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The Great Adriatic flood of 21 June 1978 revisited: An overview of the reports

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ABSTRACT

This paper describes an extraordinary tsunami-like event that occurred on 21 June 1978 that encompassed the middle and south Adriatic Sea. The flood had its culmination in Vela Luka, where a maximum wave height of 6 m was reported. This paper contains a detailed description of the event as seen by eyewitnesses, its outreach along both the eastern and western coasts, and the aftermath and recovery activities in Vela Luka. All available records have been collected and analysed to detect the source and the generating mechanism of the long ocean waves. Seismic generation is fully excluded from the consideration, while a submarine landslide seems rather unrealistic as it does not explain the characteristics of the measured ocean waves. Therefore, the source of the event was presumably in the atmosphere, where a travelling disturbance was detected that had the capability to resonantly transfer energy to the ocean via the Proudman resonance mechanism. Although these data prove the proposed mechanism, the final confirmation for such a scenario should come from a process-oriented numerical modelling study.

1. Introduction

The inhabitants of the city of Vela Luka (Fig. 1), situated in a hidden bay on Korčula Island, experienced large seiches (local name – šćiga) a number of times, reaching and even overtopping the piers and the city promenade. However, residents were not prepared for a chain of events that attacked this picturesque city in the early hours of 21 June 1978, especially as no weather storms and low wind had been forecast for the region. The sea suddenly began to rise, overtopping the piers and breaking into the city. A number of sea strokes occurred until the end of the morning hours, when the sea retreated to its bed, leaving widespread chaos and damage all over the city.

The resemblance of the event with a tsunami was too obvious, but the problem was in its generation and source. Namely, there was no recorded earthquake at that time in the Adriatic Sea. Two other sources of a tsunami came to the researchers' minds in the following days: a submarine landslide and an atmospheric process. Also, a proper assessment of the event presumes that all of the collected data, reports, and material should be treated equally and examined in a collaborative work, but a problem arises in the outreach of the event. Namely, anomalous sea level oscillations were recorded on 21 June 1978 on both sides of the Adriatic Sea, along the Yugoslav (at that time) eastern Adriatic coast and along the western Italian shore. However, the researchers did not jointly evaluate all of the information collected on both sides of the Adriatic Sea and the reports were trying to assess the origin of this event based on a limited portion of the available material. This study intends to bridge this gap in the investigations and to present all of the materials, eyewitness reports, data, and theories in one place.

The Italian Tsunami Catalogue (Tinti et al., 2004) classifies this event as a tsunami with unknown origin; however, several hypotheses have been suggested by researchers: (i) Bedosti (1980) suggested that a submarine landslide occurred along the 200 m isobath between Termoli and Vasto; (ii) Zore-Armanda (1979) hypothesised that the tsunami waves were generated by an earthquake that occurred in the Aegean Sea; (iii) Hodžić (1979/1980, 1986) assumed that cyclonically generated open ocean waves freely propagated towards Vela Luka Bay and excited local seiches; (iv) Orlić (1980) offered the Proudman resonance theory as an explanation, where the approaching ocean waves are constantly forced and amplified by atmospheric gravity waves. These theories will be carefully assessed in Section 6. In fact, it seems that this event was the strongest tsunami-like event in the Adriatic Sea in the 20th century, classified as a four on the Sieberg–Ambraseys tsunami intensity scale. Moreover, the 1978 event was the second largest tsunami in intensity in the history of catalogued Adriatic Sea events (Tinti et al., 2004), just after the 1627 Gargano tsunami whose intensity has been estimated at a five on the Sieberg–Ambraseys scale and that, together with the earthquake, claimed

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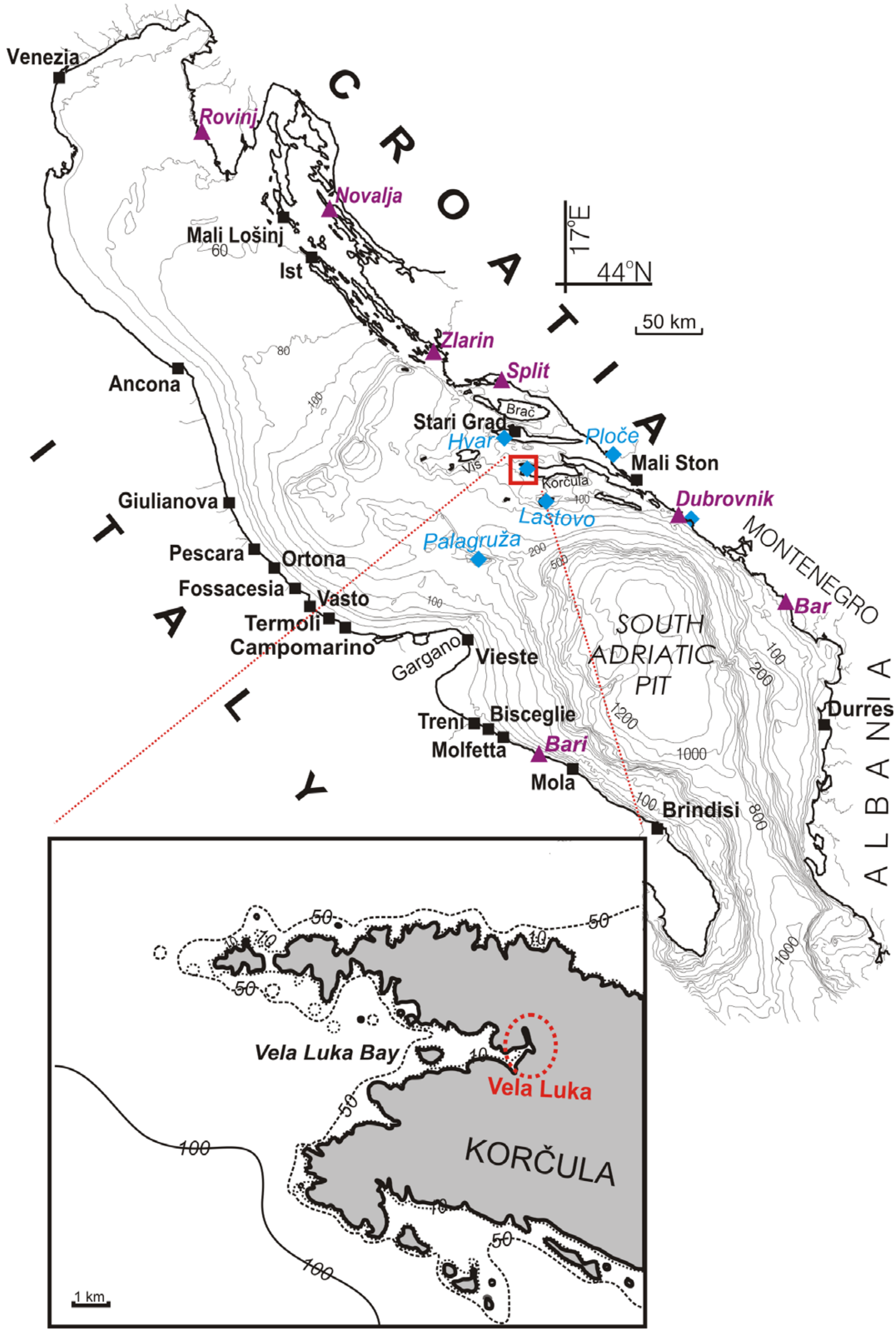

Fig. 1. Map of the Adriatic bathymetry, with locations of the tide gauges that worked during the 1978 flood (triangles) and of the meteorological stations (diamonds) used by Orlić (1980). Inset of Vela Luka local bathymetry is given too.

more than 5000 victims (Tinti and Piatanesi, 1996). It should also be mentioned that all of the other catalogued tsunami events were of seismic origin (Maramai et al., 2007). Therefore, a proper estimate of the source of the 1978 event is a high priority in the list of actions to be accomplished in assessing Adriatic tsunamis.

Apart from tsunamis listed in the Italian Tsunami Catalogue, some events were sporadically reported along the eastern Adriatic Sea shoreline, such as the 25 cm high tsunami recorded (at Bar) by the 1979 Montenegrin earthquake (Orlić, 1983/1984), or the 10 cm tsunami generated by the 2003 Makarska earthquake (Herak et al., 2001). It should be noted that the annals of the Dubrovnik Republic indicate a strong tsunami during the 1667 destructive earthquake as, “ships severely hit the ground three times,” in the Dubrovnik harbour. Paulatto et al. (2007) assessed various scenarios for seismically generated tsunamis in the Adriatic and numerically modelled a maximum tsunami height of 5 m in Dubrovnik for the worst case scenario based on a magnitude 7.5 earthquake with an epicentre just outside of Dubrovnik. Aside from the 1978 event which, according to the preliminary explanations given by Orlić (1980) and Hodžić (1986), may be classified as a so-called meteorological tsunami. Further tsunami-like events were recently attributed to an atmospheric source, such as the 2003 middle Adriatic event (Vilibić et al., 2004), the 2007 Ist event (Šepić et al., 2009), and the 2008 Mali Lošinj event. The 2003 event caused substantial damage to coastal infrastructure, destroying a large portion of the shellfish farms in Mali Ston Bay due to severe currents, and resulting in several million Euros in damage.

This paper will attempt to attribute the event of 21 June 1978 that occurred in the middle and south Adriatic Sea to its source by examining all of the available eyewitness reports, sea level and other data, and by assessing the observed properties versus common characteristics of different types of tsunamis in the literature. In addition, an overview of aftermath activities will be given to show the capacities of the local and national authorities and civil protection agencies present at the time to mitigate the consequences and the impact to the population and coastal infrastructure. All of the hypotheses collated in the literature and the media will be carefully assessed and a full explanation of the event will be presented and discussed, including the pathways for further research activities.

2. Vela Luka disaster of 21 June 1978

In the early morning hours of 21 June 1978 the sea began to rise in the city of Vela Luka (Vučetić and Barčot, 2008). The first wave and overtopping of the quays and piers occurred at 04:15 UTC, flooding the basements of sea front houses, breaking house walls, and snapping mooring lines of boats and pushing them ashore. Several minutes later, the sea retreated, emptying the top of the bay and leaving aground the moored boats and ships (Fig. 2a). The culmination of the flooding was reached around 07:00 UTC, when a 6 m high wave struck the city, almost reaching the first floor of the houses located on the top of the bay (Fig. 2b). Although there were no measurements in the bay, the maximum height of the sea level was marked on some houses and on the elementary school and stone benchmarks were placed there with the dates of the flood indicated (Fig. 2c and d). The oscillations of the sea level and currents within the bay weakened around 10:00 UTC, leaving large quantities of olive oil, wine, furniture, and other household goods mixed and spread over the bay.

The impact to the infrastructure was enormous, but, fortunately, no human casualties and few minor injuries were reported during the event. The lack of casualties was achieved primarily due to the calm and composure of the branch manager of the electrical company, Ivica Perčić, who switched off the power for the whole city just after the first wave. Telephone communications were also broken at the beginning of the flood and local authorities used amateur radio links to alert county and national authorities in Split and Zagreb. The destruction spread all over the city and included the petrol station, post office, several hotels, the Greben shipyard, the Jadranka fish factory, the pharmacy, the medical centre, the basement of the Kalos Hospital, and a large number of houses. The flood induced large-scale pollution from numerous septic tanks, mixing it and contaminating the mud layer which sank to the bottom of the bay. It should be noted that the local population was also affected by an intense fear of tsunamis returning with even larger heights. The event is also described in two poems written by local poets who witnessed the event.

An interesting experience was recorded by the captain of the ferry "Vis", which was supposed to enter the bay on its regular schedule from Lastovo to Split. It stopped at the entrance of the bay as the captain noticed unusually strong currents and saw (using binoculars) that the Vela Luka promenade and ferry port were completely inundated by the sea. The first wave had just hit Vela Luka at that time and the captain decided not to enter the bay, but instead continued towards Split.

The event and the rate of destruction attracted local and national media, and a large collection of national newspaper articles were published in the days following the tsunami (Vučetić and Barčot, 2008). The first theory for the origin of the tsunami appeared the day after the event, which associated the tsunami with an earthquake that occurred the day before in Greece. However, a second theory, introduced the very next day tried to connect the flood to the cyclone that passed over Italy and the Adriatic Sea. The initial media reports attempted to specify the destruction and to estimate the wave heights, which were reported to have a maximum wave height of 6–11 m, while the maximum inundation was estimated to have spread about 650 m inland.

3. Outreach of the event

The city of Vela Luka was not the only location on the Adriatic Sea that was affected by the severe waves on 21 June 1978. A number of eyewitness reports from other places along the eastern and western Adriatic Sea coastline can be found in the newspaper archives and technical reports. A succinct summary of these reports, containing the maximum heights of the all witnessed and measured waves, is illustrated in Fig. 3.

Severe (2–4 m high waves) were reported by eyewitnesses in the western sector of the city of Dubrovnik (Rijeka Dubrovačka and Gruž Bays), where the houses and storehouses in the seafront were flooded and some of the boats moored nearby hit the ground and were broken off their moorings by severe currents (as many as 30 yachts were reported to be damaged). The waves swept out from the beach and flooded the seashore hotel at Slano, while flooding and boat groundings were witnessed in Cavtat. The waves were also observed southeast of the Dubrovnik area, from the city of Budva to the city of Bar, but no damage or flooding were reported as the waves were witnessed to be lower than 1 m in height.

Large waves were also reported in the outer eastern Adriatic islands. Namely, 4 m waves hit Lastovo Island, flooding coastal areas, but resulting in no substantial damage. Flooding of seafront houses also occurred at Vis Island (the cities of Vis and Komiža), where the waves were larger than 2 m in height. Unusually large waves were also reported at Brač and Hvar Island (the cities of Hvar and Stari Grad) and in Split, but with no significant damage or flooding. Large waves and flooding were not witnessed northwest of the Split area and no waves were observed in the northern Adriatic Sea.

The appearance of large waves along the western Adriatic coast was documented by Bedosti (1980) and systematised by Maramai et al. (2007). The wave heights reported by Giulianova and Campomarino, under the assumption of symmetric sea level rise and depression, were 120 cm and 70 cm, respectively. Further, according to new data collected in the archives of the Osservatorio Valerio in Pesaro, a wave of 2–2.5 m was observed at Bisceglie. Further, inundation and seabed drying were documented in various locations: (i) seabed drying of 15 m at Ortona, 30 m at Fossacesia, 100 m at Vasto, Termoli, Vieste, and Bari, 2–3 m at Bisceglie, 10 m at Molfetta, and 5 m at Mola; (ii) inundation of 50 m at Giulianova, 15 m at Ortona, 20 m at Fossacesia, 30 m at Vasto, and, according to new data, 2–3 m at Bisceglie.

Fig. 2. The photos taken in Vela Luka: (a) low and (b) high waters of the 1978 event; (c) stone marks at the top and (d) in the middle of the Vela Luka harbour.

No eyewitness reports described waves northwest of Giulianova and southeast of Mola. It should be noted that the first witnessed wave was observed earlier at locations southeast of Gargano (05:30–06:00 UTC at Bisceglie and 05:00 UTC at Molfetta), whereas for locations northwest of Gargano the waves occurred later in the day (after 08:00 UTC, except at Vasto). Another interesting observation, which may be taken from Bedosti (1980), is that the maximum flood occurred at 09:15 UTC at Bisceglie, about 2 h later than observed on the opposite side of the Adriatic Sea in Vela Luka.

Several Italian newspapers released articles describing the event based on the eyewitness reports. Furthermore, research carried out in libraries and in the archive of the Osservatorio Valerio of Pesaro allows for detailed info on the effects observed along the western Adriatic coast. One account indicates that, at Termoli at 08:30 UTC, the sea withdrew by about 100 m leaving the harbour dry and stranding fish on the beach, and then violently came back. The phenomenon occurred every 15 min and lasted for 1 h. Some swimmers also referred a sudden decrease in sea temperature. At Campomarino, the sea was calm and at 10:25 UTC a sudden sea level rise was observed, like a fast tide with no waves. The sea water exceeded the usual shoreline by about 50 cm. This phenomenon lasted for about 5 min and the currents were directed towards the southeast. After 5 min the phenomenon occurred again, but the ocean currents were stronger and directed towards the northwest. At Ortona, the sea withdrew by about 15 m at about 10:30 UTC, and then came back after approximately 30 min. At Bisceglie, an eyewitness in the east harbour at 05:30–06:00 UTC observed a wave about 2–2.5 m high that violently entered the harbour and broke the moorings of two fishing boats. An inundation of 2–3 m was observed and after a few minutes the wave left the harbour with a sea level lowering of about 50 cm. The sea oscillations occurred many times during the whole day and the phenomenon lasted until 11:00 UTC, when it gradually diminished. At Bari, the sea water withdrew many times causing moored ships to go

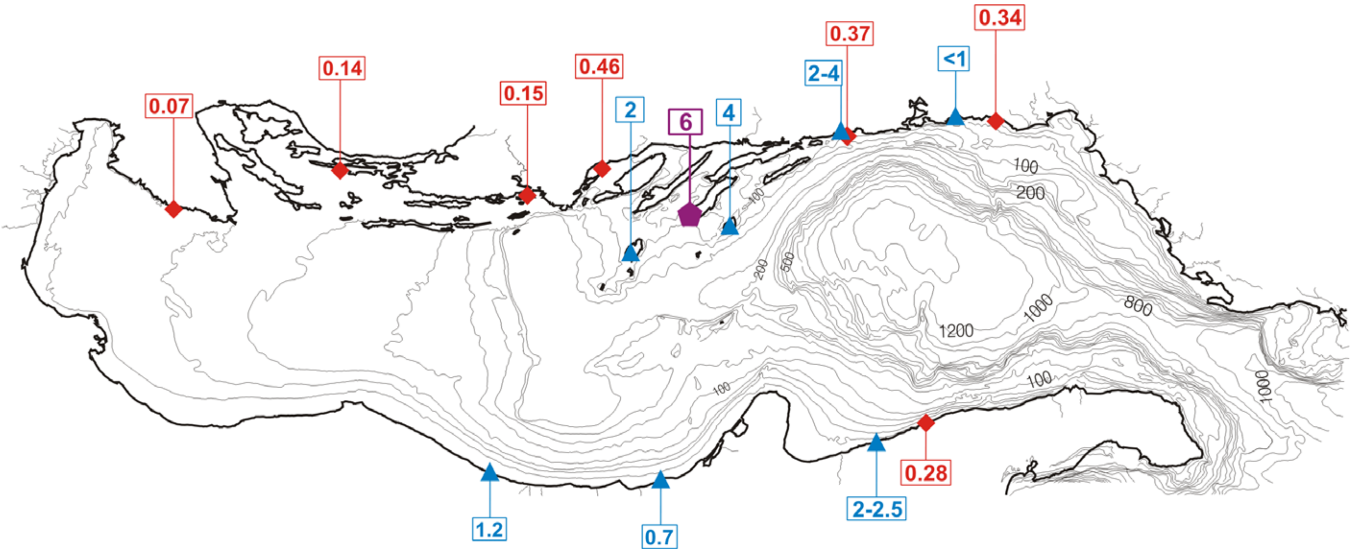

Fig. 3. Maximum wave heights (in metres) annotated on the Adriatic map, as measured by the tide gauges (diamonds) and reported by eyewitnesses (triangles). Vela Luka wave height is marked by a pentagon, being the maximal observed and measured during the 1978 event.

aground and stranding fish on the beach. At Vieste, the sea suddenly withdrew, leaving boats aground and inundating the shore with very high waves after a few minutes, causing damage to the boats, sweeping away the beach umbrellas, and injuring some people.

4. Instrumental records

As mentioned previously, no earthquake occurred in the Adriatic Sea on 21 June 1978, thus no seismographs are available for inspection. When regarding submarine landslides, a recent geomorphological study of the seabed at the western edge of the South Adriatic Pit by Minisini et al. (2006) documents the occurrence of only marginal submarine landslides in the present geological timeframe with no capacity to induce the recorded waves. In this section all available sea level charts will be presented as well as a representative record of air pressure measurements that were used by Orlić (1980) in his study of the 1978 Vela Luka event.

The most southern tide gauge at the eastern Adriatic shore, in Bar (Fig. 4a), denotes the seiching activity, which reached a noteworthy level (5 cm range) in the late hours of 20 June 1978. However, the first large sea level peak can be seen on 21 June 1978 at 05:25 UTC (6:25 a.m. on chart, marked by 1) with a wave height (crest-to-trough value) of 26 cm. The next maximal high-frequency peaks can be seen at 06:25 (marked by 2) and 06:55 UTC, followed by very large oscillations with a height of 34 cm. The oscillations decreased after 10:00 UTC and returned to their normally low values in the evening hours.

The sea level curve at Dubrovnik (Fig. 4b) is similar to the Bar sea level registration. The strongest oscillation, presumably connected to the first witnessed wave in Vela Luka, can be observed on 21 June 1978 at 05:10 UTC (marked by 1), while the second and third severe waves occurred at 05:55 UTC (marked by 2) and 06:25 UTC. The shape of the registered waves is similar, so we may presume that these three peaks, shifted in time at different stations, may be attributed to three travelling barotropic ocean waves coming from the southwest to west direction. However, the first wave needed only about 15 min to travel between Dubrovnik and Bar, while the second and third needed about 30 min to travel over the same distance. This indicates the different propagation direction of the different ocean waves. Namely, let us assume that the distance between Dubrovnik and Bar is, $D = 105$ km, the average sea depth between them is, $H = 200$ m, the time the wave needs to travel is t, and the incident angle between Bar and Dubrovnik is α. Then the simple geometrical solution and the expression for the speed of long ocean waves can be determined by:

$$\cos\alpha = \frac{t}{D}\sqrt{gH}.$$

If t is 15 min, then the incident angle α equals to 68° and the wave can be determined to have come from a direction of 238° (WSW). This result is similar to calculations done by Orlić (1980), who documented the first wave coming from 212°. The time the second and the third waves needed to travel over the same distance was 30 min, resulting in $\alpha = 41°$, which implies that the waves came from 265°. However, this simple approach is presented here to demonstrate that different ocean waves presumably came from different directions and this may be a clue for the assessment of their source; however, numerical modelling should be performed to determine the precise pathway of the waves.

The sea level record at Split (Fig. 4c) indicates the first high-frequency peak at 04:25 UTC (marked by 1), but with relatively low range (20 cm) compared to the following oscillations. Namely, the most energetic oscillation occurred at 07:05 UTC (marked by 2), with a maximum wave height of 47 cm. These two peaks (1 and 2) occurred around 10 min after the waves witnessed in Vela Luka so they may be related to the same source. The oscillations remained strong till the afternoon hours (17:00 UTC) and a few conclusions may be drawn when analysing this record:

- The first wave was weaker than the second at Split, while both waves were similar in strength at Dubrovnik and Bar. This is suggestive that the source of the first wave might have been located more to the southeast than the second wave, which is consistent with the reports from the western Adriatic shore summarised by Bedosti (1980).
- The observed waves possessed quite large energies at Split. The tide gauge at Split is positioned in a land-locked channel with two connecting passageways between the islands that are only a few kilometres wide. Thus, the incoming open ocean waves

are not expected to have large amplitudes off Split if wave generation is presumed to not occur just inside the channel. However, the oscillations are of similar amplitude to those that were observed in Dubrovnik and Bar, which are not sheltered by islands.

The strength of the high-frequency oscillations becomes lower when examining available sea level records northwest of Split. Sea level charts at Zlarin and Novalja (not shown) contain a maximum wave height of about 15 cm, whereas the oscillations did not surpass a 7 cm range at Rovinj (Fig. 4e). This is consistent with the eyewitness reports that do not mention any unusual phenomena observed over the northern Adriatic Sea.

As far as the western Adriatic coast is concerned it is important to note that, although at that time a number of tide gauges were operating, due to data archive and management problems within the Italian agencies responsible for the national oceanographic network, it was not possible to find records of the 1978 event. The only record that could be found is a copy of the weekly sea level chart of Bari, available at the Osservatorio Valerio in Pesaro and reproduced in Fig. 5a. Unfortunately, the chart resolution is poor and correct interpretation of the signal is quite difficult. However, it can be seen (Fig. 5b) that at about 05:30 UTC there is a change in the signal with the appearance of high-frequency peaks that reach a maximum amplitude of about 28 cm (marked by 1) at approximately 08:30 UTC.

5. Aftermath activities, damage assessment

Immediately after the destructive waves receded, local authorities proclaimed a state of natural disaster emergency for the city of Vela Luka (Vučetić and Barčot, 2008). Simultaneously, the civil protection service instructed the local population about the use of drinkable water, electrical installations, medicines, and other emergency issues to prevent the occurrence of contagious diseases and to avoid any casualties caused by defectiveness in electrical installations upon the return of the population to their houses. These measures succeeded to mitigate potential aftermath problems and prevent casualties. Continuous and massive voluntary actions were coordinated by civil protection in the days following the tsunami to collect all of the garbage in the bay and onshore and to remove waste from houses, parks, roads, and promenades.

A Commission established a few days after the event made a damage assessment, including households, city infrastructure, workshops and stores, industry, and city services. The final estimate was valued at 7 million US dollars at that time, of which about 10% was allotted to private households, i.e., directly to the Vela Luka inhabitants (Table 1). The estimated damage equalled 23% of the annual income of Korčula Island. The damage was also assessed for some other places along the eastern Adriatic shore, but at much lower levels, which allowed for easy mitigation of the consequences.

Three months after the event, local authorities initiated research activities, by asking the Academy of Sciences and Arts in Zagreb to build a comprehensive research program. This research program was constructed during the following 2 years, through engagement of all Croatian research institutions which were supposed to have knowledge on the phenomenon. The proposed program was comprehensive, and included an assessment of all potential sources for the tsunami, the establishment of a monitoring network in the atmosphere and sea, ocean numerical modelling, hazard and risk analyses, and mitigation measures in the city of Vela Luka. Unfortunately, although a comprehensive

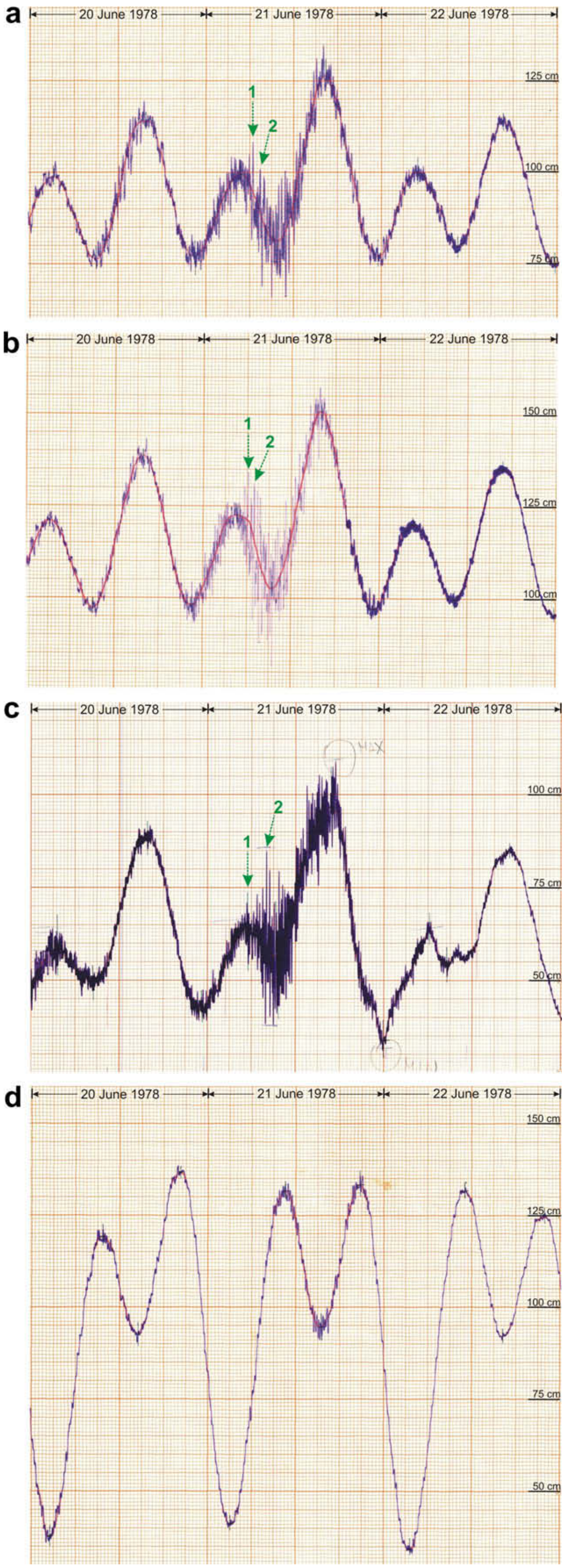

Fig. 4. Sea level charts recorded at: (a) Bar; (b) Dubrovnik; (c) Split; (d) Rovinj. The first and the second waves are marked by 1 and 2.

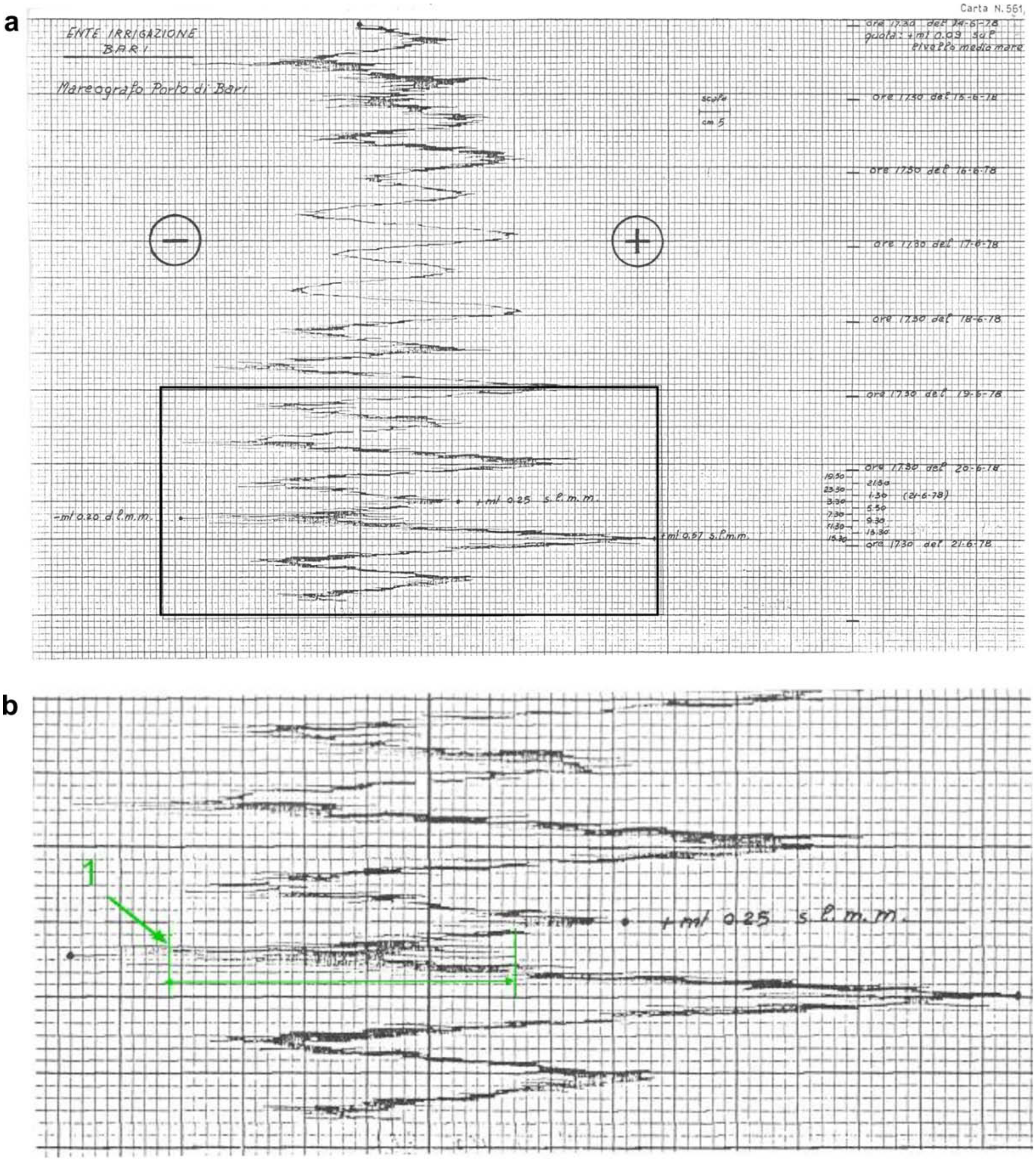

Fig. 5. Tide gauge record at Bari: (a) the whole record between 14 and 22 June 1978 and (b) zoomed between 19 and 22 June 1978. Maximal wave is marked by 1.

research program was agreed to between the research institutions, no significant steps towards its implementation were realised due to funding issues.

6. Assessment of existing theories

Four different hypotheses about the source and the generation of the tsunami-like waves were introduced after the 1978 event. Zore-Armanda (1979) tried to connect the event with the earthquake in the Aegean Sea. Bedosti (1980) and a team of Croatian scientists introduced a possibility that a submarine landslide was responsible for the generation of the observed waves. Finally, Hodžić (1979/1980, 1986) and Orlić (1980) related the event to an atmospheric mechanism, namely freely propagating "cyclonic pressure waves" and to the forced ocean waves generated by travelling atmospheric gravity waves via the Proudman resonance, respectively. Although some indications were posed in the previous chapters, herein the evaluation of each of these hypotheses will be summarised.

First, let us assess the possibility that the event was generated by an earthquake. The only candidate was the magnitude 6.4 earthquake that occurred on 20 June 1978 at 20:03 UTC with an epicentre near Thessaloniki, Greece. However, such a possibility must be rejected because: (i) the earthquake was too far from the middle Adriatic Sea and the waves were expected to detour to the Peloponnese peninsula; (ii) no tsunami was reported near the source in the Aegean Sea; (iii) the arrival times do not match the theoretical ones determined by bathymetry; (iv) the theoretical amplitude of such a tsunami would be negligible in the Adriatic Sea.

A submarine landslide was hypothesised by Bedosti (1980) to have occurred somewhere below 200 m isoline along the Jabuka

Table 1
Official estimates of damage observed in the Vela Luka households (translated from Croatian, after Vučetić and Barčot, 2008).

Damaged Item	Quantity
Households	188
Bedrooms	104
Living rooms	44
Kitchen furniture	236 pieces
Electric cookers	80 pieces
Wood cookers	44 pieces
Gas heaters	29 pieces
Oil heaters	12 pieces
Electric heaters	12 pieces
Laundry machines	51 pieces
Refrigerators	95 pieces
Televisions	43 pieces
Radios	27 pieces
Gramophones	11 pieces
Boats	15 pieces
Vehicles	13 pieces
Tractors	17 pieces
Vine	13,970 l
Olive oil	13,660 l
Sewing machines	7 pieces
Wood heaters	1 piece
Tape recorders	1 piece
Hydrophores	5 pieces
Boilers	4 pieces
Various motors	16 pieces
Other bigger machines	12 pieces
Sugar	1050 k
Coffee	50 k

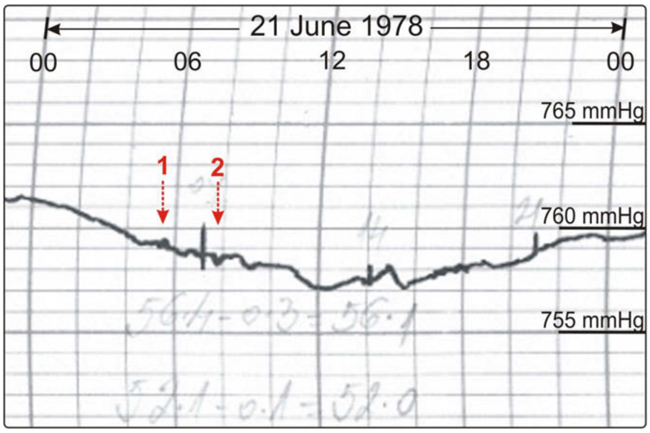

Fig. 6. Air pressure chart recorded at Hvar meteorological station. Arrival times of the first and the second waves are marked by 1 and 2. Time marks (vertical lines) can be seen on the air pressure curve, enabling precise positioning in time.

Pit shelf edge approximately halfway between Pescara and Zlarin. However, it is unlikely that these waves could have propagated far from the source and have larger amplitudes in Bar and Dubrovnik than those observed close to the hypothesised source, along both eastern (Zlarin) and western (northwest of Gargano) shorelines. Also, such a landslide would have resulted in tsunami waves of substantial height in the northern and southern Adriatic Sea as they are equally distant from the source; however, no waves were reported in the northern Adriatic Sea (just a few cm measured at Rovinj). Finally, it is not realistic that these waves strongly penetrated in the land-locked area off Split where the largest oscillations were measured at the tide gauge. Furthermore, one may consider the western South Adriatic Pit slope as a source for this event, with several large-scale submarine landslides that were found in the past (Minisini et al., 2006). However, all of these events have been determined to have occurred far in the past and in recent years only minor slides that were not capable of producing such a tsunami were reported. Summarily, it is unlikely that the 1978 Adriatic flood was generated by a submarine landslide, but the final confirmation should come from a targeted numerical modelling study simulating the possible landslide formations.

The last possible source, the atmosphere, was introduced since cyclonic activity was noteworthy over the Adriatic and middle Mediterranean Seas at that time. Orlić (1980) examined the possibility that resonant energy transfer from travelling air pressure was the source of forced long ocean waves generated over the middle and south Adriatic Sea (so-called Proudman resonance after the theoretical work done by Proudman, 1929). As two air pressure waves were captured on a number of barograms (the example at Hvar is given in Fig. 6) coinciding with the times of witnessed waves in Vela Luka. Orlić (1980) used them to estimate the direction and speed of the atmospheric disturbance and the calculus for the first wave gave a speed of 22 m/s and a direction of 212° (the waves came from the southwest). A different explanation was proposed by Hodžić (1979/1980) who assumed that long ocean waves were generated over the open sea by a cyclone, which then freely propagated towards the coast and excited local seiches within the funnel-shaped basins. Hodžić (1986) extended the analysis of favourable atmospheric conditions to a large number of measured high-frequency waves at the Split and Dubrovnik tide gauges (408 cases between 1976 and 1980), and found similarities in all of these cases, especially during the three strongest episodes of witnessed large waves in Vela Luka: 21 August 1977, 19/20 September 1977, and 21 June 1978. During all of these cases the mid-troposphere jet was observed to be stronger than 30 m/s with a strong wind-shear and instability layer (Richardson number, $Ri < 0$) at a height of 6–7 km (Fig. 7). Simultaneously, the ascertained vertical temperature inversion indicated that at lower levels a large inflow of dry, warm African air overtopped the stationary surface air mass. These conditions are favourable for the generation of instabilities and for the ducting of low-troposphere atmospheric waves that preserve their strength over long distances (Lindzen and Tung, 1976). It is important to note that these long-distance travelling atmospheric waves, visible in surface air pressure, constantly interact with the surface of the water (see also theoretical studies by Vilibić, 2008), which introduces the Proudman resonance as a relevant mechanism for the generation and propagation of open ocean waves. In addition, similar conditions in the atmosphere were found during other Adriatic Sea meteotsunamis, and are documented in detail in the works by Šepić et al. (2009) and Vilibić and Šepić (2009).

Further support for the atmospheric origin and the Proudman resonance as a generating mechanism of the 1978 event may be found in observed characteristics of the ocean waves. First, relatively large oscillations observed at Split, in a land-locked area, may be explained as the effect of the local generation of additional waves that were superimposed upon the waves incoming from the open Adriatic Sea. Secondly, the outreach of the waves, even to the Bar tide gauge station, is a result of the resonant energy transfer that occurred over the entire middle Adriatic Sea shelf area and not over a limited region, including the shelf off the southeastern Adriatic shore. Third, the difference in travel times of the three recorded waves at Dubrovnik and Bar may be attributed to the difference in atmospheric disturbance propagation direction (roughly estimated to be 27° in the previous section), which cannot be explained by any other source mechanism. Therefore, the great Adriatic flood of 21 June 1978 was presumably generated by travelling atmospheric disturbances through the Proudman resonance mechanism and therefore may be classified as a meteotsunami. In spite of these positive clues, however, we observe that the Proudman resonance process was proven for the 2003 Adriatic meteotsunami

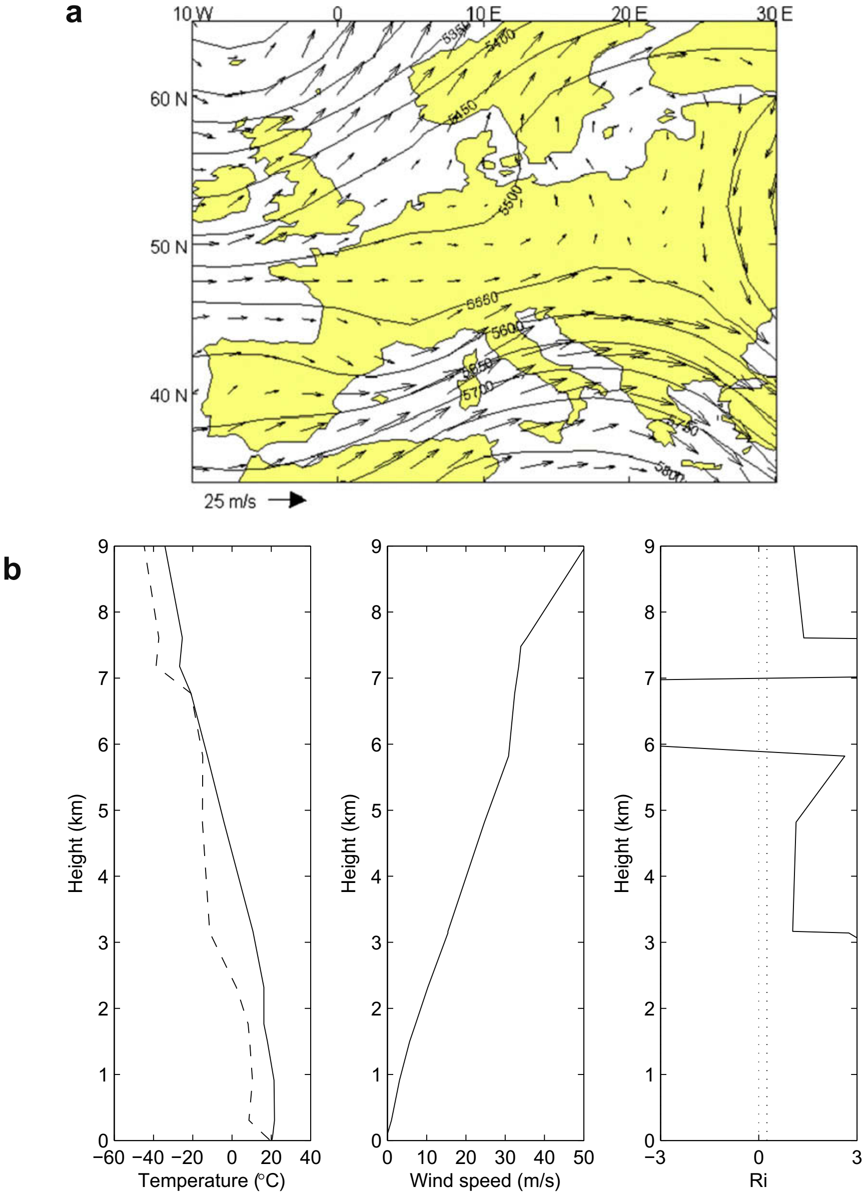

Fig. 7. Atmospheric conditions observed during the Vela Luka meteotsunami on 21 June 1978 at 00 UTC, including (a) 500 mb geopotential streamlines and winds and (b) vertical atmosphere structure (air and dew point temperature – solid and dashed line respectively, winds and Richardson number Ri) being sounded at the nearest station at Brindisi.

by conducting a process-oriented numerical modelling study (Vilibić et al., 2004), so a similar numerical approach could be the decisive proof for the source mechanism of the 1978 flood.

7. Conclusions

This paper attempts to present all available material from both Adriatic Sea coastlines, which were used in an assessment of the great Adriatic flood that occurred on 21 June 1978. Careful inspection of the possible generation mechanisms for the observed tsunami-like waves favours travelling atmospheric waves, which created long ocean waves through a long-distance resonant energy transfer from the atmosphere. Thus, these meteotsunami waves hit coastal areas and had the largest amplitudes in the bays with large amplification factors, such as Vela Luka Bay. However, this mechanism still has to be confirmed through a numerical modelling study, as well as other possible mechanisms, i.e., induction from a submarine landslide.

The damage reported after the event was pretty large, about 7 million US dollars at that time just in Vela Luka, corresponding to the 23% of the annual income of Korčula Island. This monetary impact opens a question of how to assess future risk and how to mitigate the impact. It is not a simple question, as the building of a tsunami (meteotsunami) warning system in the Mediterranean Sea requires latency (time between the detection of the potential tsunami waves and alerting the population) to be lower than 5 min (ICG-NEAMTWS, 2008). The future warning system should include: (i) a real-time assessment and watch service for meteotsunami threats; (ii) a warning service for alerting the coastal population; (iii) education activities to inform the population how to mitigate meteotsunami threats. The first part of such a service is particularly hard to develop as it demands non-standard ocean and atmospheric measurements which are not easy to upgrade to the real-time level. The efficiency of applicable numerical models in research, warning, and mitigation activities should also be improved to an operational level, starting with the production of better bathymetry charts in the most affected coastal regions. We hope that such an approach may be developed on a basin scale, e.g., for the Adriatic Sea, and may become a part of the Mediterranean tsunami warning system in the near future.

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