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{\rho_w |W| W_x}{\rho (d + \zeta)} + A_H \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)$$ (1)

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f u = - g \frac{\partial \zeta}{\partial y} - \frac{g v (u^2 + v^2)^{1/2}}{C^2 (d + \zeta)} - \frac{1}{\rho} \frac{\partial P}{\partial y} + \frac{\rho_w |W| W_y}{\rho (d + \zeta)} + A_H \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)$$ (2)

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} [(d + \zeta) u] + \frac{\partial}{\partial y} [(d + \zeta) v] = 0$$ (3)

where $t$ is time, $u$ and $v$ are vertically averaged velocities in the $x$ and $y$ directions, $g$ is acceleration due to gravity ($9.81 \text{ m/s}^2$), $\zeta$ stands for sea level above a horizontal datum, $d$ marks the water depth below the datum, $f$ is the Coriolis parameter, $\rho$ and $\rho_w$ are the water and air density, respectively, $P$ denotes air pressure, $W$ represents the wind speed at $10 \text{ m}$ height above sea level, $W_x$ and $W_y$ are the $x$ and $y$ wind components, $\gamma$ is wind drag coefficient, and $A_H$ is horizontal eddy viscosity coefficient. Seabed frictional resistance $C$ is given by

$$C = 18 \log_{10} (0.37h/z_0)$$ (4)

where $h$ is total water depth and $z_0$ is the roughness length (a level above the bed where velocity equals zero).

The model domain is taken from Vilibić et al. (2004)—see Fig. 1, as the comparison will be made with their simulations. Grid resolution was chosen to be $1 \text{ km}$; altogether there are $139 \times 68$ grid cells, while the simulations were carried out with time steps of $12 \text{ s}$ in order to satisfy the stability criterion for the grid sizes and depths considered. Horizontal eddy viscosity coefficient $A_H$ is set to $75 \text{ m}^2/\text{s}$, bottom roughness...
$z_0$ to 0.003 m, while drag coefficient $\gamma$ is chosen to be 0.001. A radiation condition was imposed at the open boundaries, together with additional smoothing and minimizing the reflection by applying sponge boundaries (Black, 1995).

3. Empirical analysis

First, let us concentrate on meteorological conditions, which prevailed during the storm event on 21 August 2004. Wind and air pressure time series are shown in Fig. 2, revealing spatial and temporal characteristics of both parameters. However, the wind data are largely modified by the position and topography of the stations. For example, the wind was strongest at PA, with speeds of up to 20 m/s at time, but the fact is that the PA station is located on the cliff island at 100 m height, far from the coastline, with no orographic barriers which may reduce or modify the winds. That is obviously the reason why relatively strong NW wind (10–15 m/s) remained there after the storm as a result of a general synoptic situation and cyclone centre situated to the northeast. More realistic winds were captured at coastal stations, ranging from 10 m/s at SP and MA to 15 m/s at HV and PL during the storm passage, which arrived in the afternoon on 21 August 2004. Strong winds lasted for about 20–40 min at all stations except at MA where it blew for about 2 h but pulsed from 4 to 10 m/s.

The air pressure time series, both analogous and digital, contain a clear mark of an incoming storm in the form of a box-function, except at PA where no sudden changes were recorded in the air pressure series (Fig. 2). The almost regular box-function had shift rates at both edges of 4–5 hPa and lasted for about 80 min, travelling over the region mainly from the west (Fig. 3). The average velocity of the travelling air pressure disturbance can be estimated at 18 m/s, at least in the central part of the affected area, which is somewhat lower compared to the case of 27 June 2003 (22 m/s, Vilibić et al., 2004). Therefore, it could be assumed that the Proudman resonance may take place at depths between 30 and 35 m, what is obtained only in the eastern part of the investigated area.

However, large sea level oscillations can be found in the whole area (Fig. 4). Oscillations outside the area are low (at DU for example), leading to a conclusion that the shape and period of these oscillations are defined by the topographic characteristics of the whole area and its smaller regions. Power spectra at all stations (Fig. 5) show the major oscillation with the period of 4 h, being in phase (Fig. 6) and increasing its amplitude towards the top of the investigated area. Therefore, the 4-h oscillation presumably represents a fundamental mode of the whole area, with the nodal line sitting somewhere between the islands of Šolta, Vis and Korčula. In addition, a number of peaks are significant, of which the most prominent are at 2.4 h at SP and 30 min at PL. The first is probably the fundamental mode of the Brač and Split Channels, whereas the latter belongs to the fundamental mode of the Ploče Harbour (Vilibić et al., 2004).

A further separation in the frequency domain yields the separation of various resonant processes. For example, almost clear 4-h oscillation dominated at
PL (Fig. 7a), damping clearly after the storm passage, having maximum amplitude comparable to the tides in the area. High-frequency seiches in Ploče Harbour also occurred, but with amplitudes 3 times lower on average. A different situation was recorded in June 2003 (Fig. 7b): the seiches of Ploče Harbour were comparable to the oscillations between 1 and 7 h. Moreover, the latter oscillations consisted of 4-h seiches and some higher harmonics, having periods of 2.6 and 1.5 h (Vilibić and Mihanović, pers. comm.). These differences in energy distributions can be easily documented by computing the ratio of sea level power spectra in August 2004 versus June 2003 (Fig. 8a). The energy of the 3-h and longer oscillations was 1.5 to 3 times larger in August 2004 than the year before, but the ratio sharply changes at periods between 2 and 3 h to inverse values. Hence, at periods between 50 min and 2 h, the ratio is changed in favour of the June 2003 oscillations, even with higher ratio values (2 to 5 times). Going further to lower periods, the spectral ratio becomes unstable due to more chaotic processes, but oscillating around 1 on average.

Although the wind was not negligible during the August 2004 episode, the distribution of sea level energy can be correlated to the distribution in air pressure energy. Namely, a cosine-like travelling air pressure disturbance combined with a box function has a cosine-like spectrum, decreasing in envelope
when moving away from the fundamental frequency (Bracewell, 1999, see Fig. 8b). Such a disturbance occurred in June 2003 (Vilibić et al., 2004) and resulted in oscillating spectrum with major frequency placed at 80–120 min (Fig. 8c). On the contrary, the spectrum of regular box function has maximum energy at low frequencies, oscillating and decreasing towards the higher ones (Fig. 8b). A box-like travelling air-pressure disturbance occurred in August 2004 (Fig. 2) and therefore large energy occurred at low frequencies, encompassing the fundamental period of 4 h (Fig. 8c). However, a number of differences may be noticed between theoretical and observed air pressure spectra. Firstly, low-frequency energies in June 2003 (>5 h) were larger than expected, as the disturbance contained not only cosine function energy but also a low-frequency signal (see Vilibić et al., 2004).

Secondly, high-frequency energies in August 2004 were lower than of a box function, as no regular box functions with rigid walls occur in the nature. In addition, 10-min sampling interval smoothed the edges of the disturbance and aliased low energies in the system. Therefore, the spectra of August 2004 air pressure series are probably not realistic in the high-frequency part, let us say for periods lower than 1 h. Nevertheless, the ratio of sea level power spectra in August 2004 versus June 2003 (Fig. 8a) follows the energetics of air pressure disturbances (Fig. 8c) fairly well. Accordingly, in August 2004 lower sea level energy than in June 2003 was computed for periods between 35 and 120 min, as the maxima in air pressure spectra in June 2003 occurred exactly in these periods. Sea level energy ratio became opposite in the periods between 2 and 4 h, exactly where air pressure
energy in June 2003 has a minimum versus the August 2004 energy. Major deviation occurred at low frequencies ($\leq 5$ h) where lower energies were expected to occur in August 2004; yet, additional impulse at these frequencies is probably the result of wind forcing, contributing to the sea level set up at low frequencies.

4. The modelling

Three sets of different model runs were undertaken: (i) air pressure disturbance travels as in Vilibić et al. (2004), but using a 10-min air pressure time series data measured at MA instead of 2-min series at SP (SP unfortunately stopped working just at the beginning of the storm), (ii) an artificial homogeneous wind blows with different speed and duration, set to be zero before and after the storm passage; and (iii) both wind and travelling air pressure disturbance are applied simultaneously. Speed and direction of the moving air pressure disturbance were set to be constant over the whole domain, although modifications in speed, direction and shape occurred during the examined episode.

The real values have been chosen in the model first. Thus, run 1 includes air pressure forcing only, with the speed of disturbance to be 18 m/s. The direction is pure west ($270^\circ$), meaning that the disturbance is travelling exactly towards the east. Unfortunately, MA series are very sensitive to aliasing at high frequencies (let us say up to 1 h) due to a 10-min sampling interval. Therefore, verification and validation of the model will be made for the frequencies between 1 and 7 h, using the same filter as for measured sea level series. In run 2 wind forcing was used solely assuming that there was no wind before the storm, rising to 15 m/s and blowing for 30 min during the storm, and vanishing again after the storm. Such an approach was used due to the quite high

Fig. 6. Coherence squared, phase difference and gain spectra computed between PL and SP sea levels for the same time interval as in Fig. 5.

Fig. 7. Sea level series at PL filtered by band-pass (cutoffs at 1 and 7 h) and high-pass (cutoff at 1 h) filters, for the (a) 21–23 August 2004, and (b) 26–28 June 2003 intervals.
variability of the measured wind, which is strongly affected by the orography and its real spatial distribution cannot be properly resolved from the data. However, the parameters of 15 m/s and 30 min are chosen to be the most realistic ones from the available data.

The results for sea levels at PL are shown in Fig. 9. It can be seen that the modelled sea level series fairly well agrees with the measured ones. The best results

Fig. 8. (a) The ratio of August 2004 and June 2003 sea level power spectra at PL, (b) power spectra of artificial air pressure series containing box-like (duration of 80 min, air pressure step of 5 hPa, solid line) and cosine (period of 80 min, amplitude of 2.5 hPa, dashed line) disturbances—a scheme of such series is given in the inner window, and (c) measured air pressure spectra at SP in June 2003 and at MA in August 2004.

Fig. 9. The verification of numerical model at PL. The model is forced separately by wind and air pressure travelling disturbance as well as both simultaneously, and sea level series are computed for the grid point ahead of Ploče Harbour. Air pressure series measured at MA were used to simulate the disturbance, moving eastward with the speed of 18 m/s. Wind speed is chosen to be 15 m/s, blowing for 30 min over the area during the storm passage.

Fig. 10. Modelled maximum sea levels at PL grid point being a result of different wind speed and duration. Wind speed is chosen to be zero before and after the storm passage, blowing from west (270°). Sea level series were filtered by band-pass filter (cutoffs at 1 and 7 h).
are obtained for the first 4-h oscillation, where the model slightly underestimates the measured values, probably due to the position of the PL station. Namely, the PL tide gauge is situated in the 2 km long and narrow embayment of the Plocˇe Harbour, not captured in the model, and some enhancement of the oscillation probably occurs between the entrance and the top of the harbour. After the first oscillation, the model underestimates the observed sea levels, incorporating some additional artificial oscillations in the series.

Although a significant wind occurred during the storm, its impact on the sea level changes is about 3 times lower than that of the travelling air pressure disturbance. However, it cannot be neglected in such cases, especially if the wind blows longer at greater velocities. Fig. 10 shows the distribution of maximum sea levels at Ploče versus wind speed and duration. It can be noted that the stronger the wind the larger the sea level setup, being more sensitive to a greater wind speed. Sea level maximum also increases when the wind is blowing longer, but only until a time duration of about 90 min. After that, the sea level maximum remains constant until a 150-min wind duration, which is quite an extreme value for the wind duration on mesoscale Adriatic storms. The maximum in sea level does not go further up due to the acting of the 4-h seiche, which forces sea level to go down after its maximum.

The changes in speed and incoming direction of travelling air pressure disturbance acting solely result in different sea level setup as well. Fig. 11 shows maximum sea levels at Ploče versus different travelling speed and direction of air pressure disturbance. The largest sea level setup is achieved for the speed of 13–15 m/s and direction of 260° to 290°, which is in general in the alongshore direction of the bay. The speed of 13 to 15 m/s leads to the Proudman resonant depth of 17 to 23 m, reducing the potential resonance area to the most eastern corner of the area, in front of Ploče and the shallow Neretva River delta. Of course, the resonance also occurs for a greater disturbance speed, but generating lower 4-h seiches; for example, sea levels generated by disturbance at 35 m/s are half the height of those at 15 m/s. The disturbance occurred on 21 August was quite efficient: it generated sea levels being 90% of the maximum achievable value.

The analysis can be extended spatially. Fig. 12 contains relative maximum sea level setup assembled both over air pressure and wind model runs. As expected, the largest sea levels occurred at the top of the basin, decreasing towards the channel entrances and vanishing at their entrances. This distribution is mainly the result of 4-h seiches generated in the whole area, whereas other oscillations are negligible and therefore do not significantly contribute to large sea level heights in the area. However, this distribution may be valid only for the box-func-
tion travelling air pressure disturbances which occurred in August 2004, but is probably not valid for the cosine-like travelling disturbance which occurred in June 2003 and possessed different distribution of energy content versus frequency.

Finally, the model will be forced by artificial air pressure disturbances, in particular by constant series which contain box and cosine travelling disturbances with the same characteristics as in Fig. 8b. Fig. 13 gives the spectra of modelled sea level series at the PL grid point, together with their ratio. Although there is obvious similarity between the sea level and the corresponding air pressure spectra (see Fig. 8b), a number of differences may be noticed. First, the energy of box disturbance run has a maximum at 4 h (Fig. 13a), documenting the transfer of energy at the fundamental bay period, which is not so pronounced for the cosine disturbance run. Next, the energy of high-frequency sea level oscillations is much higher than expected, presumably being a result of enlarged various free modes in a bay due to its complex bathymetry in the area of PL. However, the modelled sea level energy ratio (box disturbance over cosine disturbance run, Fig. 13b) well follows the observed ratio (August 2004 versus June 2003, Fig. 8a), although the scaling is not fully reproduced due to the complexity of the observed air pressure series. As the box disturbance run represents the August 2004 event, and the cosine disturbance run stands for the June 2003 event, it may be concluded that different shape of the travelling air pressure disturbance produces a different response in the sea, and results in different energy distribution in the sea level observed during the examined episodes.

5. Summary and conclusions

The paper encompasses empirical and modelling analyses of an event of exceptionally large sea level oscillations, which occurred on 21 August 2004 in the coastal area of Middle Adriatic Sea. Both winds and sharp air pressure changes were measured at a number of stations, being processed by spectral algorithms and numeric filters. Large 4-h oscillation was extracted from the sea level time series, whereas high frequency oscillations (period < 1 h) were significantly lower at that time, being related to the box-function shape of travelling air pressure disturbance. The event was compared to a similar extreme event that occurred the year before, which resulted in extensive flooding in some bays, being characterised by the presence of high frequency oscillations in the whole area. Oscillations are reproduced by the numerical barotropic nonlinear model, separately forced by travelling air pressure disturbance and wind. The following conclusions can be drawn from this work:

- Although the speed of the travelling air pressure disturbance was lower in August 2004 (18 m/s) than in June 2003 (22 m/s), resonant coupling between the travelling air pressure disturbance and sea level occurred as documented by Vilbić et al. (2004). However, energy versus frequency distributions for the two episodes were different: the cosine-like disturbance in June 2003 resulted in high energy content at periods lower than 2 h,
whereas the box-like disturbance in August 2004 resulted in a larger energy content at periods greater than 2 h, in particular at the period of the fundamental bay seiche (4 h).

- The episode in August 2004 was characterised by strong short-lasting winds, opposite to June 2003 case, when low winds prevailed. Wind-induced sea level setup was still three times lower than that of the air pressure disturbance even for such strong winds. Nevertheless, the sea level response would rapidly increase for even stronger and long-lasting winds than those observed; for example, the rise in wind speed by 30% would result in doubled maximum sea levels (Fig. 10).

- The maximum sea level oscillations at hourly frequencies, the strongest of which was at 4 h, occurred for the air pressure travelling disturbance which arrived directly from the west. However, significant sea level oscillation can occur for a span of incident directions, ranging from SW to NW, whereas the sensitivity to the travelling speed is larger than to the incident angle. Presumably it is due to a large sensitivity in the Proudman resonance, whose occurrence is required for the generation of large sea level oscillations in the area.

Finally, the occurrence of large sea level oscillations can be ascribed to the air pressure travelling disturbance, but not all of them: only to these which arrive from SW to NW with velocities necessary to generate Proudman resonance in the open waters. Cosine-like and box-like disturbances possess such properties; however, the greatest flooding of Vela Luka in June 1978 was not generated by any of these types, at least not with observed large changes in air pressure (Orlić, 1980). Therefore, sensitivity of the whole region and some particular bays should be examined with varying different shapes and strengths of travelling air pressure disturbances, which is to be the object of the forthcoming work on this topic.

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References


