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Destructive meteotsunamis along the eastern Adriatic coast: Overview

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ABSTRACT

The paper overviews meteotsunami events documented in the Adriatic Sea in the last several decades, by using available eyewitness reports, documented literature, and atmospheric sounding and meteorological reanalysis data available on the web. The source of all documented Adriatic meteotsunamis was examined by assessing the underlying synoptic conditions. It is found that travelling atmospheric disturbances which generate the Adriatic meteotsunamis generally appear under atmospheric conditions documented also for the Balearic meteotsunamis (rissagas). These atmospheric disturbances are commonly generated by a flow over the mountain ridges (Apennines), and keep their energy through the wave-duct mechanism while propagating over a long distance below the unstable layer in the mid-troposphere. However, the Adriatic meteotsunamis may also be generated by a moving convective storm or gravity wave system coupled in the wave-CISK (Conditional Instability of the Second Kind) manner, not documented at other world meteotsunami hot spots. The travelling atmospheric disturbance is resonantly pumping the energy through the Proudman resonance over the wide Adriatic shelf, but other resonances (Greenspan, shelf) are also presumably influencing the strength of the meteotsunami waves, especially in the middle Adriatic, full of elongated islands and with a sloping bathymetry. The generated long ocean waves are hitting funnel-shaped bays or harbours of large amplification factors, resulting in meteotsunami waves with heights up to 6 m at the very end of bays or harbours. Within models the mechanism is fairly well understood, but it is extremely difficult to reproduce these events (and presently almost impossible to forecast) as the meteotsunami generating process is highly variable at both temporal and spatial scales. The final part of the paper discusses the possibilities for further research of the Adriatic meteotsunamis, and meteotsunamis in general, including the basis of a meteotsunami warning system which should be able to capture potentially dangerous travelling atmospheric disturbances in real-time.

1. Introduction

Although not affecting entire ocean-wide or basin-wide regions such as seismically-generated tsunamis (Titov et al., 2005), meteotsunamis, or meteorologically-generated long ocean waves in the tsunami frequency band generated by a travelling atmospheric disturbance, are a significant hazard for the eastern Adriatic coast. They occur on a centimetre level in the open sea, but may reach several metres in some bays and harbours (Monserrat et al., 2006; Rabinovich, 2009). Several destructive meteotsunamis affected the eastern Adriatic shore in the last few decades, and therefore attracted attention of the local researchers in order to explain their source, generation and propagation mechanism, and inundation along the complex coastal topographies.

The strength of a meteotsunami is largely dependant on the topographical characteristics of the affected area, as it is a multi-resonant phenomenon in which a number of specific conditions have to be satisfied. In brief, the following conditions should be satisfied (Monserrat et al., 2006) for the appearance of a destructive meteotsunami: (i) a harbour or a bay with large amplification (Q) factor, (ii) a small-scale atmospheric disturbance visible in surface air pressure series, (iii) propagation of the disturbance towards the harbour/bay entrance, (iv) external resonance between the atmospheric disturbance and long ocean waves, and (v) internal resonance between the arriving long ocean waves and the harbour/bay eigenmodes.

Destructive meteotsunamis have been observed at a number of places, such as the Balearic Islands (Gomis et al., 1993), Malta (Drago, 2008), Sicily (Candela et al., 1999), Greece (Papadopoulos, 1993) and the eastern Adriatic Sea (Hodžić, 1979/1980) in the Mediterranean, and also on the Dutch coast (de Jong and Battjes, 2004), English Channel (Douglas, 1929), the Baltic Sea (Metzner et al., 2000), Florida shelf (Sallenger et al., 1995), the Great Lakes (Donn and Ewing, 1956), Argentina (Dragani, 2007), Japan (Hibiya and Kajiura, 1982), the Yellow Sea (Wang et al., 1987), New Zealand (Goring, 2005) and some other places in the World Ocean. Meteotsunami wave heights can be as high as 6 m (Vela Luka,

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Adriatic Sea; Daytona Beach, Florida) or 5 m (Ciutadella inlet, the Balearic Islands; Nagasaki Bay, Japan) or less, and the waves can cause substantial damage to the coastal infrastructure including human injuries and losses (Donn and Ewing, 1956; Hibiya and Kajiura, 1982; Vilibić et al., 2004; Monserrat et al., 2006).

Assessment of the Adriatic meteotsunami potential versus the conditions listed by Monserrat et al. (2006) indicates a high vulnerability of the coastal regions to meteotsunamis. Namely: (i) the eastern Adriatic coast has a quite complex topography, with a number of funnel-shaped bays and harbours possessing high amplification factor (Fig. 1), (ii) generation of small-scale atmospheric disturbances takes place mostly during the summertime (e.g. Vilibić et al., 2005), (iii) a large number of bays and harbours are open to the west or the southwest, that being the preferred direction of incoming meteotsunami waves, (iv) a wide 30–80 m depth shelf, both in the northern and in the eastern middle Adriatic, is suitable for the appearance of the Proudman resonance (Proudman, 1929), while the islands may serve as a Greenspan resonator (Greenspan, 1956) for the generation of long ocean waves, and (v) the spectra of the atmospheric disturbances reveals a substantial energy at the harbour or bay eigenfrequencies (e.g. Šepić et al., 2009), being a favourable condition for the intense amplification of the arriving long ocean waves through harbour resonance. Those are the reasons why a large number of severe meteotsunami events were observed in the last several decades, and in more-than-one eastern Adriatic bay.

The last factor (v) suggests that the Adriatic meteotsunamis will be highly variable in space and time. Gravity waves and surface pressure oscillations usually dissipate over their wavelength scale. However, during a meteotsunami event, gravity waves can be fairly preserved over several wavelengths, presumably by maintaining their energy through either wave-duct (Lindzen and Tung, 1976; Monserrat and Thorpe, 1996) or wave-CISK mechanism (Belušić et al., 2007). The wave-duct mechanism stands for the propagation

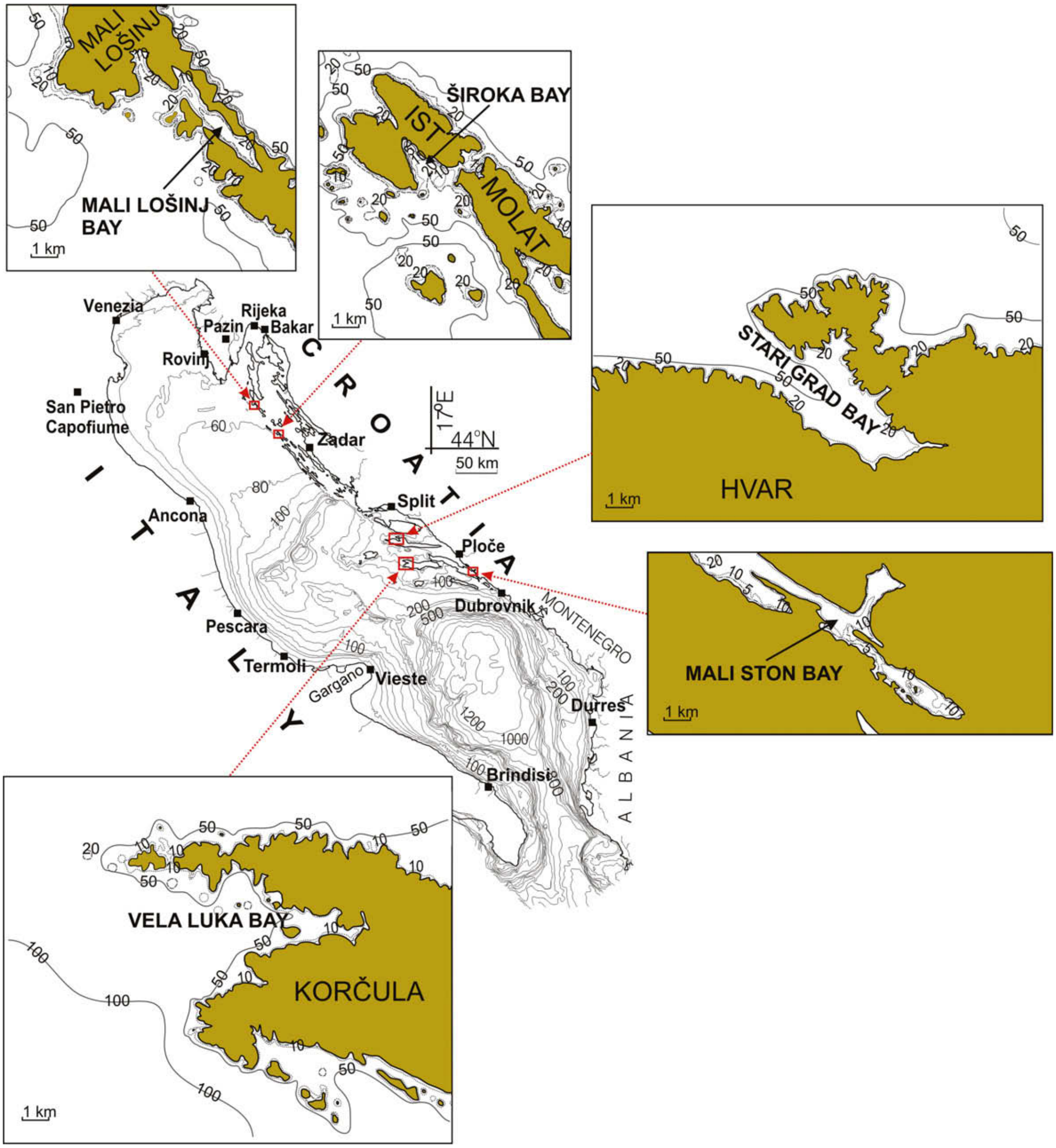

Fig. 1. A map of the Adriatic bathymetry with locations of the destructive Adriatic meteotsunamis indicated. Insets of Vela Luka, Stari Grad, Mali Ston, Ist and Mali Lošinj local bathymetries are also given. Depths are given in metres.

of the waves in a stable layer capped by a dynamically unstable steering layer, which prevents vertical energy leakage. The wave-CISK mechanism represents coupling between a gravity wave and convection: wave-associated convergence forces moist convection, and moist convection provides energy for the gravity wave. These waves are visible in surface air pressure series, constantly forcing the ocean during their passage over a certain area. If the speed of the gravity waves is equal to the speed of the long ocean waves, the latter are being constantly amplified on their way towards the coast (so-called Proudman resonance, Proudman, 1929). If the alongshore component of the atmospheric disturbance velocity equals to the phase speed of an edge wave generated along the coastlines, then the amplification of the long ocean waves is driven by so-called Greenspan resonance (Greenspan, 1956). Also, so-called shelf resonance (Rabinovich, 1993) has been documented to resonantly amplify the long ocean waves, being active when the atmospheric disturbance and generated long ocean waves have period or wavelength equal to the resonant period or wavelength of the shelf region. Finally, the generated long ocean waves hit the harbours, producing strong oscillations only if the corresponding inner basin has well-defined resonant properties and a large Q-factor (Rabinovich, 2009).

This paper will overview the present knowledge of the Adriatic meteotsunamis, from the assessment of the source mechanisms, followed by the resonant generation of the long ocean waves on the Adriatic shelf, towards the amplification of the meteotsunami waves in the coastal regions and harbours. A list of recent events will be given in the next section, preceding a summary of the scientific information derived from the published articles or available scientific resources applicable to the Adriatic meteotsunamis. The last section will discuss the present state-of-the-art and outline possible pathways for the future research both of the Adriatic meteotsunamis and meteotsunamis in general.

2. The list of recent Adriatic destructive meteotsunamis

A number of meteotsunami events were observed along the eastern Adriatic coast in the last several decades. The most astonishing event was the Great Flood of Vela Luka, which occurred in the morning hours of 21 June 1978, producing trough-to-crest waves of 6 m at the top of the harbour (Hodžić, 1979/1980; Orlić, 1980; Vučetić and Barčot, 2008). This event is listed even in a number of tsunami catalogues (e.g. Italian Tsunami Catalogue, Tinti et al., 2004; Maramai et al., 2007), where the source mechanism is marked as "unknown". The next significant meteotsunami occurred on 5 October 1984 on Ist Island (Šepić et al., 2009). Then, no severe meteotsunamis were recorded till 27 June 2003, when a particularly strong meteotsunami was observed in Stari Grad and Mali Ston Bays (Vilibić et al., 2004). In the latter bay, the generated currents severely damaged shellfish farms. The next event occurred on 22 August 2007, again on Ist Island (Šepić et al., 2009), followed by a flood at Mali Lošinj a year later (15 August 2008). The geographical locations of the affected bays are given in Fig. 1, accompanied by photographs of the events (Fig. 2).

2.1. The Vela Luka flood in 1978

In the early morning of 21 June 1978, around 4:15 UTC, the sea began to rise in the town of Vela Luka, overtopping the piers and flooding the houses at the sea front (Fig. 2a). The sea retreated rapidly several minutes later, emptying a large portion of the bay. Another meteotsunami wave hit the bay around 7:00 UTC, breaking the walls and reaching a height of about 3 m above the mean sea level. The flooding and ebbing of Vela Luka Bay continued till 10 UTC, when the sea finally retreated from the town streets and houses, leaving a vast amount of the waste, goods and oils floating in the bay and jamming most of the town (Fig 2a).

Human casualties were fortunately avoided, as the person on duty in the electrical company switched off the electricity in the whole town when the sea begun to flood the seafront. Moreover, the captain of the regular ferry line which connects the island with the city of Split, noticed unusual currents at the entrance of Vela Luka Bay and stopped there, preventing almost certain wreckage, as even larger ships (fortunately without any crew) sank inside the bay and the harbour.

A number of hypotheses were put forward at that time to explain the origin of the event. The blame was put on: (i) an earthquake that occurred in Greece, causing tsunami waves that were amplified in Vela Luka Bay (Zore-Armanda, 1979), (ii) a submarine landslide occurring somewhere on the south Adriatic shelf edge, and (iii) on the atmosphere, precisely on the middle-atmosphere jet and a cyclone, which generated long ocean waves that freely (Hodžić, 1986) of forcedly (Orlić, 1980) propagated towards the bay. The latter explanation was the closest to the reality, being also supplemented by the theoretical assessment of the Proudman resonance occurrence, while the first three explanations failed, mostly because the usual characteristics of the seismic and landslide tsunami waves were not observed during the event (see details in Vučetić et al., 2009).

2.2. Ist meteotsunamis in 1984 and 2007

Not so many records and materials are available on the meteotsunami that appeared in Široka Bay (Ist Island) on 5 October 1984. Eyewitnesses reported that a 4-m wave struck the island. However, no significant oscillations were measured by the operational tide gauges in the northern Adriatic (e.g. high-frequency oscillations at Rovinj were 5–7 cm in high only).

Another meteotsunami event happened in Široka Bay on 22 August 2007, when a 4-m wave (according to eyewitnesses a few cm lower than the one in 1984) hit the island in the afternoon hours. The oscillations with periods of around 10 min (according to eyewitnesses) lasted for an hour, having a peak around 15:30 UTC. One person was injured due to the panic induced by an incoming wave. Damage was reported in several houses and restaurants close to the seafront, including also an electricity breakdown on the island due to the flooding of the electrical installations. Fortunately, the regular ferry, which entered the harbour just at the time of the flood, escaped the wreckage at the last moment by retreating to the deeper sea, but a number of smaller boats and yachts were damaged during the flooding and ebbing of Široka Bay.

2.3. The middle Adriatic meteotsunami in 2003

Local newspapers and other media reported that "a giant tidal wave flushed all away" upon hitting Stari Grad and Mali Ston Bays on 27 June 2003 around 04:00 UTC and 5:30–07:00 UTC, respectively. In Stari Grad Bay, two meteotsunami waves were reported by eyewitnesses; the larger wave resulted in a flood height of 1.3 m above the ground. The maximum sea level height was marked at a number of houses in Stari Grad (Fig. 2b). That means (by adding ground height versus mean sea level) that the wave height was approximately 3.5 m. It is reported that "the mad sea" played with cars, garbage containers, tables and chairs, and damages were reported in the bars and restaurants, shops, tourist board offices, as well as on houses and street walls.

It is interesting to notice the sign "1830" on the house wall (Fig. 2b), which is (according to local people) an indicator of the maximum flood height during a similar event that occurred in that year.

Fig. 2. Photographs of the meteotsunamis occurring at (a) Vela Luka in 1978, (b) Stari Grad in 2003 (arrows denote the height of the first and the second wave; note also the indicator of the 1830 flood height), (c) Ist in 2007 (maximum wave height is marked), and (d) Mali Lošinj in 2008.

By contrast, the damage in Mali Ston Bay during the 2003 meteotsunami was not a result of strong sea level oscillations, but of severe currents at the bay constrictions (Vilibić et al., 2004). Strong turbulent currents swept out the shellfish farms over the 6 km long area, causing one MEuro damage and stopping shellfish production for a while. It can be noted that Mali Ston Bay is the most important area for production of the European flat oyster (*Ostrea edulis*) and Black mussel (*Mytilus galloprovincialis*) (e.g. Peharda et al., 2007).

2.4. The Mali Lošinj flood in 2008

A fresh severe meteotsunami event was witnessed in the town of Mali Lošinj, the largest town of the eastern Adriatic islands. Two metre high wave suddenly hit the town centre, flooding the sea front houses, cars and infrastructural objects, and also trying to push a large number of yachts over the piers (Fig. 2d). Fortunately, the flooding of the town was short-lived, and only one major wave was reported. At the same time tide gauge at Rovinj, located on the top of a small peninsula (that means no significant harbour/bay seiches can be observed there), recorded a sudden 40 cm wave with a period less than an hour, clearly depicting the arrival of long ocean waves generated by a resonant process over the open sea.

3. Meteotsunami characteristics

3.1. Synoptic background

Following the research studies which were undertaken for the Balearic Islands on "rissagas" (the local name for meteotsunamis, e.g. Gomis et al., 1993), one may expect that similar conditions over the Adriatic may be favourable for the generation of the Adriatic meteotsunamis, as similar general synoptic conditions may affect both areas (Jansà et al., 2007). Indeed, the conditions observed during the rissagas are often also observed during the Adriatic meteotsunamis, although not always, as it will be shown here.

Synoptic conditions favourable for the generation of the Balearic meteotsunamis are the following (Ramis and Jansà, 1983): (i) low-level Mediterranean air, with a weak surface depression west of the Balearic Islands, (ii) warm African air blowing strongly on 850-hPa level, with an inversion between this flow and the surface air, and (iii) poorly stable or even conditionally unstable layer between the African air and colder air in the upper levels, with a marked vertical wind shear across this layer (usually with a strong southwesterly wind blowing at the upper levels). Let us try to assess these conditions versus the Adriatic meteotsunamis.

Hodžić (1979/1980, 1986) assessed the synoptic conditions during the Vela Luka meteotsunami in 1978, connecting it to the cyclonic activity over the Mediterranean Sea. By analysing the charts based on the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis data, a weak surface depression may be seen over the Adriatic Sea (Fig. 3, but it can also be assessed from several Internet sites based on the reanalysis data, e.g. at http://www.wetterzentrale.de). At the same time a strong flow from the SW may be observed over the Adriatic at higher levels, ahead of a deep quasi-stationary depression over the western Mediterranean. Streamlines at 500 mb level show the maximum gradients just over the Adriatic, while a burst of African warm and dry air may be seen at 850-hPa level just southeast from the middle Adriatic and Vela Luka. Temperature gradients are quite strong at that level, depicting the strong thermal and moisture front that connected with two different air masses: (1) warm and dry African, and (2) colder and moister western Mediterranean air. Such a strong front is an efficient source of instabilities, which may be generated or additionally boosted by the orography, in particular of the Apennines. By analysing the sounding data from the Brindisi meteorological station, that being the closest operational sounding station at the time of the meteotsunami, vertical structure becomes apparent (Fig. 4a). The following relevant information is obtained from the soundings: (i) a stationary air mass was lying close

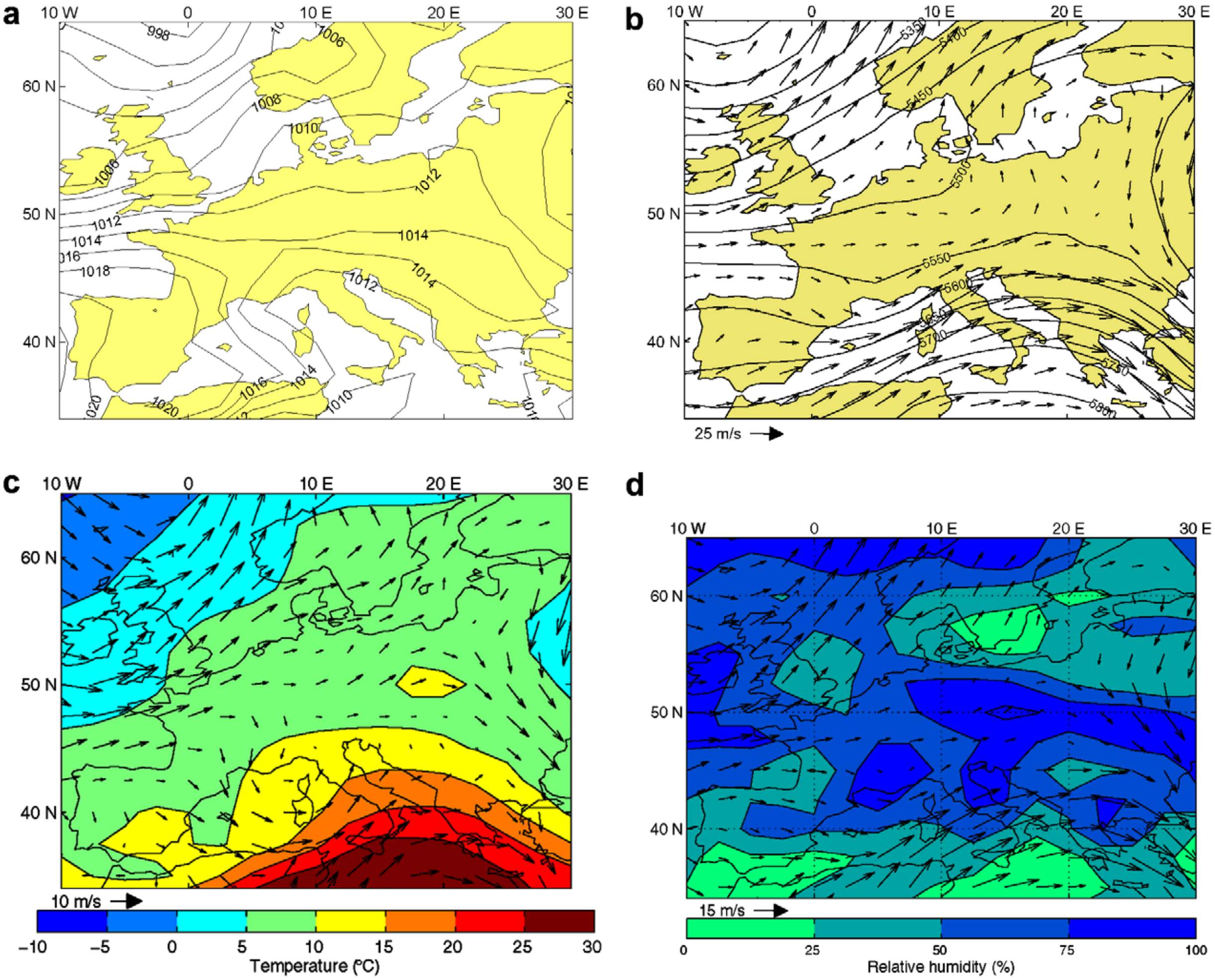

Fig. 3. General atmospheric conditions observed during the Vela Luka meteotsunami on 21 June 1978 at 00 UTC, including (a) mean sea level pressure, (b) 500 mb geopotential streamlines and winds, (c) 850 hPa winds and temperature, and (d) 700 hPa winds and relative humidity.

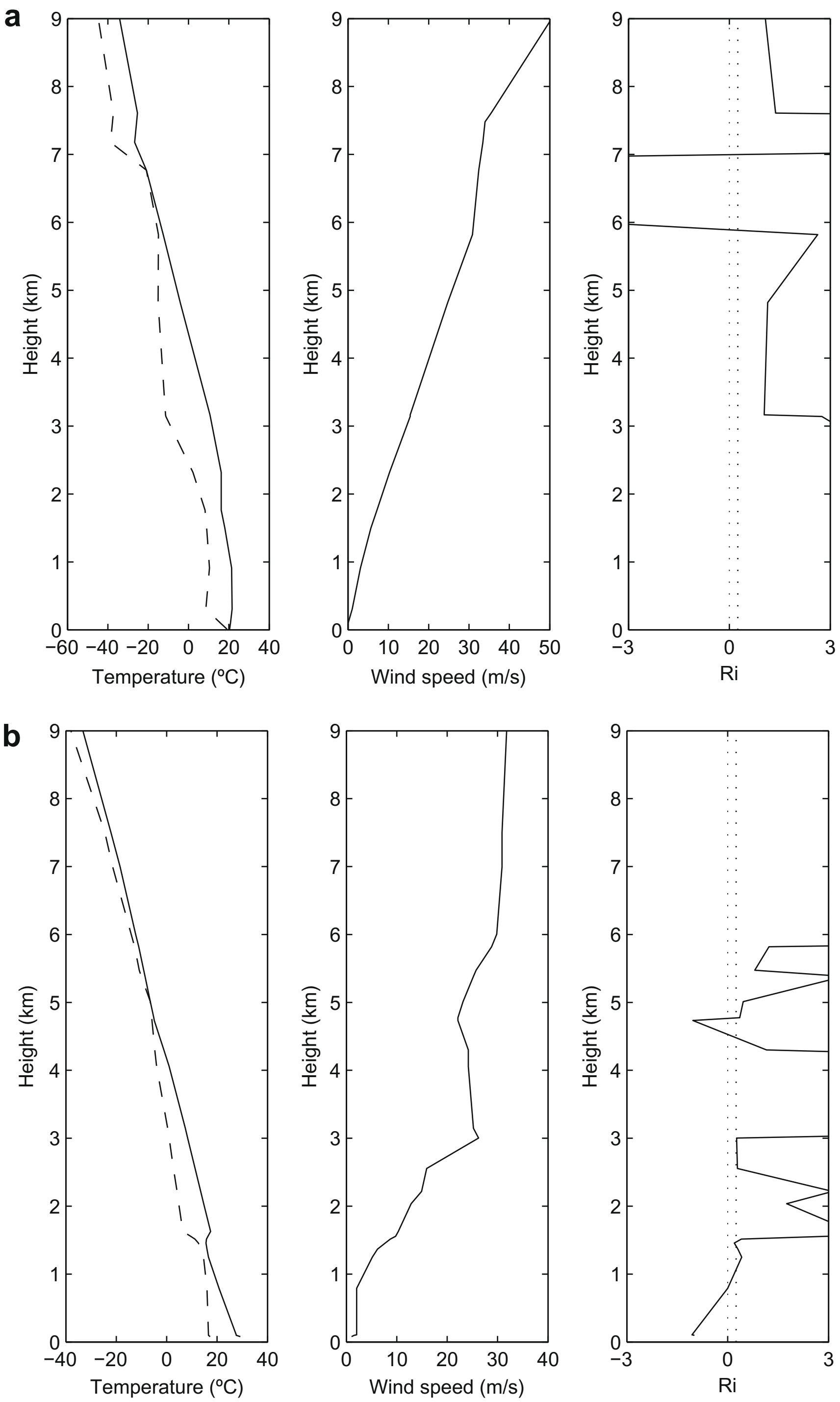

Fig. 4. Vertical atmosphere structure (air temperature – solid line – and dew point temperature – dashed line, wind speed and Richardson number Ri) obtained from radiosonde (a) during the Vela Luka meteotsunami in 1978 (Brindisi, 21 June 1978, 00 UTC), (b) the Ist meteotsunami in 2007 (Zadar, 22 August 2007, 12 UTC), and (c) the Mali Lošinj meteotsunami in 2008 (San Pietro Capofiume, 15 August 2008, 12 UTC).

to the surface (no winds reported on the surface), (ii) a temperature inversion was located a few hundreds metres to one kilometre above the surface, with the inflow from the SW of warm and dry African air, (iii) a very unstable layer was located at the heights between 6 and 7 km, with wind speeds of 32–39 m/s. Conclusively, the synoptic situation during the Vela Luka meteotsunami follows the conditions documented to be favourable for the generation of the Balearic meteotsunamis.

The next listed meteotsunami event on 5 October 1984 at Ist Island revealed similar synoptic conditions. The difference is in the position and direction of the flow at 500 mb level: here it was directed to the NNE, and the maximum geopotential gradients were stretched over the northern Adriatic (not shown). Some difference may be seen also in the surface pressure fields, as a deep (995 hPa) cyclone had a slow NE movement over western Europe, dragging the African air at its front side. Upper level (500-mb) winds were also slower (16–32 m/s as determined from the surrounding sounding stations) than those observed during the Vela Luka meteotsunami. Similar atmospheric conditions have again been observed during the 2007 Ist meteotsunami (Šepić et al., 2009),

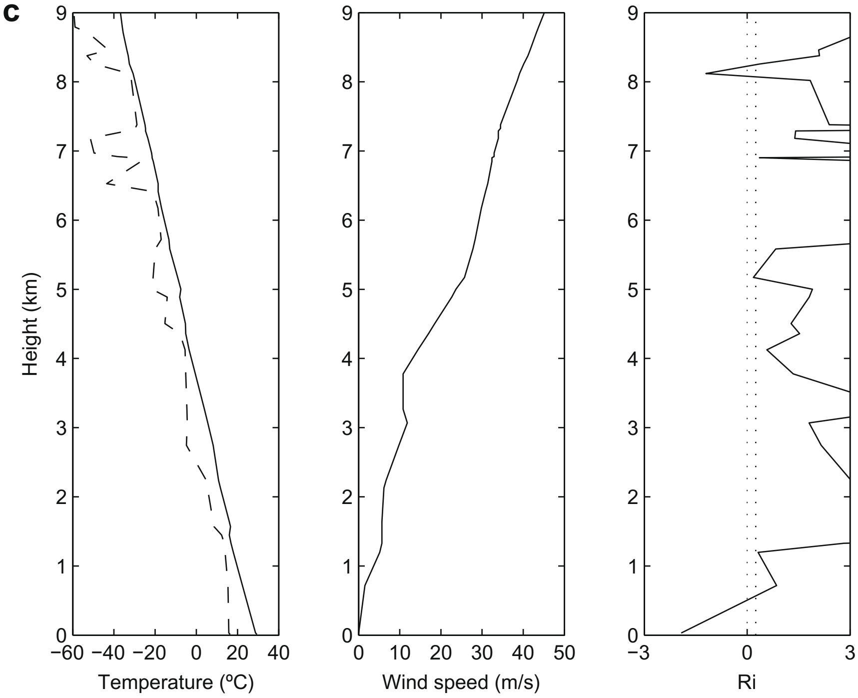

Fig. 4 (*continued*)

differing in the 500-mb wind which was lower (around 22 m/s, as observed at the Zadar sounding station; Fig. 4b) than during the 1984 event. But, again, 500-mb geopotential gradients, upper level moist gradients and 850-hPa temperature gradients were the strongest over the northern Adriatic, and quite stationary during a few days (not shown).

The synoptic scale circulation during the Mali Lošinj meteotsunami in 2008 was similar to the ones during the Ist and Vela Luka meteotsunamis. That means flow from the SSW-SW of 23–30 m/s between 5 and 7 km, large horizontal gradients of temperature at 850 hPa and of moisture at 700 hPa and above directed perpendicularly to the 500-mb streamlines (not shown). Also, a low pressure system moved over the northern Adriatic towards the NE, following a slow eastward movement of the planetary waves during a couple of days. The sounding at the nearest S. Pietro Capofiume station (Fig. 4c) again documents the vertical structure similar to the one observed during the Ist and Vela Luka meteotsunamis, with a weakly stable layer in the mid-troposphere and inflow of African warm air in the lower troposphere (inversion at about 1.5 km).

Finally, the synoptic situation during the middle Adriatic meteotsunami in 2003 was substantially different than during the other events. The orientation of the 500-mb geopotential isolines indicates flow from the WNW on 27 June 2003 over the Adriatic, with the mid-troposphere winds of 15 to 25 m/s. Other conditions were also not satisfied: (i) flow from the SW of the African air was stopped over Italy, where 850-mb temperature and 700-mb humidity gradients were directed WNW-ESE, indicating the front perpendicular to the one observed during other Adriatic meteotsunamis and (ii) there was no persisting unstable layer in the mid-troposphere. On top of the general synoptic conditions, the cold front reached the Alpine area from the northwest by 00 UTC 27 June. A strong mesoscale convective cell was generated over the northern Adriatic upon the passage of the front over the Alps. The convective cell was fed by a rather strong upward moisture flux driven by enhanced evaporation from the extremely warm Adriatic (26–27 °C, 3–4 °C warmer than the average, Grbec et al., 2007). More on the atmospheric processes observed during this meteotsunami event can be found in Hodžić (2004) and Belušić et al. (2007).

Let us conclude these analyses: (i) most of the Adriatic meteotsunamis are appearing during synoptic conditions similar to those observed and documented for the Balearic Islands rissagas, as listed in the second paragraph of this section, but (ii) the Adriatic meteotsunamis may also appear under synoptic conditions, which have not yet been reported for the Balearic Islands. Further phenomenology and physical background of these processes will be given in the following section.

3.2. Surface air pressure measurements and the physics of the source of meteotsunamis

Apart from general synoptic conditions favourable for generation of meteotsunamis, mesoscale dynamics is crucial for the “success” and strength of an event. As indicated in the Introduction, the generation of long ocean waves over limited regions (shelves and plateau with sizes up to a few hundred kilometres) may be efficient only if some resonant (Proudman, Greenspan, shelf) process occurs. A meteotsunami needs to feed its energy from a small-scale air pressure disturbance (gravity wave, pressure jump, frontal passage, squall line, etc.) propagating with certain speed and direction over the region. The process which largely prevents a widespread propagation of air-pressure disturbances is rapid dissipation of these mesoscale features on their travel over the region, except in some special atmospheric conditions. Two mechanisms were found to support long-distance propagation of atmospheric gravity waves: wave duct (Lindzen and Tung, 1976) and wave-CISK (Conditional Instability of the Second Kind, Powers and Reed, 1993). The first mechanism was found to be solely responsible for the Balearic rissaga events (e.g. Monserrat and Thorpe, 1992, 1996), while wave duct (Šepić et al., 2009) and wave-CISK (Belušić et al., 2007) were documented to be responsible for the 2007 Ist and 2003 middle Adriatic events, respectively.

If one of these mechanisms is present, then a disturbance can be preserved over a few hundred kilometres, and it may be captured by the surface air pressure measurements. However, to observe these disturbances one needs non-standard meteorological measurements on one minute timescale. This is a problem for the tracking of the Adriatic meteotsunamis since the Meteorological and Hydrological Service of the Republic of Croatia presently keeps the air pressure measurement resolution at 10 min, not sufficient to properly resolve the high-frequency pressure oscillations (e.g. Šepić et al., 2009). Fortunately, analogue air pressure charts are preserved at the most of the stations, and the high-resolution data may be extracted by careful digitisation. Fig. 5 displays these series obtained for the 2007 Ist meteotsunami, as well as the series measured at the location of the Split MedGLOSS tide gauge with a 2-min resolution during the 2003 middle Adriatic meteotsunami.

By examining the air pressure records observed during meteotsunami events, several important characteristics may be seen. First, the area affected by the travelling air pressure disturbance may be limited in some cases, and may encompass most of the Adriatic Sea in other cases. For example, the wave-CISK atmospheric wave during the 2007 middle Adriatic meteotsunami was generated over the Alps and travelled along the whole eastern Adriatic Sea (Belušić et al., 2007). Subsequently, the Proudman resonance and related long waves growth were likely to happen over a large part of the Adriatic, as the mesoscale convective cell and corresponding gravity wave passed over the Adriatic with a speed of 15–20 m/s, the former value in the early stage (northern Adriatic) and the latter in the mature stage (middle Adriatic, 22 m/s from the measurements, Vilibić et al., 2004). By contrast, the gravity wave responsible for the 2007 Ist meteotsunami was quite limited in its range, as seen both from the data and atmospheric mesoscale numerical simulations (Šepić et al., 2009). The atmospheric gravity wave was generated over the Apennines and crossed the Adriatic through a duct-layer capped by an unstable layer in the mid-troposphere. The gravity wave had a width less than 100 km. That is the reason why the related surface air pressure oscillations were recorded only at some of meteorological stations at the eastern Adriatic coast. The atmospheric disturbance has been modelled to have the maximum amplitude in the middle of its width, which passed over Ist Island (Šepić et al., 2009). Such a narrow width presumably provoked the strongest long ocean waves just over the major axis of the disturbance. Therefore, other bays and harbours prone to meteotsunamis, such as 30-km distant Mali Lošinj Bay, were only marginally hit by open sea waves. Moreover, the 2007 Ist meteotsunami was barely observed at the Rovinj tide gauge (130 km NW from Ist), on which high-frequency oscillations did not surpass 7 cm.

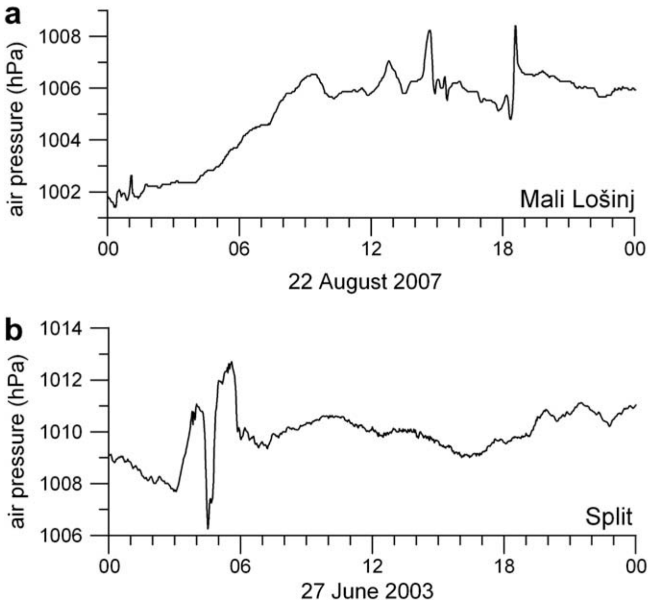

Fig. 5. Surface air pressure series measured during (a) the Ist meteotsunami in 2007 at Mali Lošinj, and (b) the middle Adriatic meteotsunami in 2003 at Split.

Similar low sea level oscillations were also measured at Rovinj during the 1984 Ist meteotsunami. Unfortunately, air pressure data during that event were of low quality and were therefore not appropriate for high-frequency analyses. Still, one may expect that characteristics of the atmospheric disturbance were similar to those observed during the 2007 meteotsunami, as the synoptic conditions were similar. By contrast, a preliminary analysis of the barograms collected during the 2008 Mali Lošinj meteotsunami suggests greater coverage and a larger width of the air pressure disturbance, being observed from the Zadar to the Pazin meteorological stations, and inducing sea level high-frequency oscillations of about 40 cm at the Rovinj tide gauge.

The next important issue, necessary to create destructive meteotsunami, is the speed and direction of the atmospheric disturbance. As said, the disturbance documented during the 2003 middle Adriatic meteotsunami came from the WNW, was parallel to the axes of the middle Adriatic channels and propagated with a speed of 22 m/s towards the entrance of Stari Grad and Mali Ston Bays (Vilibić et al., 2004). By contrast, atmospheric disturbances observed during the 1978 Vela Luka and 2007 Ist meteotsunamis were directed towards the NE (Orlić, 1980) or the ENE (Šepić et al., 2009), respectively. That is presumably a reason why no severe flooding in Stari Grad Bay occurred during the 1978 Vela Luka meteotsunami, although substantial sea level oscillations were measured in the whole region (e.g. at the Split and Dubrovnik tide gauges). In addition, a few moderate Adriatic meteotsunami events have been examined as well, and it seems that, during all of the events, air-pressure disturbances had a speed from 20 m/s (occurred over the middle Adriatic on 21 August 2004, Vilibić et al., 2005) to 24 m/s (occurred over the Rijeka and Bakar Bays on 19 August 2006, Šepić et al., 2008). In the next section we will explain why these speeds are favourable for the generation of the Adriatic meteotsunamis.

3.3. Generation and propagation of long ocean waves

Once a pronounced atmospheric disturbance is travelling over a shelf area, it generates long ocean waves through dynamical or resonant amplification. Proudman (1929) obtained an analytic solution for a situation in which the atmospheric disturbance is travelling over a channel of uniform depth (no friction has been included):

$$\zeta = \frac{1}{1 - U^2/c^2} f(x - Ut) - \frac{1}{2\left(1 - U^2/c^2\right)} f(x - ct) - \frac{1}{2(1 + U/c)} f(x + ct) \qquad (1)$$

where ζ is the sea level height, U is the speed of the atmospheric disturbance along the axis x in time t, while c is the speed of long ocean waves equal to $(gH)^{1/2}$ (g is gravity acceleration and H is ocean depth). It can be seen that fully resonant conditions happen when U equals c (then the last term is negligible). Also, both free and forced long ocean waves are generated, propagating towards the channel end. Both waves have also been found in numerical simulations in unbounded ocean (Vilibić, 2008), being controlled not only by a degree of resonance (U/c ratio) but also by the friction, Coriolis force and diffusion, as well as by nonlinearity.

Although this theory has been widely used in explanation of the generated meteotsunami ocean waves (e.g. Orlić, 1980; Vilibić and Mihanović, 2003; Vilibić et al., 2004, 2005), its existence has been confirmed only for the 2003 middle Adriatic meteotsunami (Fig. 6 of Vilibić et al., 2004; Vilibić, 2008). However, it seems that other resonances also contribute to the strength of the event, such as Greenspan resonance (Greenspan, 1956) which occurs near the islands and may enlarge the energy of long ocean waves there. Indeed the increased energy is found to occur close to the middle Adriatic islands' coasts (Vilibić and Beg Paklar, 2006). Also, there are some other possibilities which should be explored as a contributor to some meteotsunami events, such as shelf waves (shelf resonance, Rabinovich, 1993) which are for example found to be generated over the Strait of Sicily and then amplified inside the Sicilian and Maltese bays and harbours (Candela et al., 1999; Drago, 2008).

Let us try to assess the listed Adriatic meteotsunamis versus bathymetric characteristics of a particular area in front of the affected bays and harbours. The flood of Vela Luka in 1978 was not localised just in the hot spot areas, but strong sea level oscillations were reported in a number of the eastern middle and south Adriatic coastal towns and islands (Vučetić and Barčot, 2008). Even more interesting are the reports from the western Adriatic coast, where rapid sea level oscillations with the heights up to a metre were documented from Giulianova to Bari (Fig. 3 of Maramai et al., 2007). Those suggest that some other process besides the Proudman resonance was active in the area, either various shelf or topographic waves or reflection of the long ocean waves from the eastern shore.

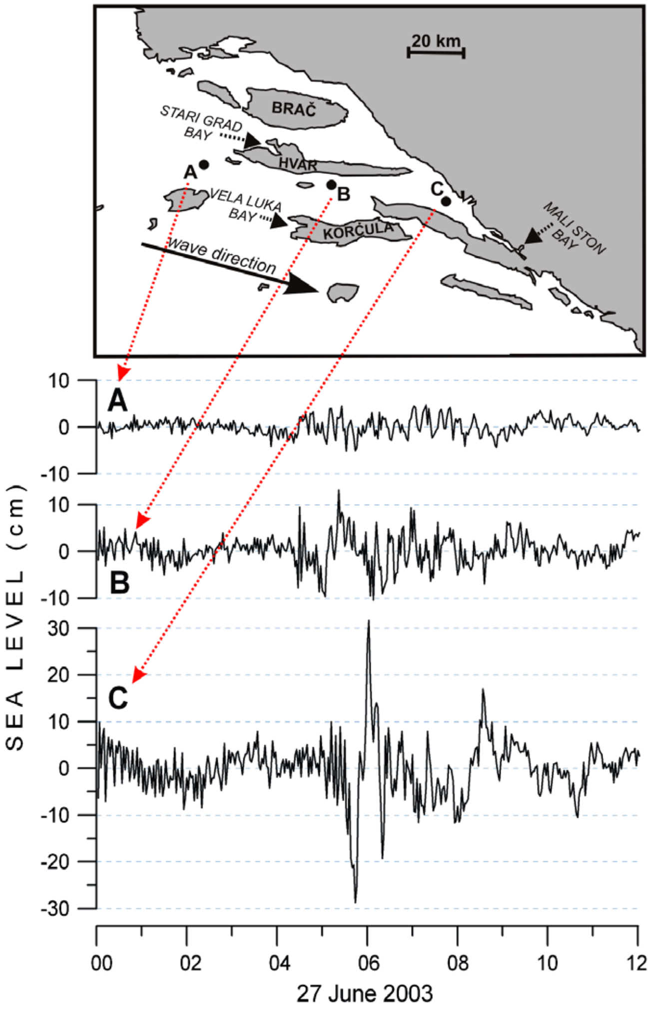

Fig. 6. Amplification of the sea level energy being a result of the travelling air pressure disturbance, as modelled for the middle Adriatic Sea (after Vilibić, 2008).

The "problem" with the explanation of the 1978 Vela Luka meteotsunami generation mechanism solely in terms of the Proudman resonance is that no wide shelf is placed SW from the bay, where the resonance is expected to occur. Instead a depth of 100 m is present already at the mouth of the Vela Luka Bay, decreasing towards 170 m at the deepest parts of the Palagruža Sill, and then again increasing towards the western shore. Orlić (1980) estimated the speed of the first atmospheric wave to be 22 m/s, which is equal to the resonant speed of the long ocean waves occurring over depths of about 50 m. This near-resonant amplification is expected to be an order of magnitude lower than the full-resonant amplification (e.g. at depths of 100 m and with the speed of atmospheric disturbance of 22 m/s, the Froude number $Fr = U/(gH)^{1/2}$ equals 0.7, see Fig. 2 in Vilibić, 2008). Consequently, if the estimates of the atmospheric disturbance speed and direction were correct some other resonant process than the Proudman resonance should be taken into consideration as a major contributor to the generation of the long ocean waves during the 1978 Vela Luka meteotsunami.

Nevertheless, one should be aware that the quality of the air pressure charts used by Orlić (1980) was quite low, and that only a first atmospheric disturbance was used for the estimation of the disturbance speed and direction. The estimated speed of 22 m/s is not in accordance with the ducted gravity wave theory (Lindzen and Tung, 1976), which is presumably responsible for the 1978 Vela Luka event as indicated through the assessment of synoptic conditions. Namely, the theory assumes that the speed of ducted wave is equal to the wind speed at the unstable reflecting layer, and the wind speed between 6 and 7 km (where the instabilities were the strongest, see Fig. 4a) was between 32 and 39 m/s (as seen from the nearest Brindisi sounding station). The latter speed values are indicating the resonant ocean conditions at depths between 100 and 150 m, and these depths are found in front of Vela Luka Bay. Therefore, the Proudman resonance may contribute significantly to the event, but still the fact remains that the topography across the Palagruža Sill (on which the resonance is supposed to occur) is highly variable, which may favour the generation of shelf or sill eigenmodes occurring at both sides of the Adriatic and being further amplified in the eastern Adriatic bays and harbours.

By contrast, we can give more credits to the hypothesis that the Ist and Mali Lošinj meteotsunamis are initiated through the Proudman resonance, as a wide northern Adriatic shelf encompasses the whole pathway of the atmospheric disturbances. The average width of the shelf SW of Ist and Mali Lošinj is around 200 km, with depth of 60–70 m off Ist and 50–60 m off Mali Lošinj. That implies the fully resonant conditions for the air-pressure disturbances travelling with speeds from 22 to 26 m/s. This has been satisfied for the 2007 Ist meteotsunami (21–24 m/s, Šepić et al., 2009). Although no modelling ocean studies have been performed to reproduce these two events, high-resolution (1-min) sea level series recorded at Rovinj during the 2008 Mali Lošinj meteotsunami support the idea of generation of long ocean waves through the Proudman resonance.

A simple approach developed by Hibiya and Kajiura (1982) may be used for estimation of the amplification rate through the Proudman resonance. The following equation is valid for the fully resonant conditions:

$$\zeta(t) = \frac{\zeta_0}{L}\frac{x_f}{2} \tag{2}$$

where ζ_0 is so-called static sea level (barometric effect only), L is the length of the disturbance and x_f is an along-track length of an area at which the Proudman resonance is occurring. Let us consider the Adriatic shelf SW from Ist favourable for the occurrence of the Proudman resonance ($x_f = 200$ km). The atmospheric disturbance provoking the 2007 Ist metotsunami propagated with a speed of 22 m/s and had an Eulerian air pressure change of 4 hPa/15 min (Šepić et al., 2009). The latter gives the disturbance length of 20 km, and the static sea level response ζ_0 of 4 hPa. Then the height of meteotsunami waves in front of Ist should had been 20 cm, twenty times lower than observed at the top of Široka Bay. Thus, it seems that the last stage of a meteotsunami, internal or harbour resonance, plays a crucial role in the destructiveness of the meteotsunami waves.

The only ocean numerical modelling meteotsunami study, which has been carried out in the Adriatic followed the 2003 middle Adriatic meteotsunami, and revealed various properties related to the generation of the meteotsunami waves. This numerical study successfully reproduced the event itself (Vilibić et al., 2004), through the forcing of ocean response by a travelling air pressure wave only. The atmospheric wave was extrapolated from 2-min series measured at one digital station, with the imposed speed and direction derived from the analogue air pressure records at a number of meteorological stations. An intensification of the long ocean wave has been achieved on its way towards the top of the basin (Fig. 6), where severe currents swept out the shellfish farms in Mali Ston Bay. As the area between the middle Adriatic islands is shallow, with depths decreasing from 80 m at its western edge towards 30 m in front of Mali Ston Bay, the Proudman resonance is likely to occur, being coupled with the atmospheric disturbance travelling towards the ESE with the speed of 22 m/s. Yet, the amplification near the coastline (both mainland and islands), especially when counting the average energy of high-frequency oscillations (Vilibić and Beg Paklar, 2006), indicates that more-than-one resonance occurs, contributing to the generation of long ocean waves. Also, multiple basin resonance driven by complex intra-basin topography between the middle Adriatic islands has been considered as an amplification mechanism for the generated long ocean waves (Vilibić, 2005). A careful study of all contributions to the generation of the long ocean waves in the middle Adriatic should be a focus of future research activities.

An additional moderate middle Adriatic event in 2004 enabled the extraction of another important property, listed in the Introduction as necessary for the generation of destructive meteotsunami. That is the energy content of the generated long ocean waves, which is relevant to the excitation of the bay and harbour eigenoscillations. Namely, a box-like atmospheric disturbance travelled over the middle Adriatic on 21 August, without producing any significant flooding in the area. Vilibić et al. (2005) modelled the generation of the long waves, and found that when compared to the 2003 event, the 2004 event had much lower energies at sub-hourly timescales but much higher energies at larger periods, including the eigenperiod of the whole middle Adriatic Sea (4 h). They related a part of these differences to the shape of the disturbance, plus the effect of the wind which blew strongly during the 2004 event, piling up the water inside the basin and triggering the fundamental mode oscillations. Also, the decrease of the disturbance spatial and temporal scales (e.g. the basic period of the cosine disturbance) results in the increased energies of sub-hour oscillations (Vilibić, 2005), revealing the importance of the pressure gradients (or pressure temporal changes, if assessing Eulerian series) to the strength of meteotsunami waves. A similar conclusion has been obtained when moderate meteotsunami waves measured at the Bakar tide gauge were assessed versus pressure gradients over the flat Rijeka Bay (Šepić et al., 2008), indicating that the higher is the pressure gradient the stronger are long ocean waves generated ahead of the affected bay or harbour.

3.4. Inundation and coastal amplification

A final ingredient, that makes the meteotsunami waves destructive, is the internal or harbour resonance in the affected bay which has a large amplification factor (Monserrat et al., 2006; Rabinovich, 2009). The matching of the energies is largely dependant on the energetic content of the atmospheric disturbance (e.g. Vilibić et al., 2005), but additional amplification may be achieved through resonant or near-resonant excitations of some external basin modes (Vilibić, 2005) or through the signal amplification when constraining the area (width and depth) of the meteotsunami waves flow. The amplification factors of the affected Adriatic harbours are not thoroughly examined, except for Stari Grad and Mali Ston Bays through the nested modelling study (Vilibić et al., 2004) and for Vela Luka Bay through idealised one dimensional modelling (Hodžić, 1986). Yet, a number of older but no less qualitative studies have been undertaken to determine and to model the eigenoscillations of a number of the Adriatic harbours and bays. For example Goldberg and Kempni (1938) measured and modelled the seiches of Bakar Bay, which may have a height of a metre during extreme atmospheric forcing.

It should be pointed out that the first analyses of the eigenoscillations in Vela Luka Bay were done a century ago (Sterneck, 1914), and that a tide gauge operated in Vela Luka at that time. This study revealed the fundamental period of the bay to be 37.8 min, while the inner part of the bay has its own seiche with period of 12.6 min. After the 1978 Vela Luka flood, a simple one-dimensional numerical model developed by Defant (1918) was applied to the Vela Luka Bay by Hodžić (1986), estimating the period of the bay to be about 14.5 min. Finally, recent measurements give the eigenperiods in the bay equal to 35.0, 25.3, 11.6 and 8.0 min (Orlić and Pasarić, 2008).

The periods measured at Stari Grad Bay are similar: 36.1, 24.8, 10.2 and 8.3 min (Orlić and Pasarić, 2008). As the destructive meteotsunami waves are not observed simultaneously during the listed episodes (some moderate waves appeared in Stari Grad during the Vela Luka meteotsunami and vice versa), it is obvious that the appearance of destructive meteotsunami waves was controlled also by some other factors, such as different orientations of the bay (in fact, the difference in the orientations is not large, around 40°), and the selective amplification of the incoming waves due to different bathymetric characteristics of the sea bottom in front off the affected bays. Furthermore, the difference may be in the underlying physics responsible for the generation of long ocean waves, as it was shown (in previous section) that the Proudman resonance was maybe not a major contributor to the generation of the long ocean waves during the 1978 Vela Luka meteotsunami, while it occurred during the 2003 middle Adriatic meteotsunami and flooding of Stari Grad. Moreover, one may say that the respective destructive meteotsunami waves in Vela Luka and Stari Grad Bays were related to different source mechanisms in the atmosphere, as the wave-duct mechanism presumably present during the Vela Luka meteotsunami was related to the atmospheric disturbances coming from the SW, bringing African air masses over the Adriatic, while the wave-CISK mechanism present during the 2003 middle Adriatic meteotsunami was related to the gravity wave generated over the Alps, then coming over the along-Adriatic track, from the NW or the WNW, and feeding the associated convective mesoscale cell with moisture.

The numerical modelling study of the affected bays was made by Vilibić et al. (2004), wherein both Stari Grad and Mali Ston Bays were nested with 50-m grid resolution within the major model domain. There are substantial differences in these two bays: Stari Grad is a funnel-shaped bay, with a narrow and long harbour at its end, while Mali Ston Bay has more complex topography, with a number of constrictions and sub-basins (see Fig. 1). Therefore, the amplification factor is substantially higher for Stari Grad Bay (up to 70), while it barely surpasses 10 in Mali Ston Bay, and only at some very high frequencies (Fig. 7). Knowing the modelled eigenmodes of the Stari Grad Bay (Vilibić et al., 2004), it can be seen that their amplification factor surpasses 25 at the very end of the bay. Thus, substantially larger sea level oscillations are modelled inside the inlet at the top of the basin than outside (Fig. 8), which increases the risk of flooding the town, as it is located at the inlet. By contrast, the amplification is not significant inside Mali Ston Bay, due to the constrictions present between outer area and sub-basins. However, these constrictions funnel the incoming meteotsunami waves, resulting in severe currents there (Fig. 9). Therefore, the risks connected with a single meteotsunami event in two different bays may be quite different: while in some bays the flooding may be predominantly responsible for the devastation, in other bays the currents may produce substantial damage (e.g. on shellfish farms during the 2003 middle Adriatic meteotsunami, or may influence the safety of navigation like in Ploče Harbour, Vilibić and Mihanović, 2005).

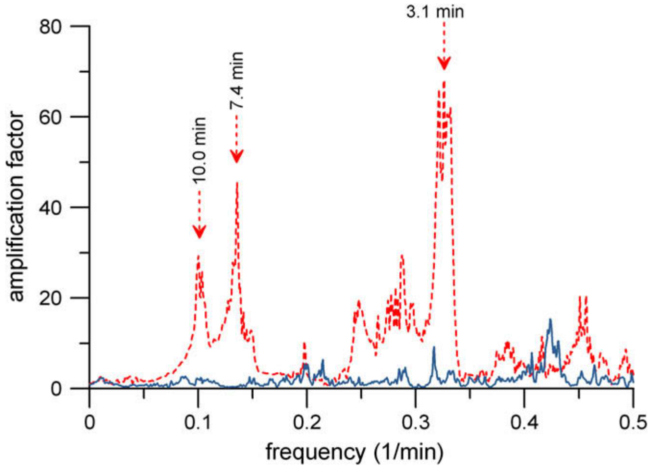

Fig. 7. Amplification factor between the top and the mouth of a basin obtained for different frequencies in Stari Grad (dashed line) and Mali Ston (full line) Bays, by using numerical modelling results from Vilibić et al. (2004). Periods of modelled eigenmodes of Stari Grad Bay are indicated with arrows.

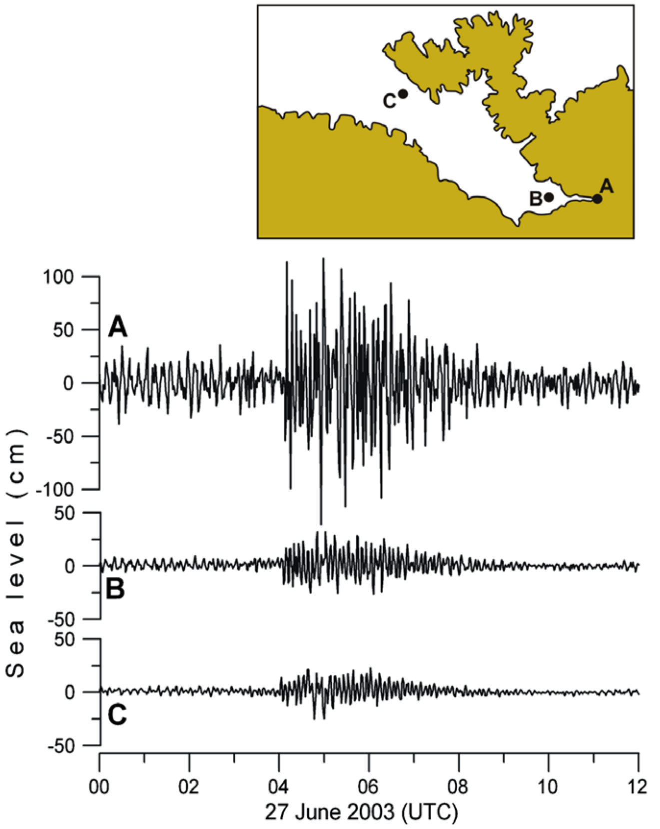

Fig. 8. Modelled sea level series during 27 June 2003 obtained for various locations inside Stari Grad Bay during the 2003 middle Adriatic meteotsunami (after Vilibić et al., 2004).

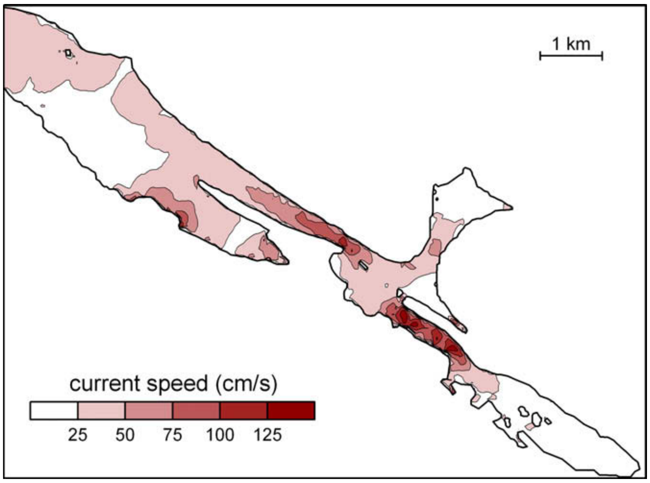

Fig. 9. Maximum currents modelled in Mali Ston bay during the 2003 middle Adriatic meteotsunami (after Vilibić et al., 2004).

The assessment of the amplification factor for two bays in the northern Adriatic attacked by meteotsunamis, Široka Bay on Ist Island and Mali Lošinj Bay, has still not been made. A preliminary estimation of the Široka Bay period was made by Šepić et al. (2009). By approximating it as a kind of semielliptic bay having a semiparaboloidal depth distribution, the fundamental period was found to be 10.5 min. Amplification factor studies have not been performed yet, but they are presumably as high as for Stari Grad Bay. The reason for that is (i) a uniform funnelling (shallowing and narrowing) from the mouth towards the top of Široka Bay, and (ii) a shallowing (but not narrowing) from the mouth towards the top of Mali Lošinj Bay, where a constriction at the mouth is located presumably enlarging the amplification inside the bay (the so-called "harbour paradox", Miles and Munk, 1961 – they concluded that narrowing the harbour entrance would increase the amplification of the arriving waves). The most populated areas in both bays are just at their top, where the largest amplification is expected and where the largest meteotsunami waves are occurring.

4. Discussion and recommendations

This paper overviews the present knowledge about the Adriatic meteotsunamis, based mostly on the research studies and assessment of all available information related to five documented Adriatic meteotsunami episodes, which occurred in: (1) Vela Luka Bay and the middle Adriatic on 21 June 1978, (2) Široka Bay (Ist Island) on 5 October 1984, (3) the middle Adriatic on 27 June 2003, (4) Široka Bay (Ist Island) on 22 August 2007, and (5) Mali Lošinj Bay on 15 August 2008. These events attracted local and national media as being quite unusual and unexpected, and resulted in a substantial damage and impact on the touristic, industrial and traffic areas in the eastern Adriatic region. Also, the damage, extent, unpredictability and the season of these events were substantially different to those of some other severe events such as storm surges, which may produce much larger damage overall since they affect wider regions of the northern Adriatic during autumn and winter (e.g. Zampato et al., 2007). However, one may pose a question even on the definition of a meteotsunami event, as the listed events may not be the only ones which occurred recently in the Adriatic Sea. For example, can the sea level recorded on 12 August 1960 (Fig. 10) be treated as a meteotsunami, although no flooding in Rovinj or elsewhere was reported on that day?

This problem when constructing such a definition is that about 99% of the background high-frequency oscillations are usually related to the atmospheric forcing. Therefore, one should be able to recognise the real meteotsunamis from the sea level data. Rabinovich and Monserrat (1996) selected a fixed sea level value as threshold for the Balearic meteotsunamis. Other suggestions came from Monserrat et al. (2006), proposing the use of a threshold based on sea level standard deviation, where an event in which wave height exceeds three or four standard deviations of sea level variability, should be considered a meteotsunami. Another approach may use percentiles as the threshold for entitling an event as a meteotsunami. However, how can one compute high-frequency sea level standard deviation (e.g. below the period of 3–4 h) if there are no one minute sea level data collected during a longer time period? That is a real problem for the Adriatic meteotsunami hot spots, as no long-term sea level measurements have been carried out in the most of the affected basins.

Therefore, a natural direction for the assessment of the characteristics of the Adriatic meteotsunamis is initiation of long-term high-frequency measurements at all sites where the destructive meteotsunamis happened in the past. The data collected after a few years will enable a proper definition of a meteotsunami event, with several thresholds being defined by the measurements (e.g. threshold for a meteotsunami, for a moderate event, and for a destructive event). These measurements should be accompanied by the process-oriented studies and measurements, which will enable the estimation of basin resonant properties (e.g. amplification factor in the bays and harbours) and may be used for verification of numerical models. Next, the vulnerability of a hot spot may be estimated, including the hazard and the risk for the humans and infrastructure, leading to development of mitigation measures for decreasing the risk in future events.

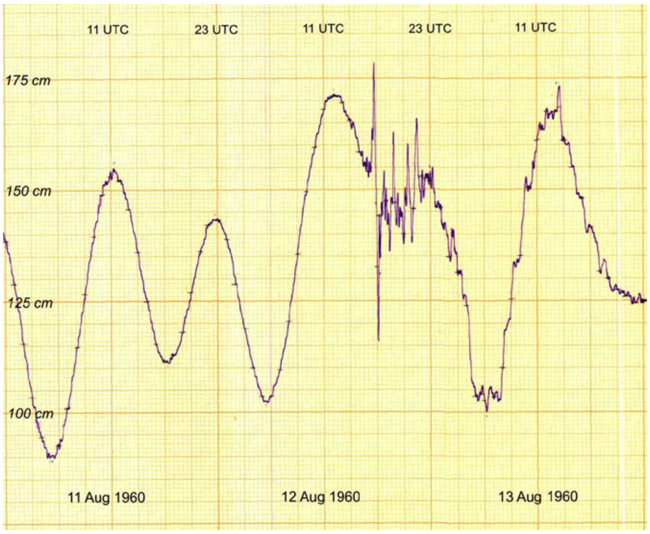

Fig. 10. Sea level curve recorded at the Rovinj tide gauge on 12 August 1960, visualising the high-frequency oscillations presumably related to meteotsunami waves.

Another direction of the Adriatic meteotsunami research is further assessment of the sources in the atmosphere, both through the initiation of widespread high-frequency air pressure measurements and through the better assessment of the general synoptic conditions favourable for the generation of meteotsunamis. The latter is partially done in this paper, but more studies should be performed and more events should be analysed before eventual application in operational meteorology and forecasting. These efforts should result in the forecast of the conditions which are favourable for the appearance of destructive meteotsunami. Such a forecast should also take into account different properties of various sub-basins and affected hot spots in the Adriatic. The forecasts should advise potentially affected populations about the level of the meteotsunami risk. This forecast may be done well in advance (a few days) through the assessment of the forecasted weather charts and their overlapping with the meteotsunami favourable conditions. Similar meteotsunami warning has been operational for the Balearic rissagas for more than 20 years, being established after the 1984 destructive meteotsunami (Jansà et al., 2007). It is possible to forecast the appearance of a rissaga by using such an approach but not necessarily the strength of a rissaga, as the latter is highly dependable not only on the synoptic conditions but on a specific atmospheric disturbance, its strength and dispersiveness. The example is the 2006 destructive rissaga, where the advisory for the rissaga-favourable conditions was issued a day before, but without warning on destructiveness (and this event was the most destructive in the last 20 years, ending with damage of several tens of MEuro, Vilibić et al., 2008).

Apart from the assessment and forecasting of synoptic conditions, the meteotsunami research should include high-resolution air pressure measurements (sampling interval 1 min or lower) at a number of microbarograph stations close to the affected areas. In fact, at least three stations should be distributed in a triangle in order to estimate properly the speed and the direction of an atmospheric disturbance (Monserrat and Thorpe, 1992). These measurements are necessary for the assessment of meteotsunami generation potential on the spatial and temporal scales of the process; i.e., for the assessment of the gravity waves and various atmospheric disturbances capable of provoking meteotsunami. The gravity waves and atmospheric disturbances are highly variable both in space and time, with a spatial scale of a few hundred kilometres at the most. For example, the 2007 Ist meteotsunami was presumably generated by an atmospheric disturbance travelling perpendicularly to the Adriatic (over the area not longer than 250 km) and being as wide as 100 km at the most.

Along with the monitoring of the ocean component of a meteotsunami, the measurements of high-frequency air pressure data should be carried out at the hot spots on a long-term basis. Such measurements will allow for the research and assessment of several meteotsunami events, as low or moderate events are presumably occurring over shorter time scales than the most destructive ones. The next step will be the development of a real-time monitoring and warning meteotsunami system, based on the real-time air pressure data collected from microbarograph stations situated a few tens of km to the SW or W of the affected area, where the disturbance is expected to appear a half an hour before hitting the affected bays or harbours. From a meteorological perspective, the tracking of convective clouds in real time may also be used for detecting the favourable conditions for a meteotsunami (Belušić and Strelec-Mahović, 2009).

The last issue to be discussed in meteotsunami hazard assessment activities is the use of both atmospheric and oceanic numerical models in both research, and warning and advisory activities. There are a number of unresolved issues in the Adriatic meteotsunami research, such as (i) why the direction of incoming atmospheric disturbance and generated long ocean waves was perpendicular to the axes of Široka Bay (Ist Island) and Mali Lošinj Bay – was this related to the reflection/refraction of the meteotsunami waves?, (ii) what was the origin of the Vela Luka meteotsunamis – Proudman resonance vs. Palagruža Strait modes vs. shelf resonance or other?, (iii) does the Greenspan resonance occur around the middle Adriatic islands?, (iv) is there any connection between the Adriatic, Balearic, Sicily and Malta, Greek or any other Mediterranean meteotsunamis. All of these issues should use either ocean or atmospheric numerical models or both. However, the usefulness of the modelling is dependant of the ability of the models to reproduce the processes listed, and that implies the bathymetries should have resolutions of up to 10 m inside the harbours/bays. Even this resolution may be unsatisfactorily when assessing meteotsunamis in long and narrow inlets, such as Ciutadella Inlet (Vilibić et al., 2008). Similar problem may be found in seismic and landslide tsunami research. For example, Choi et al. (2008) state that "for the computation of the tsunami run up and inundation, the bathymetry generally requires an extremely fine grid mesh of <5–10 m in order to achieve results that can be used in a practical way". Conclusively, the bathymetries of the affected bays should be significantly improved and charted, in order to obtain a fair reproduction of a meteotsunami event.

In summary, the present knowledge on the Adriatic meteotsunamis has been significantly improved in the last 5 years, most of the research being initiated after the 2003 event and followed up by two recent (2007 and 2008) events. It may be speculated that the number of the Adriatic meteotsunamis will increase in the future due to the increased thermal energy in the atmosphere which feeds the instabilities and favours the severity of a mesoscale event (Beniston et al., 2007). On the other hand, one cannot form any conclusion without long-term and continuous monitoring on the process scale. However, one conclusion may certainly be made: substantial funding should be provided for the proper investigations, *in sit*u measurements and construction of a future meteotsunami warning system. This may be done through the national and regional funding possibilities, but also through the inclusion of a meteotsunami research in the European- or world-wide projects and general programmes on tsunami-related research and activities.

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