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The Bakar Bay seiches and their relationship with atmospheric processes

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Large-amplitude seiches (up to 40 cm) were recorded at a tide-gauge inside Bakar Bay from 19–21 August 2006. They were analysed using available tide-gauge and meteorological (air pressure and wind, vertical sounding) data. Sea level and air pressure spectra showed simultaneous increases of energy in the periods in which the seiches of both Bakar Bay (about 20 min) and Rijeka Bay (ca. 2 h) occurred. The propagation speed and direction as well as the horizontal span of the four pronounced pressure disturbances, favourable for coupling with Rijeka Bay waters via the Proudman resonance, were determined. It is argued that only short atmospheric pressure disturbances may generate significant barotropic sea waves in a small basin such as Rijeka Bay; once generated they are amplified when hitting Bakar Bay due to the harbour resonance. Furthermore, examination of the synoptic situation and upper-air soundings revealed the presence of dynamically unstable layer at a height of around 2000 m which was also the height of temperature inversion that developed as a consequence of an advection of warm African air from the south-east. During the afternoon hours of 19 August 2006 wind speed in this layer was close to the estimated speed of propagation of the air pressure disturbances which, together with dynamical instability, made conditions favourable for long distance propagation and trapping of atmospheric gravity waves.

Key words: seiches, air pressure oscillations, air-sea coupling, Proudman resonance, harbour resonance, Adriatic Sea

INTRODUCTION

Harbour and bay seiches of exceptionally large amplitudes have been reported worldwide. The strongest and most devastating oscillations are excited by tsunami waves entering coastal basins from the open sea (TITOV *et al*., 2005; RABINOVICH *et al*., 2006). However, devastating seiches can also be triggered by incoming open-sea waves generated through a resonant coupling with the atmosphere. Due to the frequency range being similar to that of ordinary tsunami waves, these waves are also known as meteotsunamis (RABINOVICH & MONSERRAT, 1996, 1998).

The appearance of destructive meteotsunamis is quite rare, as a number of restrictive conditions should be satisfied (MONSERRAT *et al*., 2006). First, an air pressure disturbance should have high energy content at periods ranging from a few minutes to a few hours. Second, it should propagate over shallow waters, with the speed matching the speed of sea waves. Then the Proudman resonance (PROUDMAN, 1929) and generation of barotropic sea waves is likely to happen. Third, the sea waves should propagate from the open sea towards the entrance of a harbour/bay. Fourth, the harbour should have the ability to resonantly amplify the incoming signal, i.e. the Q-factor should be large (RAICHLEN, 1966). Last, but not least, matching between the dominant frequencies of incoming sea waves and normal modes of the harbour is needed, in order to amplify the energy at eigenperiods through the harbour resonance. The lack of any of the listed conditions will significantly decrease the intensity of a meteotsunami: e.g. a deviation of only 5% from the resonant conditions (i.e. in the ratio between the speeds of pressure disturbance and sea waves) will reduce the resonantly generated open-sea wave by a half (VILIBIĆ, 2008).

Already 25 years ago HIBIYA & KAJIURA (1982) executed the first numerical modelling study of meteotsunamis, in order to investigate the physics controlling extremely large seiches recorded three years earlier in Nagasaki Bay (with maximum crest-to-trough height of 278 cm). They found that the seiches were induced by incoming open-sea waves, resonantly generated on the broad shelf off China by a travelling air pressure disturbance of about 3 hPa in range. The amplification over the shelf was proportional not only to the range of the disturbance but also to the spatial air pressure gradient, resulting in large amplification of the relatively small disturbance over the shelf (HIBIYA & KAJIURA, 1982; VILIBIĆ, 2005). The connection between travelling air pressure disturbances and high-amplitude sea level oscillations has been widely examined for Cuitadella Harbour on the Balearic Islands, where abnormally strong seiches (locally known as “rissaga”) are sporadically observed during summer months with crest-to-trough height surpassing 1.5 m (MONSERRAT *et al.*, 1991; GOMIS *et al.*, 1993; GARCIES *et al.*, 1996; JANSÁ *et al.*, 2007). Additionally, pronounced sea level oscillations coinciding with passage of air pressure disturbances have been observed worldwide: in the Sicily Strait and Malta (CANDELA-PEREZ *et al.*, 1999; DRAGO, 1999), Kuril Islands (RABINOVICH & MONSERRAT, 1996, 1998), the Great Lakes (DONN & EWING, 1956), Patagonian Shelf (DRAGANI *et al.*, 2002; DRAGANI, 2007), Florida Shelf (SALLENGER *et al.*, 1995) and other places (an inventory of places and references is given by MONSERRAT *et al.*, 2006).

In the Adriatic Sea atmospheric forcing was shown to have, on rare occasions, exceptional effects in some regions and bays/harbours. Seiches in Vela Luka Bay on the island of Korčula on 21 June 1978 had crest-to-trough height of about 6 m (HODŽIĆ, 1979/80), and were apparently induced by open-sea waves, which in turn were resonantly generated by a travelling atmospheric pressure disturbance (ORLIĆ, 1980). Twenty five years later, on 27 June 2003, exceptional sea level oscillations struck Stari Grad on the island of Hvar, while strong currents swept away shellfish farms in Mali Ston Bay (VILIBIĆ *et al.*, 2004). This event was successfully reproduced by a numerical model and explained as a combination of (i) a sea wave generated by large air pressure disturbance (range of 8 hPa) travelling with a speed of 22 m s^{-1} towards ESE, (ii) its amplification at the topographic constraints upon entering funnel-shaped bays, and (iii) final increase inside harbours/bays through the harbour resonance. Besides that, BELUŠIĆ *et al.* (2007) successfully reproduced the generation and propagation of the atmospheric gravity wave which generated open sea waves during the 2003 event, and found that the wave was generated at the Alps, then came over the extremely warm Adriatic (26-27°C), and was sustained over its alongshore pathway through a convective self-feeding cell.

In this paper we will concentrate on a specific event of pronounced seiche activity observed in Bakar Bay during 19–21 August 2006, which is the largest observed since the installation of a digital tide gauge in 2003. Apart from analysing sea level, we will study the synoptic situation and available meteorological series, and will show that the air pressure disturbances favourable for meteotsunami generation, as well as the conditions for propagation and trapping of atmospheric gravity waves, persisted during the period of interest. We will also calculate propagation speed, direction and horizontal span of the air pressure disturbances, which will lead to the conclusion that the resonant generation and amplification of sea waves likely happened.

MATERIAL AND METHODS

Our study area is the small, elongated, 4.6 km long Bakar Bay, located at the north-east corner of the larger and rectangular Rijeka Bay, which is connected to the open Adriatic by a number of deep channels (Fig. 1). Being so far from the open sea, Bakar Bay is relatively protected from the disturbances coming from it. However, the Bakar Bay seiches are quite persistent (GOLDBERG & KEMPNI, 1938; ORLIĆ & PASARIĆ, 1997), presumably being provoked by barotropic sea waves coming from Rijeka Bay. Barotropic waves in Rijeka Bay could, in turn, be resonantly provoked by travelling air pressure disturbances. Speed v of the barotropic waves can be determined as $v = \sqrt{gh}$, where g is the gravity acceleration and h is the local depth. Since Rijeka Bay has a flat bottom of 60 m, it follows that the speed of barotropic waves in the bay is 24 m s^{-1}. Therefore, barotropic waves of Rijeka Bay could be resonantly coupled with the atmospheric pressure disturbances travelling over it with a speed of 24 m s^{-1}. The other possibility is that the Bakar Bay seiches are directly generated by the atmospheric forcing.

The periods of the Bakar Bay seiches were first determined by GOLDBERG & KEMPNI (1938) from tide-gauge records. They estimated the fundamental period of the whole basin to be 20.0 and 24.0 min and the period of the first mode of the whole basin to be 8.0 min. Apparently, the period of the fundamental mode of the bay varies because its nodal line is only vaguely defined and several constrictions at the mouth might actually represent the area of interaction between the bay and the open sea waters. GOLD-

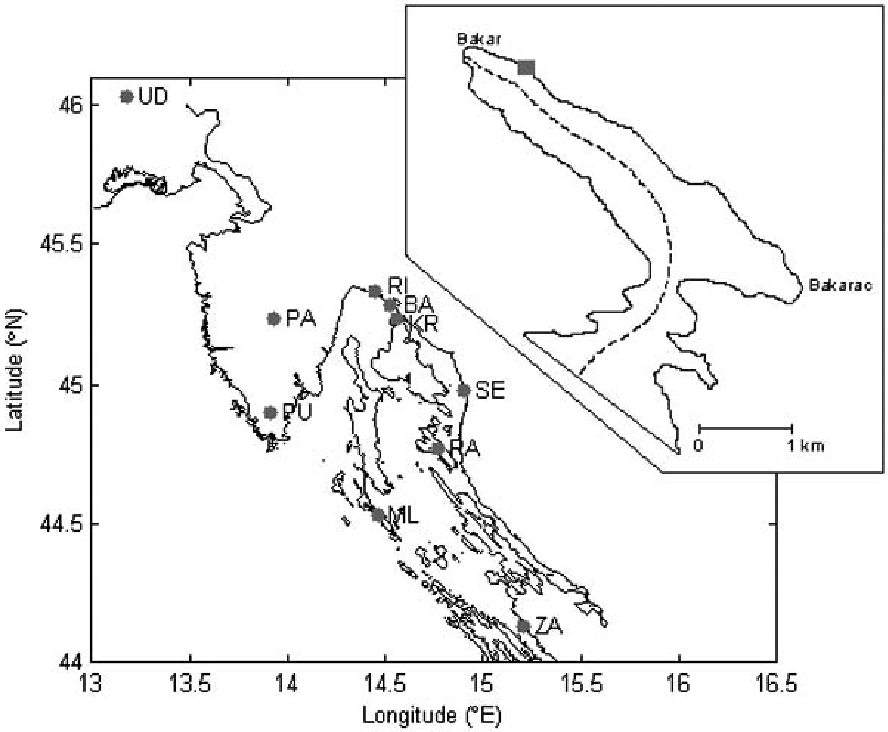


Fig. 1. Geographic location of the investigated area; the circles mark meteorological stations (UD, Udine; PU, Pula; PA, Pazin; RI, Rijeka; BA, Bakar; KR, Krčki most; RA, Rab; ML, Mali Lošinj; ZA, Zadar). The inset show Bakar Bay, with the square denoting the tide-gauge station and the dashed line the along-basin profile referred to in Fig. 2

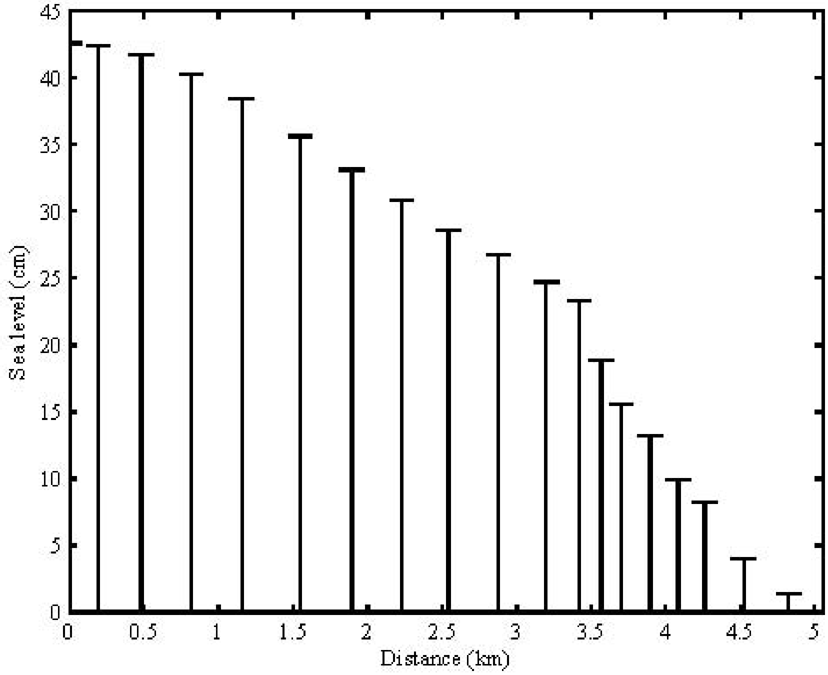


Fig. 2. Along-basin shape of the fundamental mode of Bakar Bay, adapted from GOLDBERG & KEMPNI (1938). Sea level height from the head toward the mouth of the bay, along the dashed line depicted in Fig. 1

BERG & KEMPNI (1938) also estimated periods of the inner basin of Bakar Bay (extending along the Bakar-Bakarac axis; Fig. 1) and found them at 8.0 min (fundamental mode) and 4.3 min (first mode), as well at several periods shorter than 2 min. Furthermore, they also obtained shape and periods of the fundamental mode of the whole basin and the fundamental and first mode of the inner basin by a numerical method (described in GOLDBERG & KEMPNI, 1938). The shape of the fundamental mode of the whole basin in a direction from the closed toward the open end of the bay, as determined by GOLDBERG & KEMPNI (1938), is shown in Fig. 2. Here, sea level was calculated at 19 points distributed along the dashed line marked in Fig. 1. As expected, the mode reaches its maximum height at the head of the bay (Fig. 2). Likewise, the fundamental mode of the inner basin also reaches maximum height at the head of the bay, and the first mode of the inner basin reaches around 60% of its maximal height at the same place (first mode reaches its maximum height at Bakarac, not shown). Therefore, the location of the tide-gauge station near the head of the bay is adequate for the measurement of these modes (position of the tide-gauge is marked in Fig. 1). Furthermore, determination of Bakar Bay periods based on one-month long bottom pressure measurements carried out in the bay was done by ORLIĆ & PASARIĆ (1997). They found the most pronounced oscillations at periods of 26.9, 22.3, 19.7, 7.8 and 4.3 min.

A number of meteorological stations and the tide-gauge station at Bakar have been operational during 2006, capturing the event of interest that occurred between 19 and 21 August 2006. Sea level heights have been recorded with OTT Kalesto digital radar sensor having a resolution of 1 min and an accuracy of ±1 cm. The quality of these data was additionally verified by comparing them with the data collected at another digital tide-gauge station located close to the radar gauge (at a distance of 300 m). The two data sets were highly correlated and had a correlation coefficient higher than 0.99. Air pressure data had been digitally recorded at Pazin (PA), Rijeka (RI), Bakar (BA) and Rab (RA) stations with a sampling interval of 10 min and an accuracy of ±0.05 hPa. Additionally, air pressure had been recorded by analogue instruments at Pula (PU), Mali Lošinj (ML), Senj (SE) and Zadar (ZA) meteorological stations. From analogue records the arrival times of pressure disturbances at these stations were obtained. Wind speed and direction, averaged over 10 min intervals, have been recorded by digital anemometers at PA, RI, Krčki most (KR), BA, SE and RA stations, with an accuracy of ±0.05 m s^{-1} for wind speed and ±0.5° for wind direction. Upper air soundings have been conducted at Udine (UD) station at 12 h intervals.

Propagation speed and direction of air pressure disturbances were estimated by the model developed by ORLIĆ (1980). Assuming that a pressure disturbance has a form of a plane wave, propagating over the northern Adriatic with constant speed and direction and having permanent shape, the speed and the direction of the wave-like disturbance can be determined from its arrival times observed at the meteorological stations.

Let v be the speed of the wave and γ its direction – where γ is the angle between the wave ray and the parallels of latitude. Angle γ will be measured counterclockwise, from the eastward direction toward the direction of propagation. Let δ_i be the distance between two meteorological stations and γ_i the angle between the line δ_i and the parallels of latitude (angle γ_i will be measured in the same way as the angle γ). Moreover, let Δt_i denote the computed difference between arrival times of pressure disturbances at stations whose distance is δ_i. Then the following expression is valid:

$$\Delta t_i = \frac{\delta_i \cdot \cos(\gamma_i - \gamma)}{v}. \tag{1}$$

Finally, let Δt_i denote the measured difference between arrival times of pressure disturbances at various stations, while n is the number of station pairs. The speed v and the direction γ of propagation can now be obtained by minimizing the following function through the least-squares approach:

$$f(v,\gamma) = \sum_{i=1}^{n} \left(\Delta t_i - \overline{\Delta t_i}\right)^2 = \sum_{i=1}^{n} \left(\frac{\delta_i \cdot \cos(\gamma_i - \gamma)}{v} - \overline{\Delta t_i}\right)^2. \tag{2}$$

The accuracies m_v and m_γ of speed v and direction γ of the disturbances estimated by this model will be further verified by use of the procedure of equalising the indirect measurements of more than one variable, as described by ČUBRANIĆ (1958) and ORLIĆ (1984). Furthermore, the length scale of the disturbance can be determined as a mean value of length scales at different meteorological stations obtained from the following expression:

$$\lambda_k = v t_k \tag{3}$$

Here, t_k represents the time span of pressure disturbance (i.e. the time between maximum and minimum pressure associated with the oscillation) as measured at different meteorological stations. We also calculated the standard deviation m_λ of the pressure disturbance's length scale.

RESULTS

Pronounced and long-lasting high-frequency sea level oscillations have been observed at the Bakar tide-gauge station during a three day interval in mid-August 2006, superimposed on the regular tidal regime (Fig. 3a). The oscillations started in the morning hours of 19 August, and persisted, though varied in their intensity, until 21 August. The maximum amplitude of these oscillations was around 40 cm, being recorded on 19 August at 14:20 hours. The oscillations were extracted by a high-pass filter (cut-off period of 1.5 h), thus isolating sea level cycles with periods of about 20 min (Fig. 3b), known as the fundamental seiche period of Bakar Bay (GOLDBERG & KEMPNI, 1938; ORLIĆ & PASARIĆ, 1997). It seems that the seiches were generated through a number of impulse-type forcings, of which the strongest occurred during the afternoon hours of 19 August, and again during the mid-day hours of 20 August. Furthermore, a band-pass filter with cut-off periods of 1.5 and 6 h was applied to the sea level series, in order

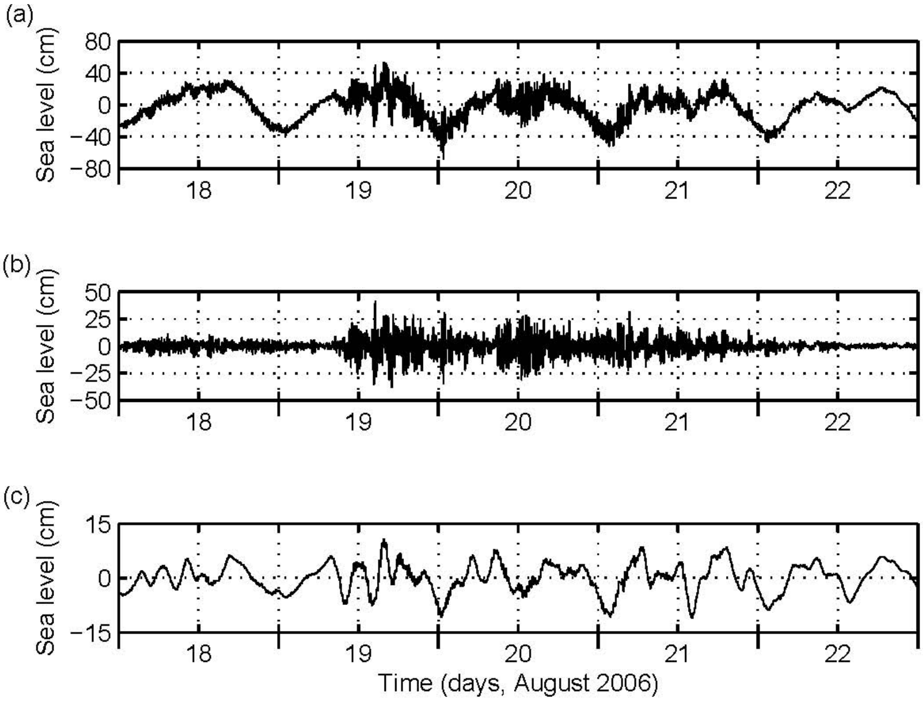


Fig. 3. Sea level time series in the interval 18–22 August 2006: (a) original time series recorded at Bakar; (b) high-frequency component of the series (with the cut-off period placed at 1.5 h); (c) band-pass component of the series (with the cut-off periods placed at 1.5 and 6 h)

to extract another known eigenoscillation in the area: the fundamental seiche of Rijeka Bay with a period of about 2 h (GOLDBERG & KEMPNI, 1938). This seiche was pronounced on 19 August (Fig. 3c), when the sea level amplitude reached 10 cm at most, but it can also be seen later during the relaxation of the Bakar seiches.

The exact period of these oscillations may be seen in the power spectra estimated: (a) for the whole time series (18-22 August), and (b) for the four-hour intervals shifted in time and using FFT with one window of 4 h width (240 points). The spectra were computed from the filtered sea level series, with a cut-off period of 3 hours in order to remove the influence of tides and Adriatic seiches from the estimates. As clearly visible in Fig. 4, the most pronounced oscillations were recorded at or close to the well known seiche periods for the area (GOLDBERG & KEMPNI, 1938; ORLIĆ & PASARIĆ, 1997). Precisely, energy peaks can be seen at 4.3 and 7.8 min, matching the eigenoscillations' periods of the Bakar Bay inner basin, then around 20 min (16.3, 19.6, 23.7 and 27.2 min), corresponding to eigenoscillations' periods of the whole of Bakar Bay, and finally at the period of 128.2 min, which is close to the known Rijeka Bay period of 2 h. The maximum energy of all oscillations was recorded on 19 August around 1600 hrs, about two hours after the passage of an intensive stepwise atmospheric disturbance over the area.

Next, we will attempt to document the meteorological conditions prevailing during the pronounced seiche activity between 19 and 21 August 2006. The synoptic situation over Europe on 19 August was characterised by a pronounced low above the British Isles (Fig. 5). An upper-level trough was positioned over Western Europe (British Isles – Portugal) and a strong south-westerly jet was maintained over the western Mediterranean and Central Europe. The jet advected warm African air at around

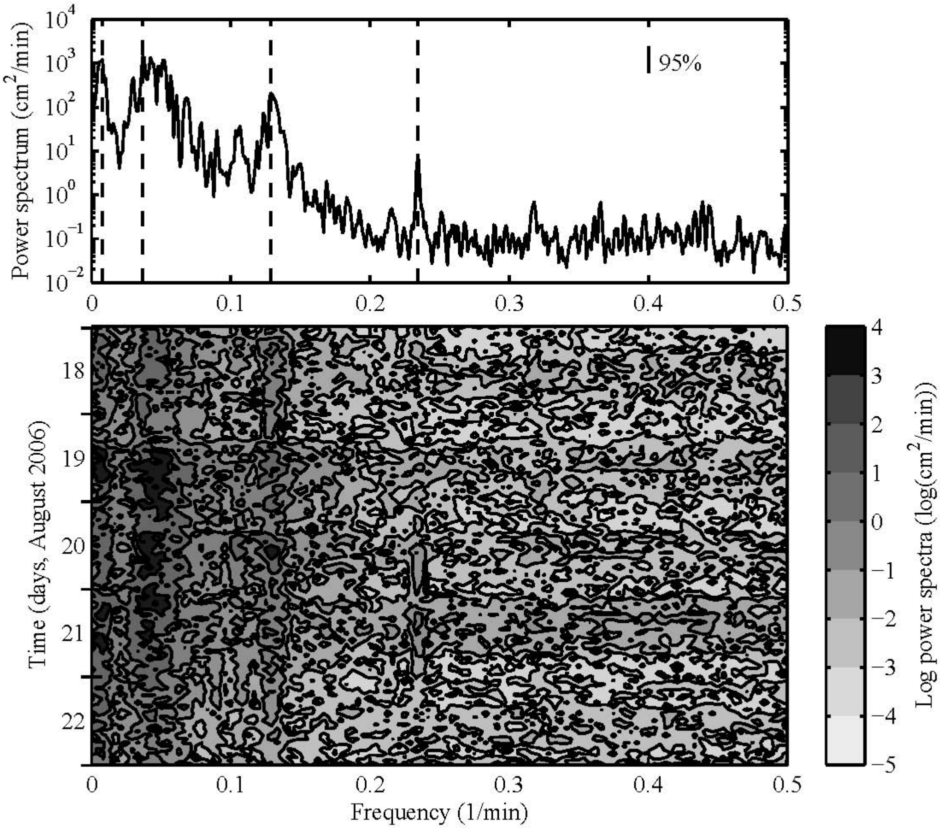


Fig. 4. Power spectra of the high-frequency component of sea level oscillations at Bakar (with the cut-off period of 3 h): (a) for the whole time series (18-22 August 2006), using FFT with eight adjacent rectangular windows, and (b) for the four-hour intervals shifted in time, using FFT with one rectangular window of 4 h width. Vertical lines are placed at the periods of 128.2, 27.2, 7.8 and 4.3 min, respectively

2000 m and consequently weak temperature inversion developed at that height (Fig. 6). This inversion was apparently long-lived and maintained its form for at least 24 hours, as revealed from UD radio-soundings (Fig. 6). Furthermore, a cold front coming from the west crossed the Alps in the morning hours of 19 August and a mesoscale low subsequently developed over Kvarner Bay (not shown). It is interesting that the pronounced air pressure oscillations which cause the "rissagas" of the Balearic Islands typically occur under synoptic conditions (MONSERRAT *et al.*, 1991) similar to those which prevailed in the atmosphere between 19 and 21 August 2006. A few separate episodes of pronounced air pressure oscillations may be seen in the air pressure time series of those dates: (i) on 19 August between 6 and 22 hours, (ii) on 20 August between 8 and 16 hours, and (iii) on 21 August between 0 and 11 hours (Fig. 7). An abrupt pressure drop (4.5 hPa during 10 minutes as measured at BA meteorological station) was observed at about 14 hours on 19 August, coinciding with the most intense seiche episode in which sea level amplitudes reached 40 cm. This is in accordance with the findings of HIBIYA & KAJIURA (1982) who found that the sea response (wave amplitude) is proportional not to the amplitude of the air pressure travelling perturbation but to its temporal gradient. Numerical simulations also confirmed that; a stepwise air pressure disturbance supports larger sea waves and at higher frequencies than a cosine-like disturbance (VILIBIĆ, 2005). Moreover, the larger

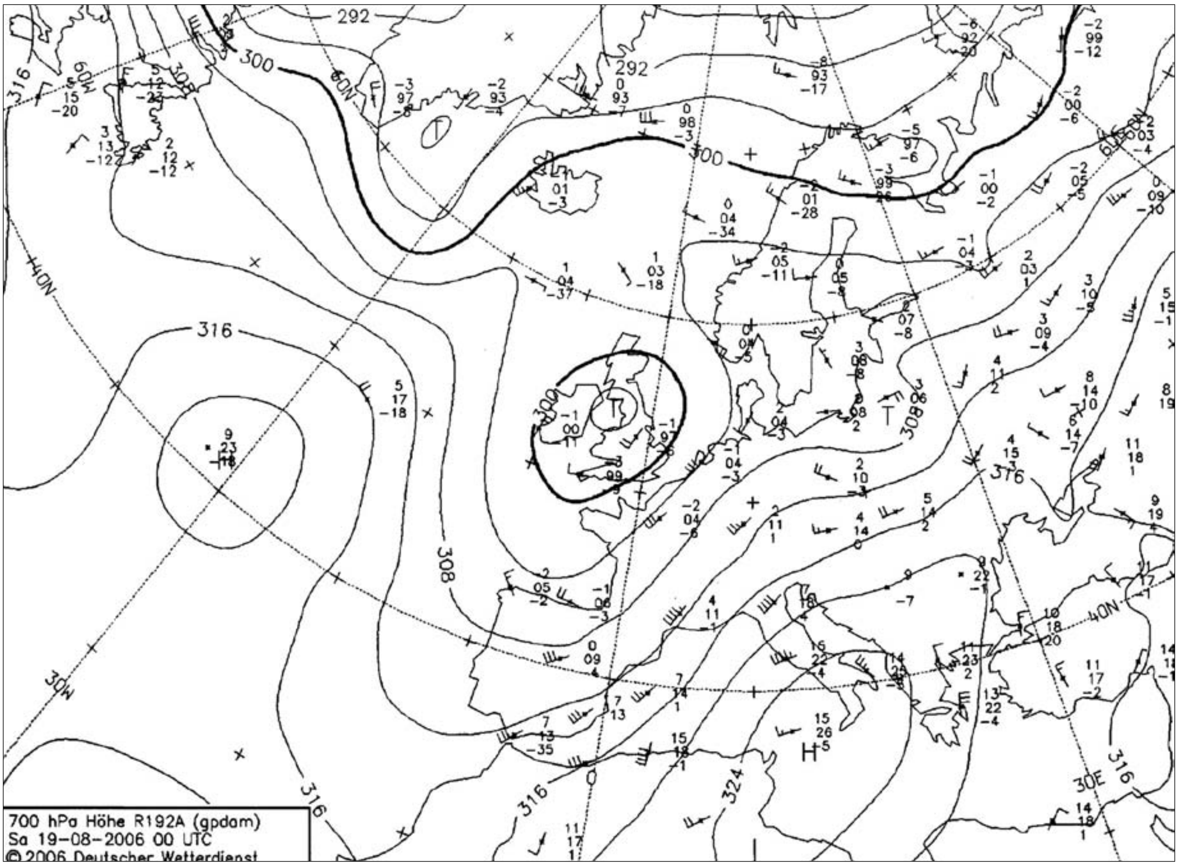


Fig. 5. Geopotential height and wind distribution at the 700 hPa surface on 19 August 2006 at 00 UTC

the air pressure gradient the smaller the required generation area (VILIBIĆ, 2008), and that may be a crucial issue for the generation of sea waves via the Proudman resonance in limited basins.

Spectral analysis of filtered pressure time series from the BA meteorological station (with a cut-off period of 3 h) was performed in the same way as for the sea level time series (Fig. 8). A significant increase of energy at all frequencies (higher than 20 min) may be noticed after 1400 hrs on 19 August which, as stated before, corresponded to the sharp air pressure drop and to the beginning of the most intense sea oscillation with the highest recorded amplitude. The broad-band spectrum of this atmospheric disturbance included the frequencies of Rijeka and Bakar Bay seiches, and both of them were generated with significant energies as seen in the sea level spectra (Fig. 4). Next, we will evaluate the generation potential of the wind during the observed large sea level oscillations. Wind speed records for the KR meteorological station are shown in Fig. 9. During the investigated interval there were few pronounced wind bursts with maximum recorded speed of about 10 m s^{-1}, but with recorded speeds below 5 m s^{-1} at meteorological stations other than KR. Therefore, the wind was not capable of producing any significant oscillations in the area. Furthermore, VILIBIĆ & MIHANOVIĆ (2005) studied seiches in Ploče Harbour with dimensions comparable to those of Bakar Bay, and concluded that even a large wind stress does not have the capability of exciting large amplitude oscillations in small basins.

All of these findings suggest that the passage of pressure disturbances was responsible for the observed large sea level oscillations. Therefore, we found it useful to estimate propagation speed and direction of three individual atmospheric

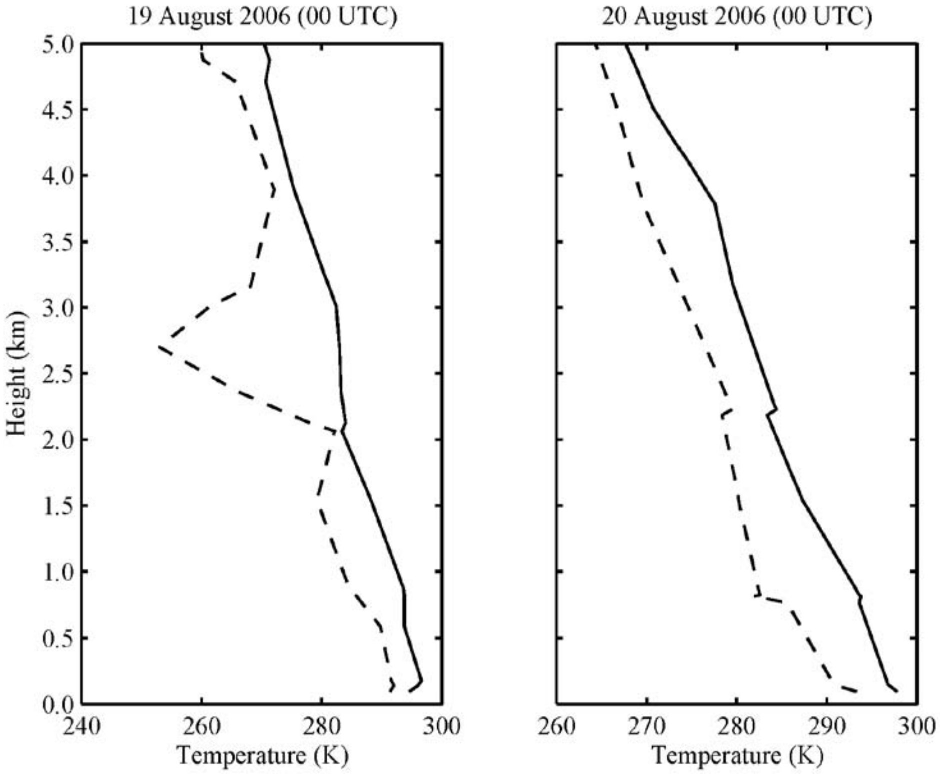
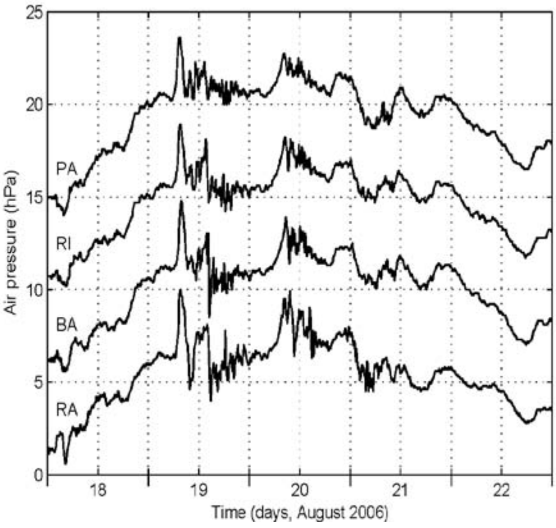


Fig. 6. Upper air soundings at the UD meteorological station for 19 August 2006 at 00 UTC and 20 August 2006 at 00 UTC. Solid line represents temperature and dashed line dew point

pressure disturbances observed on 19 August 2006 and of the one observed on 20 August 2006. Also, the length scale of pressure disturbances was obtained, as this is an important parameter in determining the possibility of atmosphere-sea resonant coupling. For determination of propagation parameters we used pressure records from all available stations. A graphical representation of the function *f(v,γ)* calculated for the propagation of the first air pressure disturbance is given in Fig. 10, and the results of analysis for all pressure disturbances, including the time span of the disturbances at the BA meteorological station, the speed v, the direction γ and the length scale λ of the disturbances, as well as the accuracies m_v, m_γ of the speed and the direction and the standard deviation m_λ of the length scale, are shown in Table 1. The results indicate that the disturbances propagated above the investigated area with a wide range of speeds

Fig. 7. Air pressure time series measured at the BA, RA, RI and PA meteorological stations with a 10 min sampling interval, between 18 and 22 August 2006. Air pressure records were offset for better visual comparison



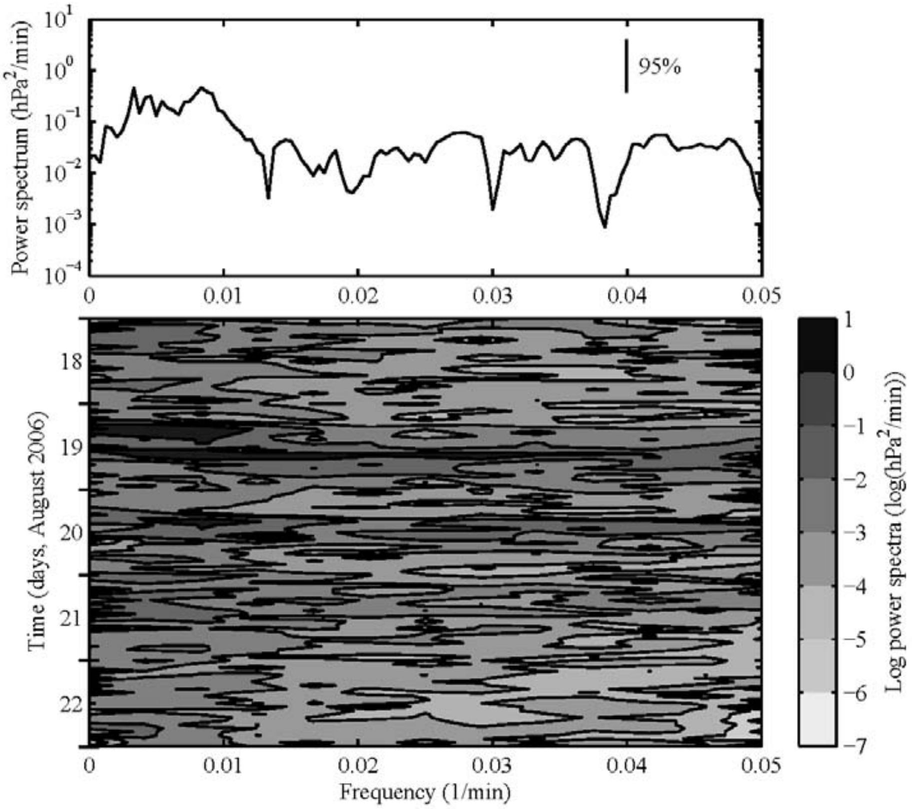
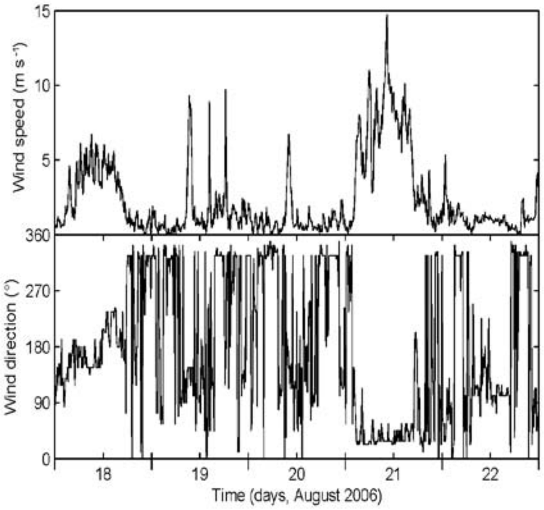


Fig. 8. Power spectra of the high-frequency component of the air pressure oscillations (with the cut-off period of 3 h) measured at BA: (a) for the whole time series (18-22 August 2006), using FFT with three adjacent rectangular windows, and (b) for the four-hour intervals shifted in time, using FFT with one rectangular window of 4 h width

Fig. 9. Wind speed and direction time series measured at KR between 18 and 22 August 2006, with a 10 min sampling interval



including the resonant speed of barotropic sea waves in Rijeka Bay (24 m s^{-1}). Furthermore, the disturbances propagated towards east-southeast to northeast. The disturbances' length scales varied from those comparable to the Rijeka Bay dimensions (maximum width around 25 km) to those with dimensions far greater than it (up to about 150 km). As shorter disturbances are more efficient at producing considerable sea waves, the strongest sea level oscillation on 19 August at around 1400 hrs was presumably provoked by a short air pressure disturbance with quite large temporal and spatial gradients over the area. This disturbance apparently generated the barotropic sea waves in Rijeka Bay, which were amplified along their pathway to Bakar Bay. As the energy content was quite high in the band-width of Bakar Bay seiche periods (about 20 min, Fig. 8), the waves were probably addition-

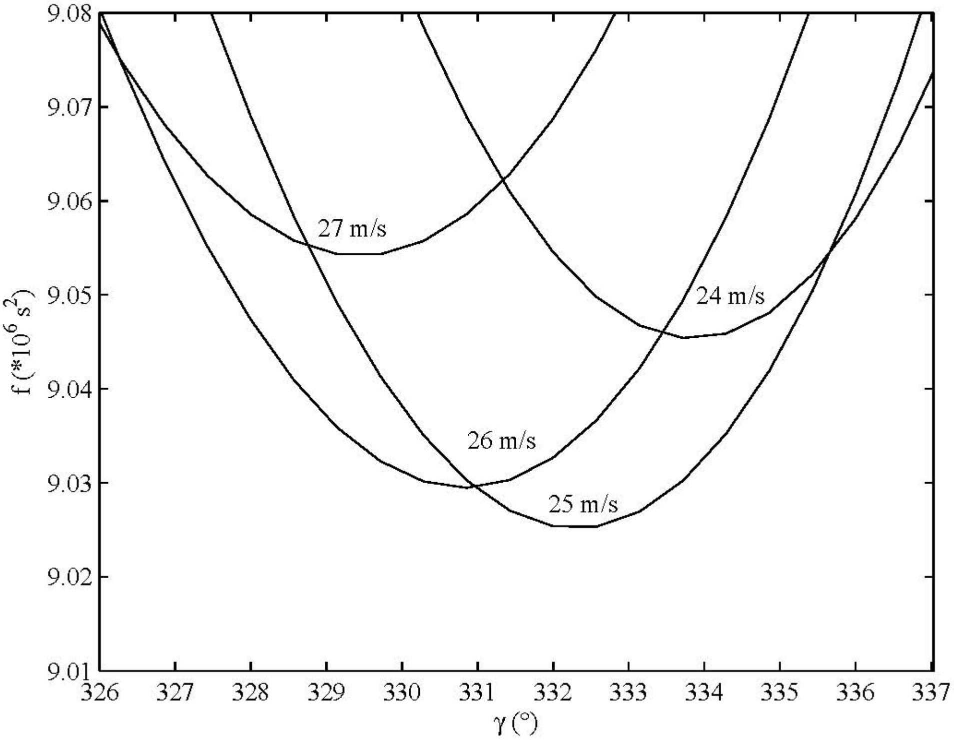


Fig. 10. Graphic representation of the function f(v,γ) defined by Eq. (2), for the disturbance recorded on 19 August 2006. The function has a minimum for $v = 25$ *m* s^{-1} *and* $\gamma = -27°$

ally strengthened in the bay through the harbour resonance, reaching their maximum at the bay's closed end, near the tide-gauge station.

Furthermore, as we already compared the synoptic situation in the atmosphere on 19–21 August 2006 with the one prevailing during the "rissaga" events on the Balearic Islands, we also posed a question as to whether the source of the observed air pressure oscillations was similar to the source of the "rissaga" - generating air pressure disturbances. Those disturbances are usually assumed to be the surface manifestation of ducted gravity waves or ducted convection jumps (MONSERRAT & THORPE, 1992; 1996, JANSÁ *et al.*, 2007). To reveal whether necessary conditions for trapping of atmospheric gravity waves existed in the atmosphere above the Adriatic Sea on 19 and 20 August, we thoroughly examined

	Time span (hours)	v (m s^{-1})	m_v (m s^{-1})	γ (°)	m_γ (°)	λ (km)	m_λ (km)
		19 August 2006					
disturbance 1	7:40 – 9:10	24	16	7	13	147	106
disturbance 2	14:10 – 14:20	19	6	-20	10	39	23
disturbance 3	17:50 – 18:30	12	3	-19	6	21	8
		20 August 2006					
disturbance 1	8:30 – 9:20	32	12	47	7	79	75

Table 1. Time span at the BA meteorological station and estimated propagation parameters speed v, accuracy of the speed m_v*, direction* γ*, accuracy of the direction* m_γ*, length scale* λ *and standard deviation of the length scale* m_λ *of four distinct atmospheric pressure disturbances observed on 19 and 20 August 2006*

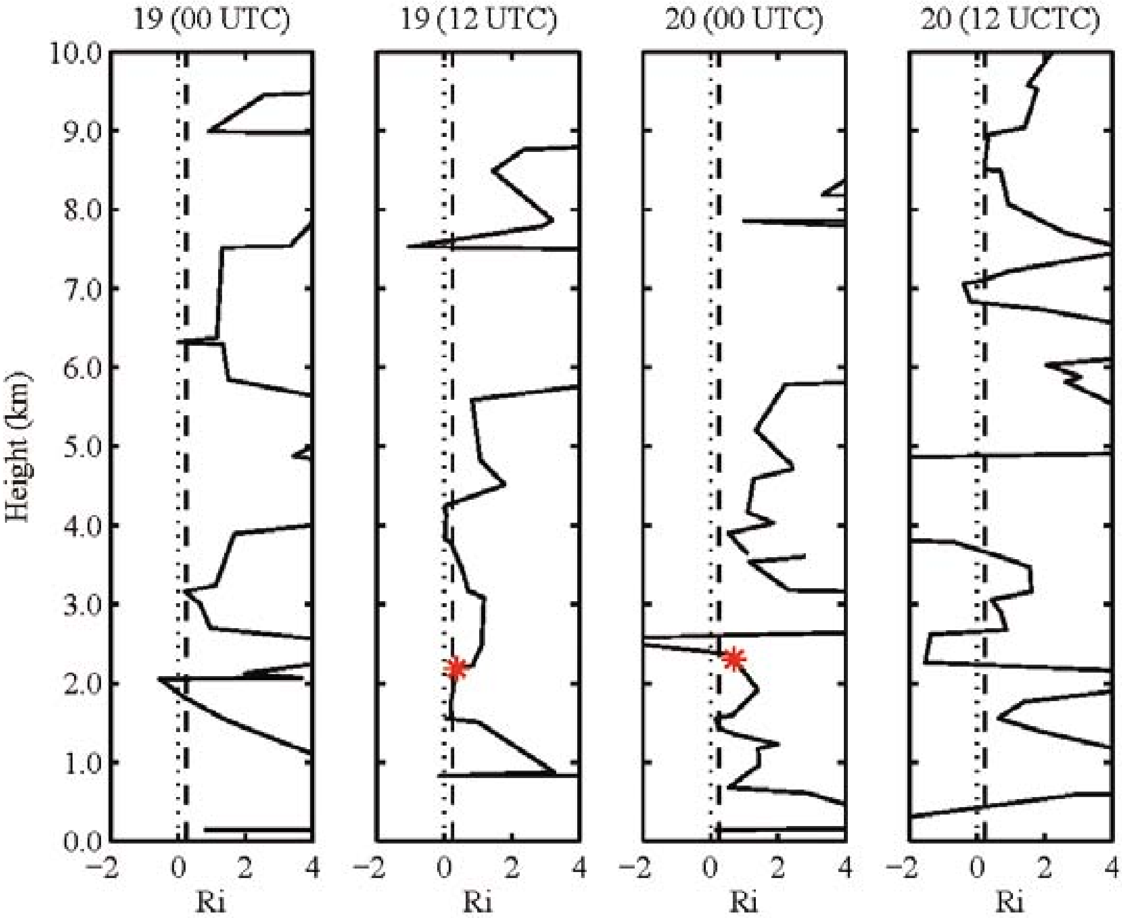


Fig 11. From left to right, and all for the UD meteorological station, Richardson number at: 00 UTC on 19 August 2006; 12 UTC on 19 August 2006; 00 UTC on 20 August 2006; and 12 UTC on 20 August 2006. Red star on the second plot from the left represents the height where the wind speed reaches 19 m s^{-1}, and on the third plot from the left it represents the height where the wind speed reaches 12 m s^{-1}

radio-sounding data from the UD meteorological station. LINDZEN & TUNG (1976) stated that trapping of gravity waves can occur in a stable layer which is capped by a statically or dynamically unstable layer, i.e. by the layer in which Richardson number is less than 0.25. In addition, wind speed in the unstable layer has to either reach the phase speed of the gravity waves or come very close to it. Data from the UD meteorological station revealed that an unstable layer persisted in the atmosphere on 19 and 20 August 2006. This layer, which had a width of 300–500 m, was placed at a height of around 2000 m on 19 August and at around 2500 m on 20 August (Fig. 11). At 1200 UTC on 19 August wind speed in the unstable layer was close to 19 m s^{-1} which is the estimated speed of propagation of the air pressure disturbance that passed above the northern Adriatic around 14 UTC. Furthermore, wind speed in the unstable layer decreased toward the end of the day, simultaneously with the estimated speed of propagation of the air pressure disturbances. Namely, the disturbance propagating through the atmosphere at around 18 UTC had a speed of 12 m s^{-1}, as did the wind right above the unstable layer at 00 UTC on 20 August 2006. Although the unstable layer was still present in the atmosphere at 12 UTC on 20 August 2006, wind speed in it was far less (10 m s^{-1}) than the estimated speed of the pressure disturbance propagating through the atmosphere at around 9 UTC (32 m s^{-1}). The above finding implies that conditions for trapping of atmospheric gravity waves existed in the atmosphere in the afternoon hours of 19 August 2006. As that is also the time when the most pronounced air pressure oscillations occurred, we suspect that they were surface manifestations of ducted gravity waves.

DISCUSSION AND CONCLUSIONS

This paper comprises an empirical analysis of pronounced sea level oscillations recorded during 19–21 August 2006 at the tide-gauge station located in Bakar Bay. Through the examination of available meteorological and sea level data, we came to the following major conclusions: (i) high-frequency air pressure disturbances propagated over the north Adriatic and were coupled with barotropic open-sea waves presumably through the Proudman resonance mechanism, and (ii) upon hitting the coastal area these open sea waves were amplified - particularly at the Bakar Bay eigenfrequencies through the harbour resonance mechanism.

The above scenario still needs to be confirmed either by measurements or modelling studies. However, it is quite plausible since we rejected some other possibilities for the generation of the large seiches. Namely, we speculated on the possibility of a direct generation of Bakar Bay seiches by a moving air pressure disturbance. For that purpose, the analytical model developed by RAO (1969) was modified by substituting the wind by the air pressure gradient, where the air pressure disturbance is propagating towards the open end of a bay. The model was forced with idealised pressure disturbances having amplitude, horizontal length scale and speed equal to those estimated for the four distinct pressure disturbances propagating above the northern Adriatic on 19 and 20 August. The response of the bay was thus modelled, reproducing direct energy transfer to the bay normal modes. However, the model was able to explain only a negligible percentage of observed sea level variance (up to 3%), as a result of the substantially larger spatial scale of the atmospheric disturbances than of Bakar Bay. For example, the modelled sea height induced by the idealised disturbance which had speed, amplitude and length scale equal to those of the pressure disturbance causing the most extreme sea oscillations in Bakar Bay was only 1 cm, as opposed to the measured height of 40 cm. On the contrary, the application of such a model was successful in the Bay of Fundy, whose longitudinal dimension is around 200 km, ending in sea level oscillations up to 1.2 m high at the head of the basin.

Although the application of the model to Bakar Bay was not successful in clarifying the observed seiches, it confirmed that atmospheric disturbances, being significantly larger than the dimensions of the basins they are affecting, are not capable of provoking a significant sea response. GOMIS *et al.* (1993) came to a similar conclusion while examining seiches in Cuitadella Bay. Namely, they concluded that air pressure disturbances with the capacity to directly excite pronounced sea level oscillations in small bays/harbours would have characteristics of a standing wave, and that was not the case for Cuitadella seiches, whose appearance clearly coincided with the passage of travelling air pressure disturbances. Consequently, excitation of the bay eigenoscillations by the open-sea waves remained the only possible scenario. Support may be also found in GOLDBERG & KEMPNI (1938), who noticed that Bakar Bay seiches may be excited by open-sea waves. Furthermore, numerical modelling studies were conducted for Ploče Harbour (with similar dimensions to Bakar Bay), and showed that even rather extreme direct forcing can not produce strong seiches in the harbour, yielding to the conclusion that they are mostly excited by incoming open-sea waves (VILIBIĆ & MIHANOVIĆ, 2005).

It would thus appear that atmosphere-sea interaction occurs in Rijeka Bay, and that it is therefore essential to further elaborate the possibility of the Proudman resonance occurring in such a flat-bottom and rectangular basin. A major limitation of the effectiveness of the resonance are the dimensions of Rijeka Bay which is a relatively small basin (with a maximum width of 25 km). Therefore, the atmospheric disturbances are not only required to propagate with the resonant speed, but they must also have horizontal dimensions equal to or smaller than the dimensions of Rijeka Bay. The parallel coexistence of these two conditions explains why some of the observed atmospheric disturbances, for which one of the conditions was fully satisfied but the other severely failed, were not able to provoke significant seiches in Bakar Bay.

The effectiveness of the Proudman resonance may be estimated by using the formula derived by HIBIYA & KAJIURA (1982) after the devastating 1979 Nagasaki Bay meteotsunami. As already mentioned, they stated that the resonant response $\Delta\zeta$ is proportional not only to the intensity (range) of the atmospheric disturbance but also to its spatial pressure gradient, i.e.

$$\Delta\zeta = \frac{\Delta\bar{\zeta}}{L_1}\frac{x_f}{2}, \qquad (4)$$

where x_f is the distance travelled by the pressure jump, L_1 is the length of the disturbance, and $\Delta\bar{\zeta}$ is the static sea level (proportional to the air pressure change following the inverted barometer rule of – 1 cm hPa^{-1}). We applied the formula to the strongest case of Bakar Bay seiches, caused by an abrupt pressure drop of 4.5 hPa over 10 minutes, as measured at BA around 1400 hrs on 19 June 2006 (Fig. 7). For that case L_1, if estimated only from the BA station air pressure data, was equal to 14 km (24 m s^{-1} x 10 minutes), $\Delta\bar{\zeta}$ to 4.5 cm, and x_f to 25 km (the width of Rijeka Bay). Then the dynamic sea level change $\Delta\zeta$ in front of Bakar Bay may be estimated at 4 cm. However, this is less than 10% of the observed oscillations inside Bakar Bay, still not enough to result in the 40 cm amplitude at its head. One of the problems may result from the coarse resolution of the air pressure measurements, which cannot capture fine spatial and temporal features in atmospheric disturbances. Namely, examined high-resolution air pressure series (resolution of 30 s) collected during “rissaga” event and found that the pressure gradient was occasionally four times larger at the original resolution time scale (30 s) than at the 10 min resolution time scale. By assuming that the Bakar Bay seiches are also caused by fine pressure changes, let us say four times larger than the observed ones (10 min series), we could end up with 16 cm sea level height in front of the bay, due to the Proudman resonance in Rijeka Bay. Then this signal would be amplified topographically in Rijeka Bay and finally in Bakar Bay through the harbour resonance with a factor of about four, which is realistic when compared to the amplification factor obtained for the Ploče Harbour (around three, see VILIBIĆ & MIHANOVIĆ, 2005).

To conclude, we hypothesise that the Proudman resonance in Rijeka Bay was responsible for the observed large seiches in Bakar Bay. Naturally, this discussion opens a number of further questions. For example, how does Bakar Bay amplify sea level oscillations imposed at its mouth? Is there a possibility for producing damage, or could the oscillations be merely perceived as an interesting phenomenon? In order to answer these questions, to confirm generation mechanisms of Bakar Bay seiches, and to properly quantify the areas of atmosphere-sea coupling, process-oriented numerical modelling should be performed, encompassing the whole north Adriatic area. In addition, targeted and more precise measurements of air pressure and sea level in Rijeka Bay itself would also be of great help.

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Seši Bakarskog zaljeva i njihova povezanost s atmosferskim procesima

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SAŽETAK

Seši iznimne amplitude (do 40 cm) zabilježeni su u nekoliko navrata na mareografskoj postaji u Bakarskom zaljevu između 19. i 21. kolovoza 2006. Analizirani su dostupni mareografski (razina mora) i meteorološki (tlak zraka, brzina i smjer vjetra, radio-sondažna mjerenja) podaci. Spektralna analiza vremenskih nizova razine mora i tlaka zraka ukazala je na istovremeni porast energije na periodima koji uključuju periode seša Bakarskog (oko 20 min) i Riječkog zaljeva (oko 2 h). Izračunati su brzina i smjer rasprostiranja te horizontalna širina četiri poremećaja u polju tlaka zraka koji su Proudmanovom rezonancom mogli djelovati na Riječki zaljev. Konačno, zaključeno je da su samo kratki poremećaji u polju tlaka zraka mogli generirati značajne barotropne valove u zaljevu ograničenih dimenzija kakav je Riječki zaljev, te da su se ti valovi dodatno pojačali u Bakarskom zaljevu mehanizmom lučke rezonance. Uz to, analiza sinoptičke situacije i radio-sondažnih mjerenja ukazala je da su na visini od oko 2000 m postojali dinamički nestabilan sloj te temperaturna inverzija koja se razvila zbog advekcije toplog afričkog zraka. Tijekom popodnevnih sati 19. kolovoza brzina vjetra u ovom sloju je bila bliska izračunatoj brzini rasprostiranja poremećaja u polju tlaka zraka. Ovakvo podudaranje brzina uz postojanje dinamički nestabilnog sloja pogoduje dugotrajnom rasprostiranju i zarobljavanju atmosferskih težinskih valova.

Ključne riječi: seši, oscilacije tlaka zraka, povezivanje atmosfere i mora, Proudmanova rezonanca, lučka rezonanca, Jadransko more