Real-time procedure for detection of a meteotsunami within an early tsunami warning system

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Article Info

Article history:
Received 20 January 2009
Accepted 24 August 2009
Available online 28 August 2009

Keywords:
Meteotsunami
Tsunami warning system
Meteotsunami detection algorithm
Adriatic Sea
Ciutadella

A B S T R A C T

A meteotsunami detection algorithm, based on real-time measurements of air pressure, was developed and tested. The algorithm consists of two modules: the first module detects potentially dangerous air pressure disturbances with tendencies exceeding a certain threshold value; the second module determines the speed and direction of propagation of those disturbances. The algorithm was tested on artificial and measured air pressure time series from three Mediterranean meteotsunami hot-spots (the Balearic Islands, the northern Adriatic, the middle Adriatic). Functionality, rapidity and reliability of two methods for determination of the air pressure disturbance’s propagation speed and direction, the isochronal analysis method and the pressure tendency method, were tested. Both methods work acceptably well, and the detection algorithm is generally able to detect potentially dangerous air pressure disturbances and to determine their speed and direction of propagation.

1. Introduction

Real-time detection and assessment of a signal is crucial for the mitigation activities during severe and rapid ocean processes, which may affect and attack coastal areas on a minute or an hourly scale. There are ocean processes, such as storm surges, which may be detected and forecast several hours or days ahead, but uncertainty in forecasting their magnitudes still remains (Zampato et al., 2007). Contrary to that, the appearance of some ocean processes, such as tsunamis, cannot be foreseen as their source (tsunamigenic earthquakes) cannot be forecast. Thus the mitigation of a tsunami hazard is primarily based on operational tsunami warning systems, such as the Pacific Tsunami Warning System (e.g. Meinig et al., 2005).

Within the warning system, a danger is first detected from seismic data and then confirmed or extended by tide-gauge data and more importantly by data from Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys. Sea pressure which is measured within DART is processed instantaneously and, when a tsunami is detected, the communication channel to the tsunami warning centre is activated. The reality of an alarm is then estimated in the tsunami warning centre, and if necessary a warning is issued for the coastal population. These measurements have recently been assimilated in the operational numerical models, and the real-time modelling forecasts have become useful in the ocean-scale simulations (Bernard et al., 2006).

Apart from the robust measuring and communication equipment, adapted to the deep moorings exposed to open water conditions, an essential piece in such a system is a detection procedure, which should be able to recognize a tsunami from the measurements. But this procedure should detect only a tsunami and not other similar processes, which may lead to false alarms. Moifeld (1997) documents a cubic polynomial fitting approach for a prediction of disturbing wave patterns, being operationally used within the DART system. The predictions are updated every sampling interval (15 s), raising an alarm to the warning centre when an anomaly is detected. A more modern approach may use an artificial neural network which allows a detecting system to learn and upgrade itself (Beltrami, 2008).

Some tsunamis such as meteotsunamis (atmospherically induced long ocean waves in a tsunami frequency band), may be assessed through additional atmospheric measurements, as they are generated through multiresonant processes by distinct atmospheric disturbances which propagate over a coastal region (Monserrat et al., 2006).

Although just a few percent of worldwide tsunamis are classified as meteotsunamis, they may be frequent in some specific places and basins. A list includes the Balearic Islands (Gomis et al., 1993), the eastern Adriatic Sea (Vilibić et al., 2004) and many other places in the Mediterranean and the World Ocean (Monserrat et al., 2006). During some extreme meteotsunamis there may even be human casualties (Donn and Ewing, 1956; Hibiya and
Due to their similarities, meteotsunamis are often mistaken for ordinary tsunamis. For example, it seems that the Great Adriatic flood of 21 June 1978 (Vučetić et al., 2009), being the second strongest of all catalogued Adriatic tsunamis (four at Sieberg-Ambraseys tsunami intensity scale, Tinti et al., 2004), was in fact generated by travelling atmospheric waves visible in surface air pressure time series, and may be classified as a meteotsunami. This meteotsunami produced a loss of about 7 million US dollars (as estimated in 1978), but other meteotsunamis may also result in a MEuro damage, as was the case with the 2006 Balearic rissaga (local Catalan name for meteotsunamis, Jansà et al., 2007) or the 2003 middle Adriatic meteotsunami (Vilibić et al., 2004).

The source of a meteotsunami is an atmospheric pressure disturbance, which can be associated to a travelling gravity wave, pressure jump, frontal passage, squall line, etc. A pressure disturbance may be detected by a microbarograph network as a rapid change in air pressure travelling over a region (examples are given in Fig. 1). Several conditions should be fulfilled in order for a destructive meteotsunami to happen (Monserrat et al., 2006): (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 atmospheric disturbance towards the harbour or bay entrance, (iv) external resonance between the atmospheric disturbance and ocean waves, and (v) internal resonance between the arriving ocean waves and the harbour or bay eigenmodes. While the conditions (i) and (v) are given by topography, the other required conditions are related to the atmospheric disturbance and may be assessed by a network of precise high-resolution air pressure measurements. The condition (ii) may be assessed by measuring temporal air pressure changes on a measuring network and assessing the strength of changes through a threshold-exceeding procedure, while the conditions (iii) and (iv) may be assessed by a rapid estimation of the disturbance’s propagation speed and direction by one of the documented algorithms (e.g. Orlić, 1980; Monserrat and Thorpe, 1992; Vilibić et al., 2008).

The motivation for this paper came from the fact that no meteotsunami warning system has been established in the World Ocean. Only for the Balearic Islands are meteotsunami advisories regularly issued. These advisories are based on the assessment of synoptic conditions which are similar during severe rissagas (Jansà et al., 2007). However, such a system cannot forecast the strength of an event - an example is the 2006 rissaga, for which a warning was issued one day ahead, but no information on the strength of the event was given (Jansà et al., 2007). The 2006 rissaga was the strongest in the last two decades and produced damage of several tens of MEuro.

Herein we will present a meteotsunami detection algorithm which may be used in a meteotsunami detection network comprised of high-resolution microbarographs. We will focus on two methods for determination of speed and angle of air pressure disturbances and compare their functionality, rapidity and reliability. Synthesized and measured air pressure series will be tested. Final comments and recommendations on future use of the developed procedure will be discussed in the last section.

2. Proposed detection approach and test regions

2.1. Meteotsunami detection algorithm

The meteotsunami detection algorithm applied over a network of microbarograph stations consists of three consecutively activated major modules: (i) the first module is designed to detect small scale atmospheric disturbances having a potential to produce a meteotsunami, (ii) the second module estimates the speed and direction of such meteotsunami-generating disturbances, and (iii) the third, yet to be developed, module assesses the level of threat and raises an alarm to potentially affected area.

2.1.1. Detection of a threshold-exceeding air pressure tendency – the first module

After the 1979 destructive meteotsunami in Nagasaki Bay, Japan, Hibiya and Kajiura (1982) have found that the amplification of long ocean waves versus an atmospheric disturbance is proportional to the spatial gradient and tendency of an air pressure disturbance, and to the length of a pathway over which meteotsunami waves are being generated. The second condition...
is defined by the bathymetry of an area, while the first condition may be estimated from the air pressure measurements.

The first module of a meteotsunami detection algorithm determines pressure tendencies \( PT = \frac{\Delta p}{\Delta t} \), which may be defined over a certain period of time (e.g. over 10 min). Air pressure tendencies are computed by subtracting the last measured air pressure value from the value measured before \( (\Delta t) \) the prescribed time. If the pressure tendency is exceeding the prescribed threshold value \( (PT_{max}) \) at a minimum of three stations in a triangle (or over the whole network), then the event is marked as potentially dangerous and the execution of the second module starts.

### 2.1.2. Estimation of the disturbance speed and propagation direction – the second module

Once an air pressure disturbance with a threshold-exceeding pressure tendency \( (PT > PT_{max}) \) is detected over the network, the disturbance’s speed and direction of propagation are computed within a second module. Two methods for determination of the disturbance’s speed and direction will be tested in this paper: (i) the isochronal analysis method (IAM), introduced by Orlić (1980) during the study of the 1978 Vela Luka meteotsunami, and (ii) the simplified version of the pressure tendency method (PTM), developed by Vilibić et al. (2008) during the study of the 2006 Balaric meteotsunami. Both methods are described in detail in the Appendix A, but can be also found in papers by Šepić et al. (2009) and Vilibić et al. (2008). The performances of these two methods in respect to their use in a real-time warning system will be assessed, including the processing time and estimation of the speed and direction errors.

### 2.1.3. Meteotsunami decision matrix – the third module

After the execution of the second module, the speed and direction of a potentially dangerous air pressure disturbance are known. The final module should compare these values with the ones defined in a meteotsunami decision matrix and issue a warning if favourable conditions for a potentially dangerous meteotsunami are satisfied. A similar decision matrix is developed and operational in the tsunami warning system (ICG-NEAMTWS, 2008).

An elementary meteotsunami decision matrix could be based on the bathymetry of a meteotsunami prone area and literature references solely. Namely, for a meteotsunami to occur, an air pressure disturbance should propagate: (i) above the open sea with the speed equal to the speed of barotropic ocean waves \( c = \sqrt{gh} \), where \( g \) is the gravity acceleration and \( h \) is the local depth, and (ii) towards the entrance of the harbour or bay. Thus, for example, to provoke a meteotsunami in the northern Adriatic harbours or bays which are opened to the south-west, an air pressure disturbance should propagate with speeds between 20 and 26 m/s towards the north-east over the 40–70 m shelf depths of the northern Adriatic. Critical pressure tendency could be deduced from the literature references for that area or some similar area.

However, such a basic matrix in not enough and would probably result in numerous false alarms. Meteotsunamis are highly localised processes strongly dependent on both the bathymetry of the affected area (open sea and stricken bay) and on properties of air pressure disturbances. Two well researched middle Adriatic meteotsunamis, the 1978 Vela Luka bay meteotsunami and the 2003 Stari Grad bay meteotsunami, caused major damage in only one of those two bays, distanced by only 30 km, while in the other, no damage was reported (Vilibić et al., 2004). This was presumably due to different directions of propagation of the air pressure disturbances and different bathymetries in front of the bays and in the bays.

Thus, to construct a truly efficient meteotsunami warning matrix, simultaneous long-term measurements of air pressure and sea level for any potentially endangered harbour are needed. Air pressure should be measured at a minimum of three stations in front of the harbour and sea level should ideally be measured at the open sea and in the harbour itself. In that way, sea level oscillations of certain amplitude (both in the open sea and in the harbour) could be associated with a certain range of air pressure disturbance’s tendencies, speeds and directions of propagation, and hopefully a timely and reliable warning could be issued for a specific bay or harbour.

As, for the moment, we have no simultaneous air pressure and sea level measurements long enough to construct a meteotsunami decision matrix, we will focus on the first two modules of the meteotsunami decision algorithm in this paper. High-resolution air pressure data, measured or synthesized on microbarograph networks spread over three regions (the middle Adriatic, the northern Adriatic, the Balaric Islands) in which destructive meteotsunamis are known to happen, will be used to test the detection algorithm.

### 2.2. Synthesised air pressure series

The first studied region encompasses the middle Adriatic (Fig. 2), known for several destructive meteotsunamis: the 1978 Vela Luka flood (Orlić, 1980) and the 2003 middle Adriatic meteotsunami (Vilibić et al., 2004). However, no high-resolution air pressure data measured at three microbarograph stations is available over the area (air pressure time series from at least three stations are needed for determination of speed and angle of propagation of an air pressure disturbance), so the detection algorithm will be tested using an artificial network consisting of 5 measuring sites (Palagruža – PA, Svetac – SV, Vis – VI, Stari Grad – SG and Vela Luka – VL). These stations are also chosen because: (i) as of 2009 a meteotsunami research network consisting of three stations (SG, VL, VI) will become operational at the area (www.izor.hr/barograf); and (ii) the proposed Adriatic meteotsunami warning and research network would include all of the mentioned stations (Dadić and Vilibić, 2008).

Air pressure series will be constructed with 15 s resolution, by imposing a cosine signal with an amplitude of 3.5 hPa and a period of 10 min within the constant air pressure values. The signal is assumed to propagate over the network with a certain constant speed \( C (22 \text{ m/s}) \) and direction \( \alpha (32°) \), as documented for the 1978 Vela Luka flood (Orlić, 1980). A time lag \( t_{i+1} \) of the air pressure disturbance on a station \((i + 1)\) compared to a station \((i)\) is given by:

\[
 t_{i+1} = \frac{1}{C} (\Delta d_x i+1 \sin x + \Delta d_y i+1 \cos x),
\]

where \( \Delta d_x i+1 \) and \( \Delta d_y i+1 \) are distances between the stations \(i\) and \((i + 1)\) in the west–east and the south–north direction, respectively. Thus, if given at the first station, air pressure time series can be reproduced on all other stations. A maximum speed variation of \( \pm 3 \text{ m/s} \) and a maximum propagation direction variation of \( \pm 5° \) will be embedded randomly into the signal, in order to simulate uncertainties introduced by real measurements, signal deformations and eventual instrumental errors. The construction of the artificial air pressure series over the network will be repeated 600 times, first with randomly introduced speed variations (200 runs), then with randomly introduced direction variations (200 runs) and finally with randomly introduced speed and direction variations (200 runs) (Monte Carlo approach). The testing of the detection algorithm will be repeated over all runs.

Artificial time series from all the stations will be used in the IAM, and artificial time series from three triangles of stations (PA–SV–SG, PA–SV–VL and PA–VI–VL) will be used in the PTM. In the latter case, determined propagation speed and direction will
be calculated as mean values of speeds and directions determined for three triangles.

### 2.3. Air pressure series measured during meteotsunami events

Two meteotsunami events have been studied by analysing high-resolution air pressure time series: (i) the 2007 Ist destructive meteotsunami (Šepić et al., 2009), and (ii) the two 1997 moderate Balearic meteotsunamis (Vilibić et al., 2008). The Ist event which occurred on 22 August 2007 was captured by a network of microbarographs spread over the northern Adriatic (Fig. 2), having temporal resolution of 2 min. The Balearic moderate events which occurred on 8 June and 22–24 July 1997, were assessed by a triangle of microbarographs (maximum distance between microbarographs was 3 km) set up on Menorca Island (MB2, MB3 and MB4), being a part of the LAST-97 experiment (Monserrat et al., 1998). Temporal resolution of these measurements was 30 s.

### 3. Testing the detection algorithm on artificial time series

We tested the IAM and the PTM on artificial air pressure time series imposed on five middle Adriatic stations (SG, VL, VI, SV and PA).

In the first run of the detection algorithm, a disturbance propagating with a constant shape, speed (22 m/s) and direction (32°) was assumed. Expectedly, both the IAM and the PTM gave true values of the speed and direction of the propagation.

#### 3.1. Sensitivity to the speed variation

For the first 200 runs a speed error was randomly introduced to the artificial time series. A disturbance was allowed to propagate with a certain speed between one pair of stations \( i \) and \( i + 1 \) and with a different speed between another pair of stations \( i + 1 \) and \( i + 2 \). A speed variation was imposed as a function of distance between two stations; the greater the distance, the greater the allowed speed variation. The maximum speed variation was set to be ±3 m/s. A disturbance was synthesized to propagate with the given speed \( C (22 \text{ m/s}) \) and angle \( a (32°) \) between the first and the second station; and with the speed \( C_{i,i+1} \) \( (i > 2) \) between other pairs of stations:

\[
C_{i,i+1} = C_{i,j} \pm D_{i,j} \cdot \frac{3}{D_{\text{max}}} \cdot \text{rand}(-1, 1),
\]

\[
D_{i,j} = \delta_{i,j} \cdot \cos(a_{i,j} - \pi).
\]

Here, \( D_{i,j} \) is a length of the path that the disturbance has to cross between two stations \( i \) and \( i + 1 \), \( \delta_{i,j} \) is the distance and \( \cos(a_{i,j} - \pi) \) is the angle between the two stations \( i \) and \( i + 1 \), and \( D_{\text{max}} \) is a maximum of all \( D_{i,j} \).

Further on, the speed and angle errors \( (E_C \ and \ E_a) \) were calculated as:
\[ E_C = C_{co} - C_{in}. \]  
\[ E_x = x_{co} - x_{in}. \]

Here, \( C_{co} \) and \( x_{co} \) are the computed speed and angle; and \( C_{in} \) and \( x_{in} \) initial speed and angle (22 m/s and 32°). Evolution of the speed and direction errors is shown in Fig. 3. For both methods, the mean value of the absolute speed error was less than 0.2 m/s and the mean value of the absolute angle error was less than 0.2°; a quite satisfactory result. Maximum errors were somewhat higher in the IAM than in the PTM (1.2 m/s vs. 0.9 m/s, and 2° vs. 1.7°). Standard deviation of the speed error was 0.5 m/s for both methods, and standard deviation of the angle error was 0.7° for both methods. Finally, error curves for both methods fitted each other (Fig. 3), thus showing that both methods give similar results.

3.2. Sensitivity to the angle variation

The following 200 runs had a randomly introduced angle variation. The angle variation was introduced in the same way as the speed variation in the runs with a variable speed. The maximum angle variation was set to be 5°. A disturbance was propagating with the given speed (22 m/s) and angle (32°) between the first and the second station; and with an angle \( \alpha_{i,i+1} (i \geq 2) \) between other pairs of stations:

\[ \alpha_{i,i+1} = \alpha_{i-1,i} \pm \frac{5}{D_{\max}} \text{rand}(-1,1). \]

In both methods for determination of the speed and angle of propagation, the mean value of the absolute speed error was less than 0.3 m/s and the mean value of the absolute angle error was less than 0.3°; a result quite similar to the one obtained in the runs with the varying speed. However, individual errors showed more variation in these runs, which for the speed achieved absolute values up to 2.4 m/s and for the angle up to 2.6°. Likewise, standard deviations of the errors were greater, and amounted to 0.9 m/s and 0.7° for the IAM, and to 1.0 m/s and 1.0° for the PTM. Greater errors could be a consequence of a greater initial variation of the angle (5°) than of the speed (3 m/s).

3.3. Sensitivity to the speed and angle variation

The final 200 runs had randomly introduced speed and angle variations. The variations were introduced in the same way as in the runs in which the speed and angle variations were introduced separately. The disturbance was propagating with the given speed (22 m/s) and angle (32°) between the first and the second station and with the speed \( C_{i,i+1} (i \geq 2) \), and angle \( \alpha_{i,i+1} (i \geq 2) \) between the other stations (speed and angle at other stations are given by Eqs. (2a) and (4)).

Distribution of the absolute speed and angle errors for the final 200 runs is shown in Fig. 4. The maximum speed error was 3.1 m/s; and the maximum angle error was 3.1°. Standard deviations of the errors were 1.0 m/s and 0.9° for the IAM; and 1.1 m/s and 1.0° for the PTM. Likewise, a mean value of the absolute speed error was less than 0.3 m/s and a mean value of the absolute angle error was less than 0.3°. A summary of the results is shown in Table 1. Apparently, the IAM based on the least square fit gives somewhat better results than the PTM. Calculated mean errors most clearly show the difference between the two methods, as mean errors of the IAM are up to 10 times smaller than the mean errors of the PTM. Maximum errors of the speed and angle variations, being presumably more important parameters than the mean errors, are around 10% smaller for the IAM than for the PTM. Oppositely, the time of calculation is longer in the IAM, but is, however, still short enough to be used in a meteotsunami warning system (maximum computation time was shorter than 14 s on the standard PC used).

4. Testing the detection algorithm on the measured time series

Next, we tested the detection algorithms on measured time series from the northern Adriatic and the Balearic Islands.

4.1. The 2007 Ist meteotsunami

The bay of Široka on the island of Ist was hit by a destructive meteotsunami around 1530 UTC on 22 August 2007 (Šepić et al., 2009).

Fig. 3. Evolution of speed (upper plot) and direction (lower plot) errors \((er)\) for the IAM and for the PTM, during 200 runs with uncertainties in the speed included. Mean speed and direction are also plotted.
Shortly before the event, a pronounced air pressure disturbance (0.25 hPa/min) passed above the north Adriatic (see Fig. 2 for the area). We applied the detection algorithm on the air pressure time series measured at the Mali Lošinj (ML), Rab (RA), Senj (SE) and Zadar (ZA) meteorological stations. Threshold tendency limit of the detection algorithm was set to 0.18 hPa/min. Three disturbances exceeding this threshold limit were detected on 22 August 2007, but only one of those disturbances was detected on all four stations (Fig. 5), and thus the second module of the detection algorithm was activated only once. The speed and direction of the disturbance were estimated by the IAM to be 24 m/s and 83°; and by the PTM to be 25 m/s and 85°. The values obtained by the PTM are the mean values obtained from the triangles composed of stations ML–RA–ZA and ML–SE–ZA. Šepić et al. (2009) estimated the propagation parameters to be 24 m/s and 86° (obtained by the IAM with one more station used); and 21 m/s and 86° (obtained by the cross-correlation method; developed by Monserrat and Thorpe, 1992). Conclusively, fairly good agreement – was achieved between the values obtained by the detection algorithm and the values referred to in the literature.

We can use the Ist meteotsunami to show the importance of proper configuration of a research/warning network. Namely, when we used only stations ML–RA–SE to determine the speed and angle of propagation of the air pressure disturbance we obtained a speed of 35 m/s and an angle of 51° (the PTM). If the disturbance had really been propagating with this speed it would not have been able to provoke open sea waves via the Proudman resonance over the 50–70 m shelf depths in front of the island of Ist. The reason for such a discrepancy between values obtained for this particular set of stations vs. the others is that ML–RA–SE stations form a very scalene triangle (almost a line, Fig. 2), and for line configurations, only the component of the speed in the direction of the line is determined.

### 4.2. Rissaga in June 1997

The first strong Ciutadella rissaga of the summer of 1997 occurred on 8 June when a distinct air pressure disturbance (amplitude of 3.5 hPa), preceded by several smaller amplitude air pressure oscillations, passed over the area around 3 h UTC (Vilibić, 2009).

**Table 1**

<table>
<thead>
<tr>
<th>Method</th>
<th>$T_{avg}$ (s)</th>
<th>$E_c_{max}$ (m/s)</th>
<th>$E_c_{avg}$ (m/s)</th>
<th>$E_a_{max}$ (°C)</th>
<th>$E_a_{avg}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAM</td>
<td>7.97</td>
<td>2.84</td>
<td>0.12</td>
<td>2.92</td>
<td>0.02</td>
</tr>
<tr>
<td>PTM</td>
<td>0.01</td>
<td>3.09</td>
<td>0.28</td>
<td>3.10</td>
<td>0.26</td>
</tr>
</tbody>
</table>

**Fig. 4.** Distribution of the speed and angle errors for both the IAM and the PTM, summarised for the Monte Carlo simulations with uncertainties in the speed and the direction included.

**Fig. 5.** Temporal evolution of measured pressure tendencies at ML, RA SE and ZA microbarographs between 21 and 23 August 2007. The threshold value $PT_{max}$ is set to 0.18 hPa/min. Tendencies exceeding $PT_{max}$ are marked with stars.
et al., 2008). Induced sea level oscillations lasted for about 8 h and reached the maximum height of 140.5 cm at the head of Ciutadella Inlet. Vilibić et al. (2008) estimated the speed and direction of the most pronounced air pressure disturbance to be 23 m/s and 79°, respectively. They used a somewhat more complicated version of the PTM (the pressure gradient method in Vilibić et al., 2008). Although possibly more precise, the original version of the method cannot be used on stations distanced by more than one half of the wavelength of the air pressure disturbance. Due to greater distances between the middle and northern Adriatic stations, we were not able to use this more complex method at those two areas. Thus, we also decided not to use it on the Balearic data.

For the Balearic data, we set the threshold tendency limit to 0.2 hPa/min. Only one disturbance with such a tendency was recognized by the algorithm on 8 June 1997 (not shown). Upon detection of that disturbance, the second module of the algorithm was activated and the speed and angle of propagation were calculated. Both the IAM and the PTM yielded the speed and angle values of 27 m/s and 72°. Although, somewhat differing from the values estimated by Vilibić et al. (2008), our results still indicate a strong possibility for a meteotsunami event. Namely, the 60–120 m shelf depths between the islands of Mallorca and Menorca favour generation of open ocean waves provoked by air pressure disturbances propagating with speeds between 22 and 31 m/s. Moreover, Rabinovich et al. (1999) found that Ciutadella meteotsunamis are most likely to be provoked by air pressure disturbances propagating with angles between 10° and 70° (coming from the southwest).

4.3. Rissaga in July 1997

Another strong rissaga event occurred on 23 July 1997 (Vilibić et al., 2008). This time, extreme sea level oscillations were induced by a series of air pressure disturbances. Sea level oscillations started in the early morning hours of 23 July and lasted for more than 30 h, reaching a maximum wave height of 155.4 cm (measured at the head of Ciutadella Inlet) after passage of a pronounced air pressure disturbance above the area (4.5 hPa amplitude jump, around 1620 UTC). Vilibić et al. (2008) estimated the speed and direction of this jump to be 25 m/s and 75°, respectively.

The detection algorithm (threshold tendency set to 0.2 hPa/min) detected three possibly dangerous air pressure disturbances, all occurring on 23 June 1997 (Fig. 6). The second module of the algorithm was thus activated three times and the speed and direction of three disturbances were calculated. Results are presented in Table 2. For this event, results of the algorithm are not so encouraging. Apart from the third disturbance (22 m/s), estimated speeds (14–16 m/s) are too small for the Proudman resonance and generation of open sea waves. Although differing from the ones estimated by Vilibić et al. (2008), angles (24–72°) are within a range of meteotsunami favourable angles.

Discrepancy between the results obtained by Vilibić et al. (2008) and our results might be due to the short propagation time of the disturbance from one station to another and the coarse sampling resolution (30 s). Namely, propagation times between two stations for all of the observed air pressure disturbances were between 30 s and 3 min. As we are dealing with very short distances (up to 3 km), an offset of the propagation time for only one time step (30 s) can yield significantly different values of the propagation parameters. On the other hand, in the original method, Vilibić et al. (2008) were able to circumvent the sampling interval and to determine propagation times more precisely.

**Table 2**

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>IAM</th>
<th>PTM</th>
<th>Literature</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>C (m/s)</td>
<td>x (°)</td>
<td>C (m/s)</td>
</tr>
<tr>
<td>1</td>
<td>14 72</td>
<td>14 72</td>
<td>25 75</td>
</tr>
<tr>
<td>2</td>
<td>16 93</td>
<td>16 93</td>
<td>25 NA</td>
</tr>
<tr>
<td>3</td>
<td>22 24</td>
<td>22 25</td>
<td>25 NA</td>
</tr>
</tbody>
</table>

Fig. 6. Temporal evolution of measured pressure tendencies at MB2, MB3 and MB4 microbarographs between 22 and 24 July 1997. The threshold value $PT_{max}$ is set to 0.2 hPa/min. Tendencies exceeding $PT_{max}$ are marked with stars.
5. Conclusions

We developed a meteotsunami detection algorithm based on real-time high-resolution measurements of air pressure. The detection algorithm: (i) tracks potentially dangerous air pressure disturbances having tendencies which exceed a certain threshold limit (e.g., 0.2 hPa/min); (ii) determines the speed and direction of propagation of those dangerous disturbances. The third part of the detection algorithm, assessment of an air pressure disturbance’s meteotsunami potential, should be constructed individually for any given area. We tested the detection algorithm on artificial and measured air pressure time series which were either imposed or measured at three Mediterranean meteotsunami hot-spots (the Balearic Islands; the northern Adriatic, the middle Adriatic).

We tested two methods for the determination of the speed and direction of propagation of air pressure disturbances: the IAM developed by Orlić (1980) and the PTM developed by Vilibić et al. (2008). Tests done on artificial time series revealed that both methods give satisfactory results providing that variations of the disturbance’s propagation parameters are within reasonable limits. For a maximum variation of the propagation speed and angle of 3 m/s and 5° over the 100x80 km wide middle Adriatic network, the mean absolute speed errors of the propagation speed and angle were below 0.3 m/s and 0.3°, while maximum observed errors over 200 runs were 3.1 m/s and 3.1°.

Errors of the IAM were generally smaller than the errors of the PTM. The time of calculation was on the other hand shorter in the IAM. However, both the larger errors in the PTM and the longer calculation time in the IAM were within acceptable limits. Thus both methods can be used in a meteotsunami warning system. Tests done on measured time series showed a reasonable agreement between propagation parameters determined by the detection algorithm and values referred to in literature. However, some limitations apply. If stations are placed too close to each other and the sampling resolution is too coarse, a small offset in the disturbance’s propagation time can cause a significant offset in determined speed and angle of propagation, as shown for the second Balearic episode. On the other hand, if stations are placed too far away, the disturbance’s propagation parameters can significantly change between two stations, not allowing for their proper identification. This problem could be especially pronounced when dealing with less distinct short lived air pressure disturbances which cause sea level oscillations not high enough to present a threat, but important for the fine-tuning of a warning network.

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Acknowledgments

We would like to thank Dr. Sebastian Monserrat for providing us with meteorological data collected at the Balearic Islands during the LAST-97 experiment. We would also like to thank reviewers Fred Stephenson and Paul Whitmore for the comments that improved the manuscript. Meteorological data collected at stations in the northern Adriatic were provided by the Meteorological and Hydrological Service of the Republic of Croatia. This work is an outcome of the training activities carried out by Lydie Denis at the Institute of Oceanography and Fisheries. The work was supported by the Ministry of Science, Education and Sports of the Republic of Croatia (Grant 001-0013077-1122).

Appendix A

A.1. Isochronal analysis method (IAM)

The IAM for determining the speed and direction of air pressure disturbances was developed by Orlić (1980). This method assumes that the pressure disturbance is a plain wave, propagating over the given area with constant speed and direction. Let C be the speed of the wave and α its direction, where α is measured clockwise from the northward direction toward the direction of propagation. Moreover, let δij be the distance between two meteorological stations (i) and (i+1), and αji the angle between the line δij and the parallels of longitude (where angle αji is measured in the same way as angle α). Let Δtij stand for the estimated difference between arrival times of pressure disturbances at stations whose distance is δij. Then the following geometric expression is valid:

$$\Delta t_{ij} = \frac{\delta_{ij} \cdot \cos(\alpha_{ji} - \alpha)}{C}.$$  \hspace{1cm} (A1)

Finally, let $\overline{\Delta t_{ij}}$ denote the measured difference between arrival times of pressure disturbances at various stations, while n is the number of station pairs. Speed C and direction α can then be obtained by minimizing the following function using the least square approach:

$$f(\nu, \alpha) = \sum_{i=1}^{n} \left( \Delta t_{ij} - \overline{\Delta t_{ij}} \right)^2$$

$$= \sum_{i=1}^{n} \left( \frac{\delta_{ij} \cdot \cos(\alpha_{ji} - \alpha)}{C} - \overline{\Delta t_{ij}} \right)^2.$$  \hspace{1cm} (A2)

Additionally, the accuracy of ν and α estimated by this calculation can be verified by the procedure of equalizing the indirect measurements of more than one variable (Orlić, 1984).

A.2. Pressure tendency method (PTM)

The speed U and direction φ of travelling atmospheric waves based on observations on a triangle of microbarographs with coordinates ($x_1, y_1$), ($x_2, y_2$) and ($x_3, y_3$) may be estimated by applying the following assumptions: (i) the disturbance does not change during its travel over the domain, and (ii) the disturbance has a constant speed C and a direction α. A simple plane geometry yields to the following expressions:

$$\tan \alpha = \frac{y_2 - y_1}{x_2 - x_1}, \hspace{1cm} \frac{1}{C} = \frac{1}{t_{12}} \frac{y_1 - a \cdot d x_{1,2}}{\sqrt{1 + a^2}} = \frac{1}{t_{13}} \frac{y_3 - a \cdot d x_{1,3}}{\sqrt{1 + a^2}}.$$  \hspace{1cm} (A3, A4)

where $d x_{1,2}, d x_{1,3}, d y_{1,2}$ are distances between stations $1$ and $2$ and between stations $1$ and $3$ in the north–south and east–
west direction, respectively; \( t_{1,2} \) and \( t_{1,3} \) are measured time lags of a threshold-exceeding air pressure tendency between stations 2 and 3 and station 1.

References


