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Fresh evidence relating the great Adriatic surge of 21 June 1978 to mesoscale atmospheric forcing

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[1] On the morning of 21 June 1978, exceptional sea level oscillations with a trough-to-crest height of 6 m and a period of 10–20 min were observed in Vela Luka Bay. Slightly less pronounced variability was observed in a wider middle and south Adriatic east coastal area and, with some delay, along the west coast. In this paper, one of the original hypotheses put forward to interpret the event, relating it to a mesoscale air pressure disturbance, is reconsidered by using all the available data as well as state-of-the-art meteorological and oceanographic models. A fresh look at the meteorological data confirms that the atmospheric disturbance propagated at about 22 m/s in a northeastward direction. Additionally, the data suggest that it had the shape of the boxcar function characterized by an air pressure offset of 3 mbar and duration of 10 min. The meteorological model employed (Weather Research and Forecasting (WRF)-Advanced Research WRF) proves unable to reproduce the mesoscale disturbance coinciding with the surge, but it shows that the background atmospheric conditions were favorable for the development of such disturbances. The oceanographic model Advanced Circulation Model for Shelves, Coasts and Estuaries (two-dimensional depth integrated), forced by the described air pressure disturbance, successfully reproduces sea level variability in Vela Luka Bay reaching a few meters and thus surpassing the inverted barometer response by two orders of magnitude. The enhancement appears to be due to a four-phase process. The model also suggests that the scattering due to the variable bathymetry and the reflection from the east Adriatic coast resulted in waves that returned towards the west coast and generated considerable sea level activity there.

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1. Introduction

[2] On the morning of 21 June 1978, a tsunami-like event occurred in the Adriatic Sea. With the trough-to-crest height reaching 6 m in Vela Luka Bay on the Island of Korčula (Figure 1) and exceeding 1 m in a number of locations along both the east and west coasts of the middle and south Adriatic, this was the most pronounced sea level fluctuation observed in the Adriatic in the 20th century. There were no casualties in Vela Luka, but the town was so heavily damaged that a state of emergency had to be proclaimed. The event was extensively described in contemporary newspapers [*Vučetić and Barčot*, 2008], with attention being paid not only to Vela Luka but also to other Croatian and Italian towns. A dozen or so tide gauges operated in the Adriatic at the time, and although some of them did record an intensification of high-frequency variability, none registered the sea level maxima observed by eyewitnesses. An additional problem with the tide gauges was that, in 1978, all of them were of analog type, with the high-frequency signals being blurred in their records; therefore, the signals could be inspected only visually. This made eyewitness reports, published mostly in newspapers, particularly valuable. The reports were often interspersed with speculations on the cause of the phenomenon, apparently fuelled by the fact that the dramatic sea level variability did not correspond with an equally dramatic event in either the atmosphere above the Adriatic or the earth below it.

[3] In the years following the event, its cause was addressed more seriously. The investigations were mostly inspired by the observations of exceptional sea level oscillations that started in Vela Luka at 0515 LT on 21 June 1978, had an amplitude of ca. 3 m, a period of 10–20 min, and lasted about three hours. The studies resulted in four hypotheses regarding the generating mechanism, with two of them finding the cause at the sea bottom and two finding it in the atmosphere. Thus, *Zore-Armanda* [1979] related the Adriatic event to an earthquake that occurred the day before in the Aegean Sea area, whereas *Bedosti* [1980] connected it with a landslide that presumably occurred off the middle Adriatic coast of Italy. Obviously, both Zore-Armanda and Bedosti

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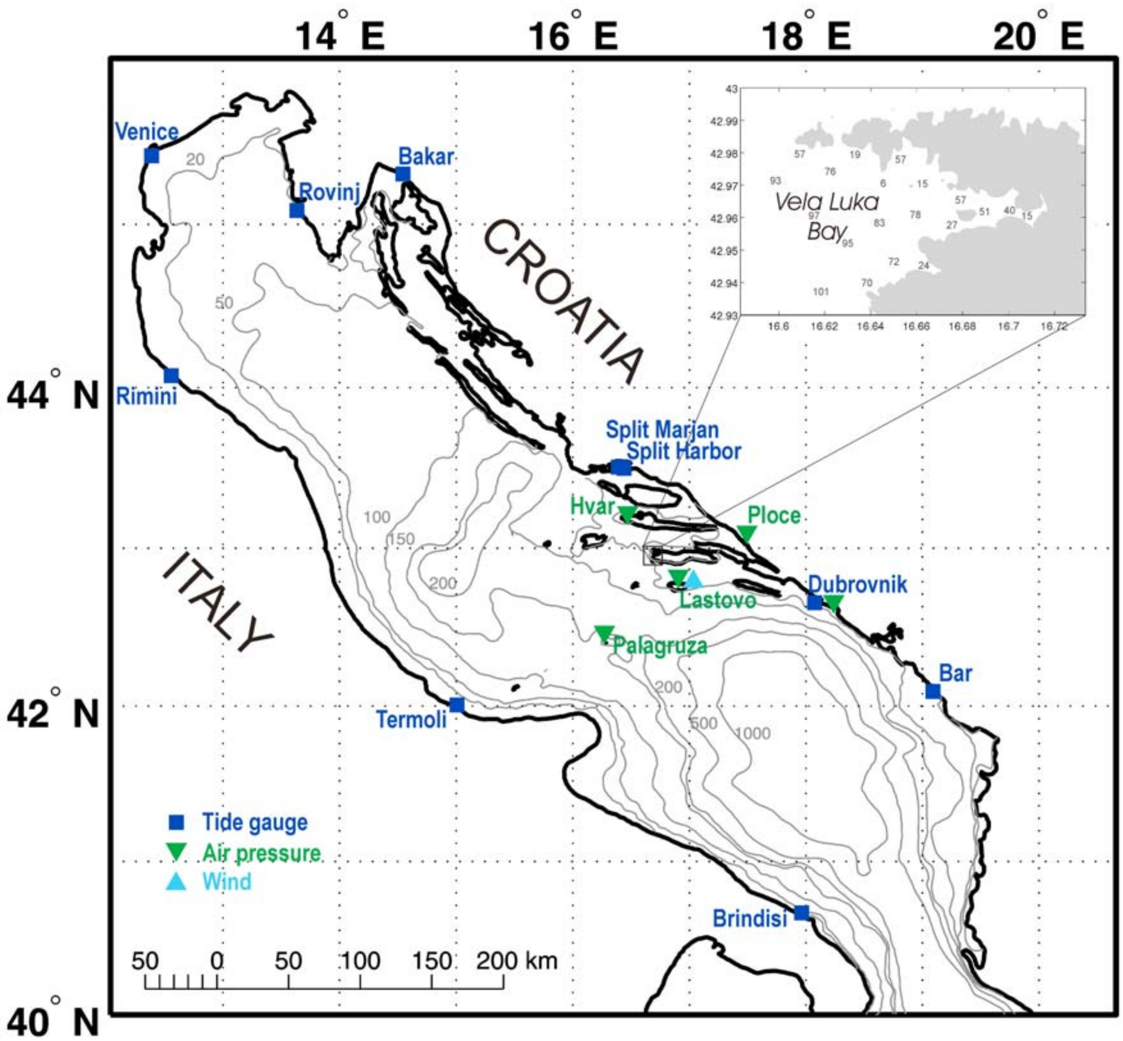

Figure 1. Position and bathymetry of the Adriatic Sea, with the depths given in m. Also shown are the positions of tide gauge and meteorological (air pressure, wind) stations. In the inset, Vela Luka Bay is depicted in some detail.

proposed that the Adriatic event was a tsunami, but they attributed it to different triggering mechanisms. On the other hand, *Hodžić* [1979, 1988] attributed the surge to free waves impulsively generated in the open Adriatic by a cyclone, whereas *Orlić* [1980] related it to forced waves resonantly driven by an atmospheric gravity wave. Therefore, both Hodžić and Orlić pointed to a meteorological origin of the Adriatic event. However, while the first of these authors stressed the importance of synoptic atmospheric processes, the second underlined the relevance of mesoscale atmospheric phenomena.

[4] Among the four hypotheses, the hypothesis put forth by *Bedosti* [1980] stands out as the only one that did not relate the Adriatic surge to a well-documented phenomenon; i.e., no precise information on the place and time of the landslide was provided by the author. The remaining three hypotheses were based on good descriptions of the possible causative phenomena. *Zore-Armanda* [1979] thus invoked an M = 6.5 earthquake that occurred in the Aegean Sea area close to Thessaloniki at 2105 LT on 20 June 1978 as a causative factor. *Hodžić* [1979, 1988] described a cyclone that travelled from the Tyrrhenian Sea to the middle Adriatic between 0100 and 0700 LT on 21 June 1978. Finally, *Orlić* [1980] documented an atmospheric gravity wave that crossed the middle and south Adriatic from the Italian to the Croatian sides between 0400 and 0600 LT on 21 June 1978. The three hypotheses were based on equally precise information on the possible causes, but they also shared a common weakness: explanations of the relationship between the cause (earthquake-related bottom movement, cyclone, atmospheric gravity wave) and the consequence (surge) were purely descriptive.

[5] The aim of this paper is to use numerical modeling to dynamically connect a mesoscale atmospheric perturbation resembling the one that crossed the Adriatic in the morning hours of 21 June 1978 with the surging concurrently observed in the area. First, oceanographic and meteorological data collected in 1978 will be overviewed (section 2). Mesoscale meteorological modeling will then be used to explore the atmospheric conditions on 21 June 1978, and thus to supplement the data (section 3). The available meteorological information will then be utilized to force an oceanographic, finite element model that is able to adequately resolve both

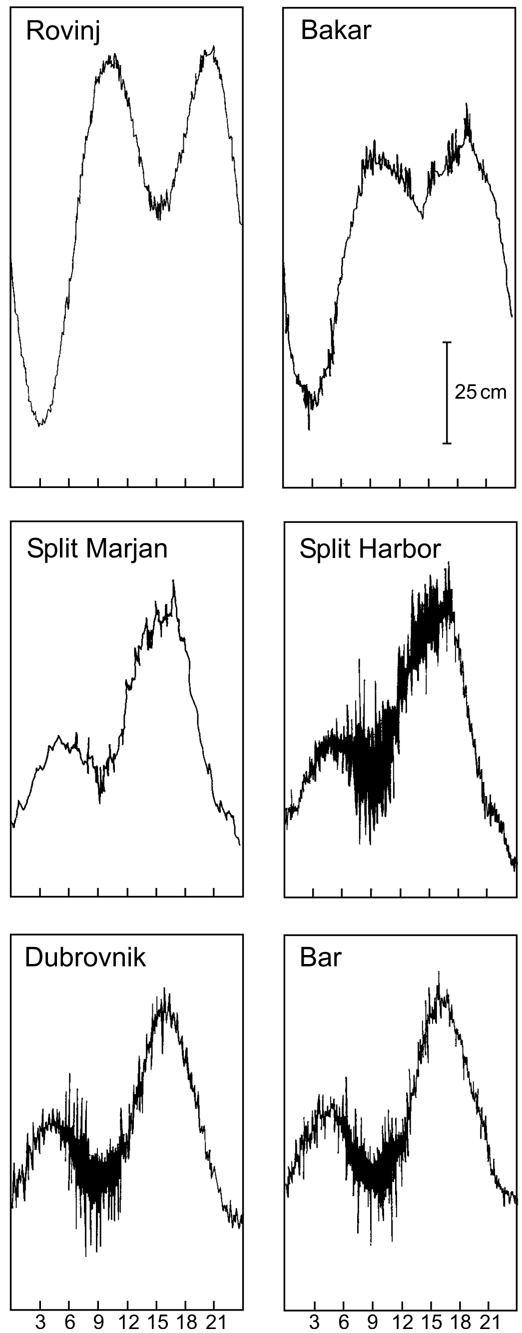

Figure 2. Sea level variability recorded by six analog tide gauges on 21 June 1978. Positions of the stations, distributed along the east Adriatic coast, are indicated in Figure 1.

the open sea and coastal bathymetry (section 4). The modeling reveals that a mesoscale air pressure disturbance not surpassing a few mbar and traveling at the speed and direction determined by *Orlić* [1980] could have excited sea level variability in Vela Luka Bay reaching a few meters and thus implying an increase of two orders of magnitude over the simple inverted barometer response. In section 5, the dynamics underlying the atmosphere-sea coupling will be discussed, the Adriatic surge will be related to similar phenomena observed elsewhere, and the applicability of the term "meteotsunami" to such processes will be commented upon. In the final section (section 6), possible future activities will be briefly addressed.

2. Data

2.1. Sea Level Observations and Measurements

[6] The outstanding surge in Vela Luka was recorded on amateurs' photographs and movies, and the level of run-up was marked on some walls, but no instrument was operating in the town in 1978 to record the event. Here, we present and combine all the observational evidence collected in Vela Luka and also present findings resulting from observations and tide gauge measurements elsewhere in the Adriatic in order to deduce a wider picture of the event. Toward this aim, we examined the trough-to-crest wave height and the onset time by concentrating on the first of the several wave packets that apparently hit the east and also west Adriatic coasts, since this is the only packet for which the meteorological data could be analyzed with some confidence.

[7] Eyewitness observations of the 1978 event are available today from two sources: for the east coast in a collection of newspaper articles [*Vučetić and Barčot*, 2008] and for the west coast in an overview of answers to a questionnaire [*Bedosti*, 1980]. The newspaper reports from the Croatian coast are numerous but often rather imprecise, mostly concentrating on how the sea rose over the seafront, entered the houses and then withdrew, leaving boats and even ships on a dry sea bed. Such accounts were used to estimate the wave height and the onset time. The observation records from the Italian coast based on a questionnaire are more precise, giving the onset time and, in several places, the run-up water level.

[8] Tide gauge charts for 21 June 1978 show that in harbors along the east side of the middle and south Adriatic, a pronounced high-frequency activity was initiated at around 0600 LT, and that at Bar and Dubrovnik it lasted with changing intensity until midday, while at the Split Harbor and Split Marjan stations it continued until the evening (Figure 2). At the Split Marjan tide gauge, located close to the Split Harbor instrument but outside the harbor, the signal was relatively weak and characterized by rather low frequencies; still, in the Split Marjan marigram, one can observe a series of distinct narrow peaks preceded by a broader maximum, all with counterparts in the Split Harbor record. Two east coast stations in the North Adriatic, Bakar and Rovinj, did not record any signal that stands out from the background noise.

[9] For the present study, copies of tide gauge charts originating from four west coast stations, Brindisi, Termoli, Rimini, and Venice, were also available (not shown). The record from Termoli appears to have been heavily damped for some reason and is therefore useless for the investigation of high-frequency variability. The copy of the Rimini marigram is of rather poor quality, but it does not seem to contain any pronounced signal on 21 June 1978. The remaining two records, from Brindisi and Venice, apparently indicate increases in high-frequency activity at about 0500 and 1300 LT, respectively, but the ensuing signals barely rise above the background noise.

[10] In extracting wave heights and onset times from the useful tide gauge records, we tried to make them consistent with those reported by eyewitnesses. To that end, we defined the wave height as the difference between the maximum and

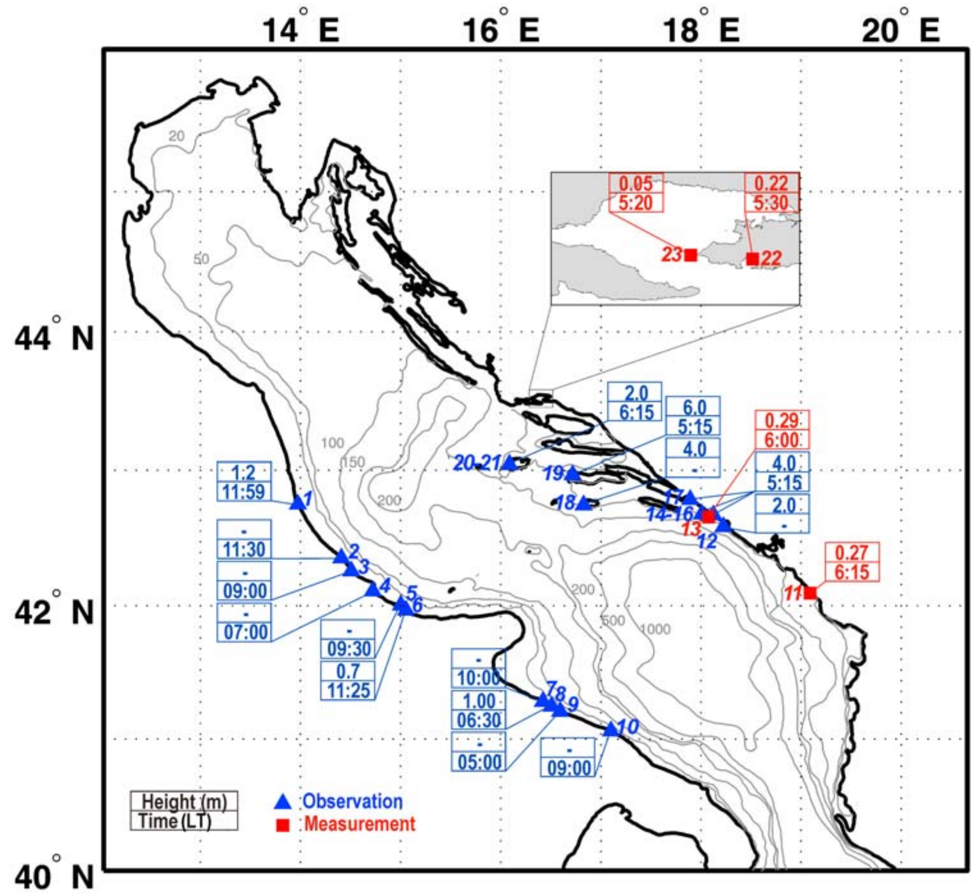

Figure 3. Wave heights (upper number, in m) and onset times (lower number, LT) recorded along both Adriatic coasts on 21 June 1978. Triangles mark visual observations, and squares indicate instrumental measurements. The inset shows data originating from two nearby tide gauge stations, Split Marjan (left) and Split Harbor (right). The station numbers correspond to those in Figure 17.

minimum sea levels within the first wave packet, and the onset time as the time of the maximum sea level within this wave packet. A summary of all the estimated heights and times, based on observations and tide-gauge measurements, is given in Figure 3. The summary shows that the east coast heights were much larger than those observed at the west coast and that, in general, the west coast oscillations lagged behind the east coast oscillations. Moreover, it is obvious that there is considerable small-scale variability in both the heights and times. These findings will be discussed in some detail when considering the modeling results and when comparing them with the empirical findings.

2.2. Meteorological Data

[11] It has previously been shown that if an atmospheric disturbance is responsible for this type of inundation, it should be sought in the surface air pressure signal [e.g., *Vilibić et al.*, 2005]. Although the meteorological measurements were sparse over the region of interest, the larger problem is the sensitivity and temporal resolution of the barographs. At the time, the barographs in the area recorded weekly charts, thus having poor temporal resolution as well as rather low sensitivity to sudden changes in the air pressure. Based on that data, *Orlić* [1980] noticed an air pressure perturbation appearing at different stations in the region, and from the observed time shifts he managed to determine the speed and direction of propagation of that disturbance. Here, we repeat some of his findings, and additionally examine measurements of wind speed and direction that might be helpful in determining the details of the surface appearance of the disturbance. Figure 4 depicts an example of air pressure trace from the barograph at Lastovo, the station closest to Vela Luka. While one can with some effort estimate the onset time of the air pressure perturbation, it is hardly possible to distinguish its magnitude and, in particular, its shape. All of the other records (see Figure 1 for the locations of barographs) are of similar quality, and taken together they result in the estimated speed (c = 22 m/s) and direction (γ = 58°) of the perturbation, as illustrated in Figure 5. As is obvious from Figure 5, the direction determines where the perturbation propagates to and is measured in a positive (i.e., anticlockwise) sense from an eastward direction. The method used by *Orlić* [1980], which is explained in some detail by *Orlić* [1984], also resulted in an estimate of the error of the speed (±2 m/s) and direction (±2°). The errors reflect the departure of the air pressure disturbance from the assumed plane wave traveling at a constant speed and direction, but they may also be due to the timing errors of the barographs if these errors are randomly distributed at various stations. Since the number of barograph stations used was rather small (five), and therefore

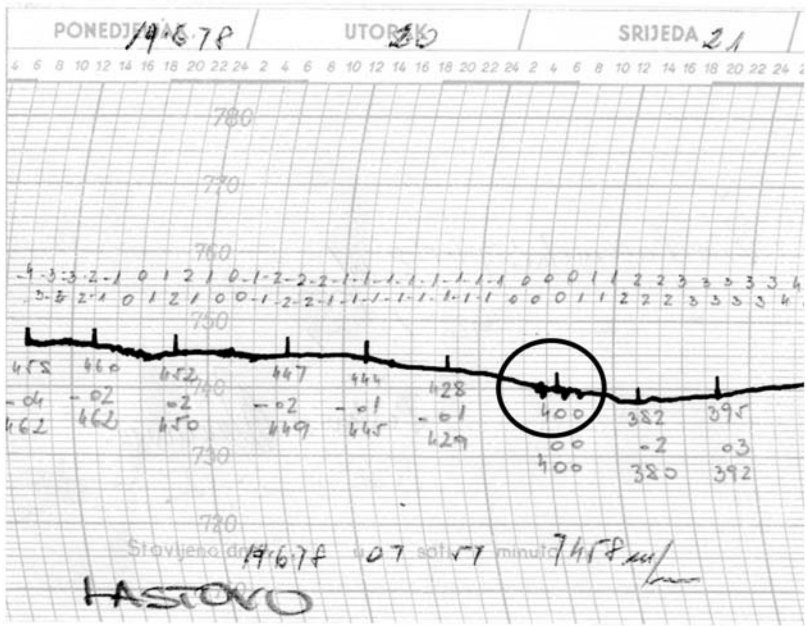

Figure 4. Part of the original weekly barograph record from Lastovo for 19–21 June 1978. The black circle indicates the air pressure perturbation that occurred around the time of the Vela Luka inundation. The air pressure scale is given in mmHg. Notice that time marks were regularly made (at 0700, 1400 and 2100 LT), thus minimizing the timing errors.

the latter contribution to the errors could easily have been underestimated, we performed an additional analysis of the movement of the disturbance using the bootstrap method, thus allowing for errors in the onset times at the stations to be randomly distributed. Using this method, the same propagation speed and direction error as those found by *Orlić* [1980] were obtained for the onset time error of ±5 min. If the onset time error was allowed to be ±10 min, then the speed error roughly doubled and the direction error tripled.

[12] In order to determine the shape, duration, and magnitude of the disturbance, as required for the oceanographic modeling, we utilized the wind speed and direction records from Lastovo, the only available wind record of good quality and significantly higher temporal resolution than the air pressure records (Figure 6). At the time of the onset of the air pressure perturbation and just prior to the Vela Luka inundation, there was an approximately 10 min surge of strong (10 m/s) winds accompanied by oscillations of wind direction from roughly N to S through E (unless stated otherwise, the wind direction is defined here according to the meteorological convention, i.e., as the direction from which the wind blows). Since the air pressure records were unusable for determining the perturbation duration, we assumed that the time scale of the wind perturbation was equal to the time scale of the air pressure perturbation. This is in accordance with recent similar cases in the Adriatic area that had higher-quality air pressure measurements [e.g., *Vilibić et al.*, 2004; *Šepić et al.*, 2009; *Belušić and Strelec Mahović*, 2009]. However, the shape of the air pressure perturbation can not be straightforwardly determined from the wind data. Therefore, we chose the simplest shape resembling other similar cases, namely the boxcar function. The magnitude of the perturbation, when read both from the air pressure record and indirectly from the wind speed magnitude, appeared to be about 3 mbar. To summarize, the chosen air pressure perturbation had the following characteristics: duration of 10 min, the shape of a boxcar function, and a magnitude of 3 mbar.

[13] The concurrent synoptic situation has been described in detail by, e.g., *Hodžić* [1979]. Its most pronounced feature was a deep, upper level trough and the related SW jet stream over the Apennines (Figure 7). The stream enabled warm, humid air to flow from the southwest towards the Adriatic

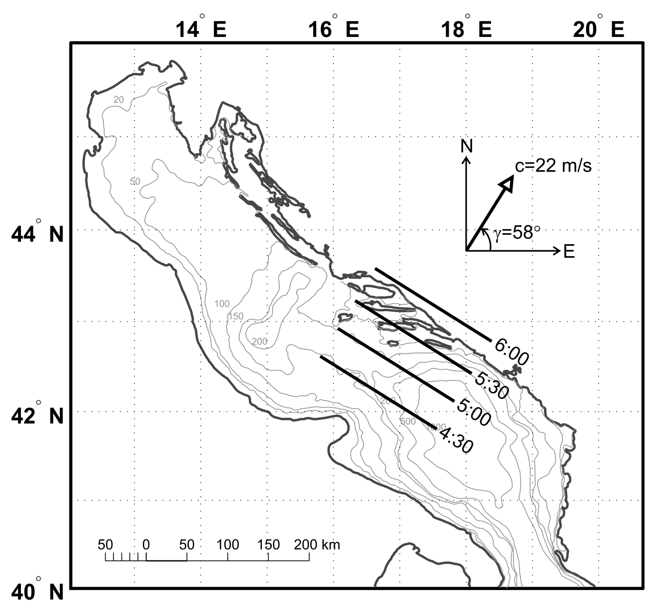

Figure 5. Reproduction of the main result of *Orlić* [1980], indicating the arrival times (LT) of the air pressure perturbation observed on 21 June 1978 as well as the speed and direction of its propagation.

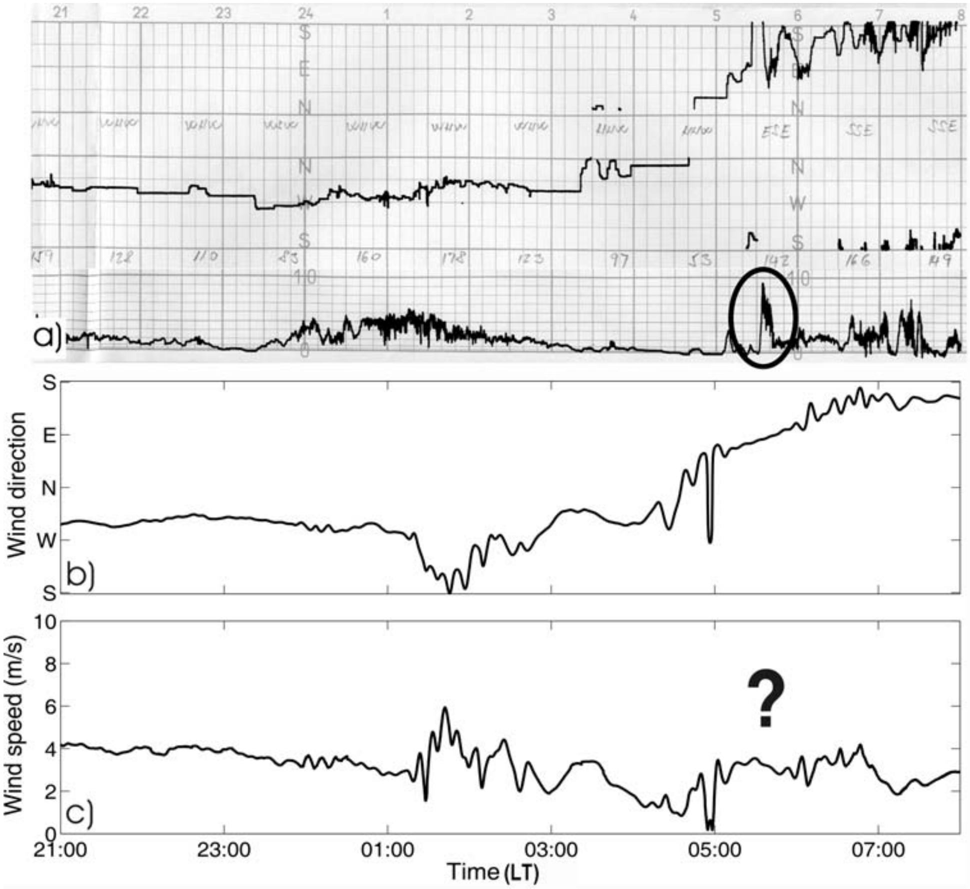

Figure 6. Wind speed and direction at Lastovo between 2100 LT on 20 June 1978 and 0800 LT on 21 June 1978. (a) The original anemograph record with wind directions in the upper part (the direction scale changes from S, through W, N and E, back to S, the seeming gap between two N's is due to the mechanical nature of the recording instrument) and wind gusts (m/s) in the lower part. The black oval indicates the 10 min surge of strong winds corresponding to the Vela Luka inundation. (b) Wind directions from the finest model grid. (c) Wind speeds from the finest model grid. The question mark signals the lack of the 10 min wind episode.

and created an environment favorable for the generation of convective storms.

3. Meteorological Modeling

[14] The meteorological observations and the preliminary simulation of this event [*Belušić and Strelec Mahović*, 2009] point to a convective system appearing over the wider area close to the time of the inundation. *Belušić and Strelec Mahović* [2009] reported the possibility of a general relation between the propagating convective storms and the large-amplitude sea waves. Air pressure perturbations inherent to the convective storms, when propagating with the speed of an ocean gravity wave, may be capable of provoking open sea waves that can, through a series of events, lead to inundations. It is the purpose of this section to examine the general mesoscale environment and to verify whether meteorological modeling is capable of reproducing the perturbation.

[15] We utilized the Weather Research and Forecasting-Advanced Research WRF (WRF-ARW) model, version 3.0.1 [*Skamarock et al.*, 2008]. It is a nonhydrostatic, primitive equation, atmospheric model capable of simulating phenomena from planetary scales to turbulence. The setup of the model employed herein is as follows. There are three, two-way-nested domains at horizontal resolutions of 24, 8, and 2 km with 86 × 86, 100 × 100, and 165 × 165 grid points, respectively (Figure 8). The vertical model domain extends from the surface up to the 50 mbar height and is covered with 81 vertical levels at spacings that increase with height. The set of parameterizations used includes: the Mellor-Yamada-Janjic scheme for turbulent vertical mixing, the unified Noah land-surface model, the Lin et al. microphysics scheme, and, for the two coarser resolution domains, the Kain-Fritsch cumulus scheme. The initial and boundary conditions were taken from the ECMWF ERA-40 forecasts, which are available every 3 h.

[16] As in the previous studies of similar phenomena [e.g., *Belušić et al.*, 2007; *Šepić et al.*, 2009], the simulation results were shown to be highly sensitive to various details of the model setup. The simulation shown herein is the optimal one in terms of the correspondence of the simulation to the measurements and observations. Nevertheless, the model could not reproduce the fine-scale surface disturbance seen in the measurements. This is evident in Figure 6, where the modeled time series of wind speed and direction are compared to the measured values. There is a wind speed perturbation in the model between 0100 and 0200 LT that

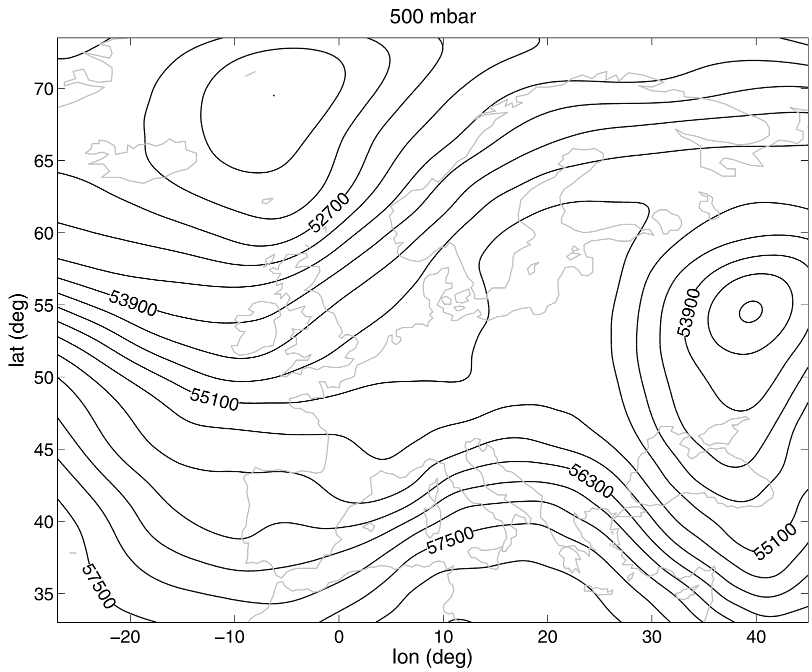

Figure 7. Geopotential height of the 500 mbar surface at 0100 LT on 21 June 1978 (source of data: ECMWF).

somewhat resembles the measured perturbation occurring at 0500 LT. It is possible that a numerical model sometimes reproduces such features before they actually appear in the measurements and reproduces them with a modified shape [e.g., *Belušić et al.*, 2007]. However, in this case it is obvious that the model correctly simulated a larger-scale change, evident as the wind direction shift from NNW to SSE in both the model and the measurements between 0400 and 0700 LT. The small-scale disturbance is embedded within this larger-scale change, and the model should thus reproduce the disturbance at the correct time. Since this is not the case, we cannot use the model either for enhancing our knowledge of the details of the air pressure perturbation or for relating the surface disturbance to the atmospheric mesoscale features. The inability of the model to reproduce the surface perturbation is due the nonlinear nature of the atmospheric system that generated the perturbation. It has been shown that the appearance of similar features in the model depends on many factors, in particular on the parameterization of microphysics, initial and boundary conditions and the setup of the model domains (see *Belušić et al.* [2007] for details). Nevertheless, an additional comparison of the model results with the soundings and upper level charts (not shown) confirms that the model did perform well in terms of the reproduction of the wider mesoscale environment and the larger-scale flow features, so the model can document the general atmospheric background favorable for the development of the perturbation. Figure 9 depicts the convective available potential energy (CAPE) and the flow at 700 mbar. The moderately high CAPE values over the region, together with the flow over the Apennines, introduce a setup favorable for the formation of moist convective systems. Indeed, as shown in Figure 9, the cloudiness develops over the area as the moist, warm air from the southwest flows over the mountain barrier and reaches the Adriatic. The cell structure is indicative of convective cloudiness, which, as mentioned earlier, is capable of creating air pressure disturbances. Additionally, the soundings indicate that the vertical structure was favorable for the ducting of atmospheric gravity waves. Consistent with more recent similar cases, it is not always easy to distinguish between the surface effects of the convective system and the gravity waves, particularly because they are often coupled in some manner [e.g., *Belušić et al.*, 2007; *Šepić et al.*, 2009]. However, since the atmospheric setup considered herein closely resembles those examined previously, the method used to determine the details of the surface air pressure per-

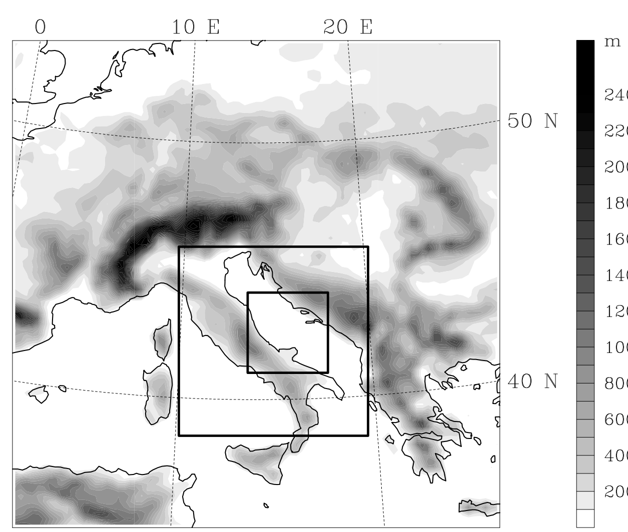

Figure 8. The setup of the WRF-ARW model domains. The terrain from the largest domain is given with a 100 m increment. The two squares denote the two inner domains.

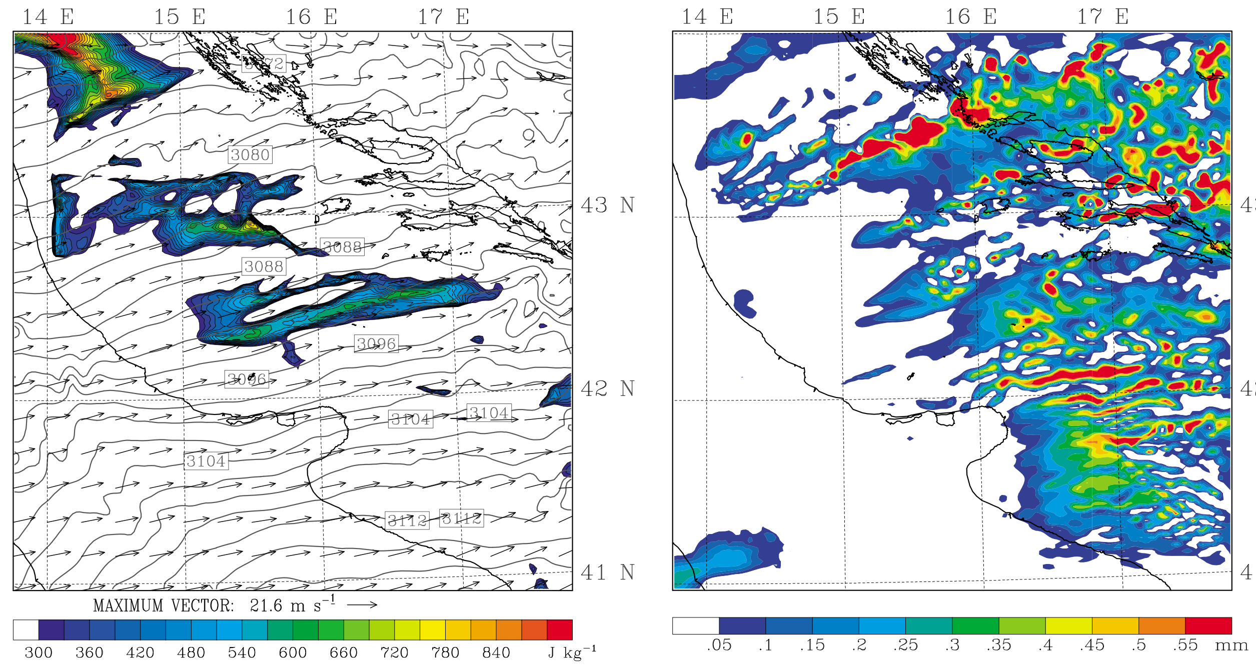

Figure 9. (left) The convective available potential energy (CAPE, shaded) with the geopotential height (contours) and wind vectors at 700 mbar, at 0300 LT on 21 June 1978. (right) Column-integrated cloud hydrometeors at 0400 LT on 21 June 1978.

turbation used in the previous section is further justified as it partially relies on the comparison with other cases.

4. Oceanographic Modeling

[17] The response of the Adriatic sea level and currents to the atmospheric perturbation analyzed above was modeled using the fully nonlinear, two-dimensional, barotropic, hydrodynamic model ADCIRC-2DDI (where ADCIRC means "Advanced Circulation Model for Shelves, Coasts and Estuaries" and 2DDI stands for "two-dimensional depth integrated"). The model was developed by *Luettich et al.* [1992] and *Westerink et al.* [1994] and has since had a successful history of tidal and storm surge prediction in coastal waters and marginal seas (http://www.adcirc.org/Related_publications.html). The depth-integrated, shallow water equations, derived through vertical integration of the three-dimensional momentum and mass balance equations subject to the hydrostatic assumption, form the basis of the model. The equations are

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -\frac{\partial}{\partial x}\left(\frac{p_a}{\rho_o} + g\xi\right) + \frac{\tau_{sx}}{\rho_o H} - \frac{\tau_{bx}}{\rho_o H} + D_x, \quad (1)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU = -\frac{\partial}{\partial y}\left(\frac{p_a}{\rho_o} + g\xi\right) + \frac{\tau_{sy}}{\rho_o H} - \frac{\tau_{by}}{\rho_o H} + D_y, \quad (2)$$

$$\frac{\partial \xi}{\partial t} + \frac{\partial (UH)}{\partial x} + \frac{\partial (VH)}{\partial y} = 0, \quad (3)$$

where t represents the time, (x, y) are the Cartesian coordinates, ξ is the sea surface elevation relative to the geoid, (U, V) are the depth-averaged horizontal velocity components, $H = \xi + h$ is the total water depth (with h being the bathymetric depth relative to the geoid), f is the Coriolis parameter defined as 2 Ω sin φ (where Ω is the angular frequency of rotation of the earth and φ is the latitude), g is the acceleration due to gravity, ρ_o is the reference density of water, p_a is the applied air pressure, τ_{sx} and τ_{sy} are the wind stresses, τ_{bx} and τ_{by} are the bottom stresses, and D_x and D_y are the horizontal momentum diffusion terms defined through the standard scheme developed by *Smagorinsky* [1963]. The bottom stress terms are parameterized using the usual quadratic friction law

$$\left(\tau_{bx}, \tau_{by}\right) = C_f \rho_o \sqrt{U^2 + V^2}(U, V), \quad (4)$$

where C_f is the nonlinear bottom friction coefficient. In this study, the coefficient was assumed to equal 0.003.

[18] ADCIRC-2DDI is a finite element model, which represents the modeled domain using triangles of different shapes and sizes. This feature is important for the complex Adriatic Sea, characterized by numerous small islands and narrow channels. The numerical grid used for the computation encompassed 44965 elements and 26956 nodes that, in a realistic way, represent the Adriatic (as seen in Figure 10). Using the model, we were capable of faithfully simulating the response of the sea to the atmospheric forcing, which sensitively depends on the main bathymetry features characterized by large scales in the open Adriatic and by small scales in the coastal basins. In order to keep the computational costs low, we could not afford too high of a grid resolution in the open sea, nor could we consider individual buildings in Vela Luka. However, with a grid size not surpassing 7 km in the open Adriatic and being as small as 150 m in the Vela Luka Bay, the simulations turned out to be realistic. All of the runs in the

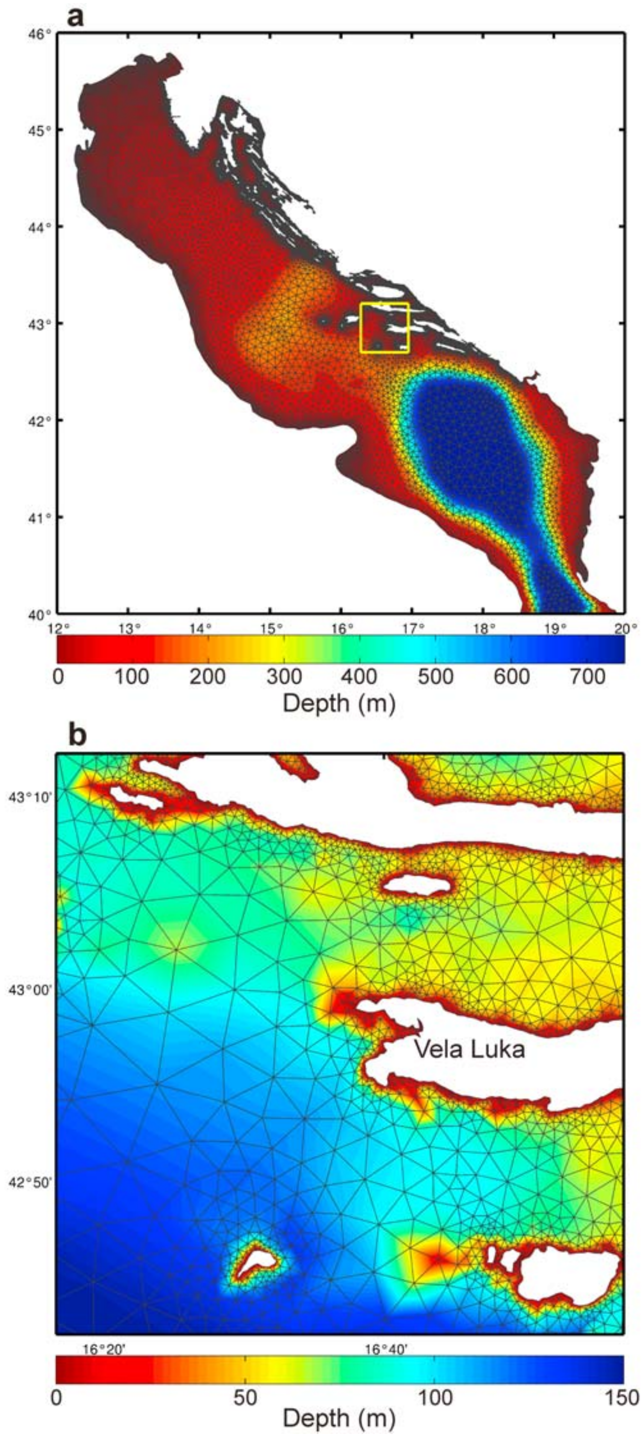

Figure 10. (a and b) The Adriatic Sea as resolved by the ADCIRC-2DDI model. The solid rectangle in Figure 10a marks the area shown in Figure 10b. Notice that the depth scales in Figures 10a and 10b differ.

present study covered the whole Adriatic, with the open boundary being placed in the Otranto Strait. No normal flow was imposed along the closed boundaries, and a radiation condition was applied at the open boundary. By positioning the open boundary far from Vela Luka, which is of primary interest for the present study, we insured that no artificial open boundary interferes with the waves developing in the Adriatic and influencing our area of interest. Additionally, we insured that the waves, if partially reflected at the boundary, do not reach the area of interest before the run ends.

[19] Each run was started from a state of rest, with the atmospheric perturbation positioned above Italy in order to avoid triggering spurious waves, and was performed with a 1 s time step over 12 hours. The model time was transformed to LT by assuming that the sea level maximum simulated for Vela Luka corresponds to the high water observed there at 0515 LT.

[20] External forcing was restricted to a disturbance in the air pressure field only. In accordance with the meteorological analyses described in the second section, the disturbance had the form of a boxcar function characterized by a 3 mbar increase in the air pressure that was 200 km wide and propagated across the Adriatic at varying speeds and directions, but it always lasted 10 min and had a midpoint passing over Vela Luka Bay. Air pressure disturbances of different forms (step, ramp, sine) were also considered, but our Adriatic model forced by these perturbations underestimated the observed sea level variability in Vela Luka by an order of magnitude. As for the air pressure forcing resulting from the WRF-ARW model run, the Adriatic model subjected to the forcing did produce an increase in high-frequency sea level activity in Vela Luka Bay, but it was again too small (the trough-to-crest height being ca. 50 cm) and occurred too early (between 0100 and 0200 LT); at 0500 LT, the modeled sea level variability was even smaller, reflecting the failure of the meteorological model to reproduce the main mesoscale perturbation, as discussed in the third section.

[21] A series of runs, forced with a traveling band of 10 m/s wind having similar characteristics as the air pressure disturbance, showed that the wind stress is much less important as the forcing agent than is the air pressure. This finding is supported by a simple comparison of the p_a and τ_s terms in (1) and (2). If the air pressure changes by 1 mbar over a distance of 10 km, the wind stress should amount to 1 N/m^2 in a sea that is 100 m deep in order for the wind stress effect to be similar to the air pressure influence. This implies that the realistic wind forcing may be important in coastal areas where depths are of O (10 m), but it is not as important in the open middle and south Adriatic or even in Vela Luka Bay where the 50 m isobath is found close to the coast (Figure 1).

[22] To explore conditions under which the boxcar air pressure perturbation is capable of resonantly driving the Adriatic Sea, a series of runs was performed by varying the speed (c) of the perturbation from 15 to 40 m/s and its direction (γ) from 10 to 80°. Let us reiterate that the direction determines where the perturbation propagates to, and it is measured in a positive sense from an eastward direction (so that, for example, γ = 45° means that the air pressure disturbance travels towards the northeast). To start with, results obtained by the 754 runs of the Adriatic model were considered only for Vela Luka. Two parameters were selected to illustrate the response of the bay to variation in the speed and direction of the air pressure disturbance: the difference between the maximum and minimum sea level heights obtained by each run (Figure 11a) and the total energy determined by integrating the sea level energy density spectrum resulting from every simulation (Figure 11b). Also shown in Figure 11 are the ranges of speeds (20–24 m/s) and directions (56–60°) determined by *Orlić* [1980] as well as the

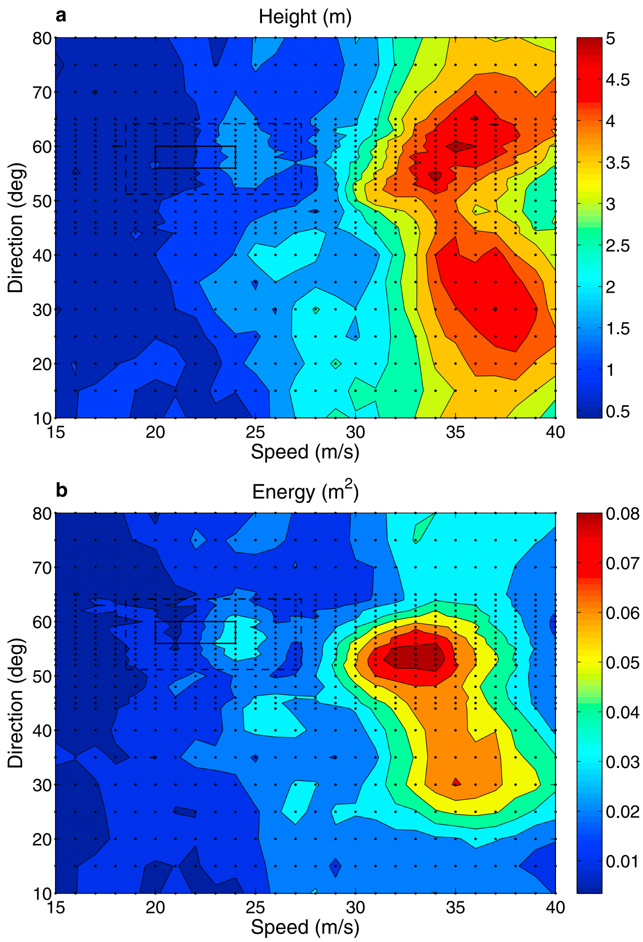

Figure 11. (a) The difference between the maximum and minimum sea level heights and (b) the integral of the sea level energy density spectrum obtained for the head of Vela Luka Bay by forcing the Adriatic model with the boxcar air pressure perturbation traveling at various speeds (c) and directions (γ). Each dot represents a run of the Adriatic model; the total number of runs is 754. The solid rectangle indicates the ranges of speeds and directions determined by *Orlić* [1980], and the dashed rectangle marks the ranges obtained in this paper by assuming that the timing error of barographs used in the Adriatic in 1978 was ±10 min.

ranges (18.5–27.3 m/s, 51.2–64.2°) obtained in this paper by assuming that the timing error of the barographs used in the Adriatic in 1978 was ±10 min.

[23] Figure 11 contains a wealth of information that deserves careful consideration. Obviously, there is a primary maximum in the response of the Vela Luka sea level to the air pressure forcing achieved for speeds ranging between 30 and 40 m/s and a secondary maximum obtained for speeds close to 25 m/s. Both maxima show a decrease in speed with an increase in direction. This may be interpreted in terms of the so-called Proudman resonance and its change with the varying direction of atmospheric perturbation. The Proudman resonance occurs when the speed of an air pressure disturbance c is close to the speed of shallow water waves $v = (gh)^{1/2}$ [*Proudman*, 1929, 1953]. (Let it be mentioned that the term "Proudman resonance" has been questioned recently, on the grounds that Horace Lamb preceded Joseph Proudman in theoretically exploring the mechanism [*Vennell*, 2007]. The fact, however, is that Proudman published a detailed theoretical study [*Proudman*, 1929] before a part of it appeared in the 6th edition of Lamb's Hydrodynamics [*Lamb*, 1932], whereas the mechanism was not mentioned in the 5th edition of the book [*Lamb*, 1924]. Of course, an analogous mechanism has been previously noted in studies addressing the response of the sea to the tidal forcing in the 19th century [see e.g., *Proudman*, 1953, and references therein], but Proudman appears to be the first who stressed its importance for atmosphere-sea coupling.) When the direction of the atmospheric perturbation changes, so does the path it follows over the Adriatic, and consequently the speed of shallow water waves: e.g., for $\gamma = 30°$, the mean value of v between the coast of Italy and Vela Luka is 32.6 m/s, and for $\gamma = 60°$, the mean value decreases to 30.8 m/s (Figure 12). The closer c is to v, the stronger the amplification is of the sea wave driven in the Adriatic by the air pressure wave that travels from the coast of Italy to Vela Luka.

[24] Another interesting finding stemming from Figure 11 is that the response of the Vela Luka sea level to the air pressure forcing is patchy, and, in particular, that besides the primary maximum there is also a secondary maximum. The multiple maxima in Vela Luka Bay were obtained previously

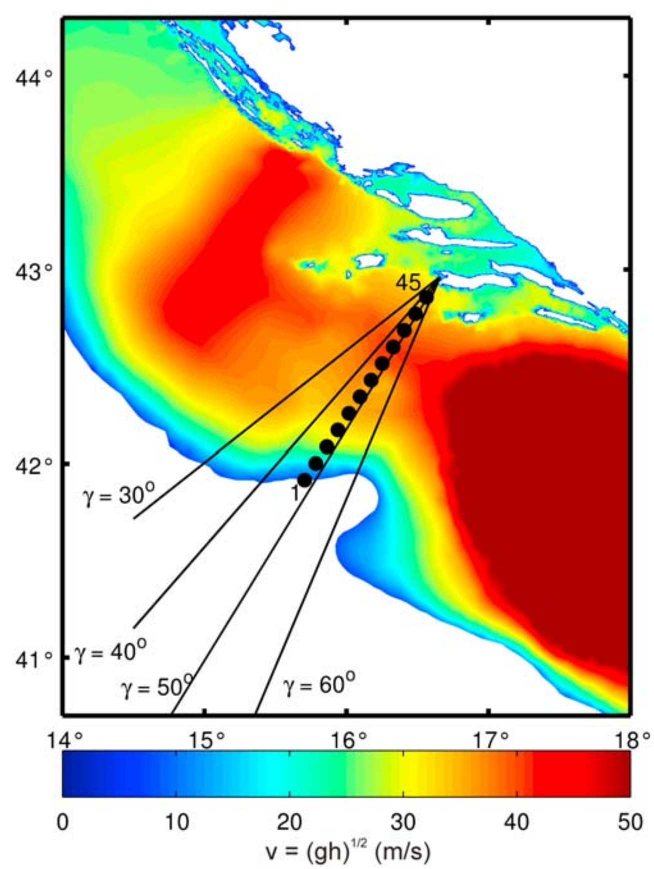

Figure 12. Distribution of the speed of shallow water waves (v, m/s) in the middle and south Adriatic. Superimposed are tracks of the air pressure perturbations traveling from the Italian coast to Vela Luka at four different directions. A subset of the points (1–45) used to prepare Figure 15 is also indicated.

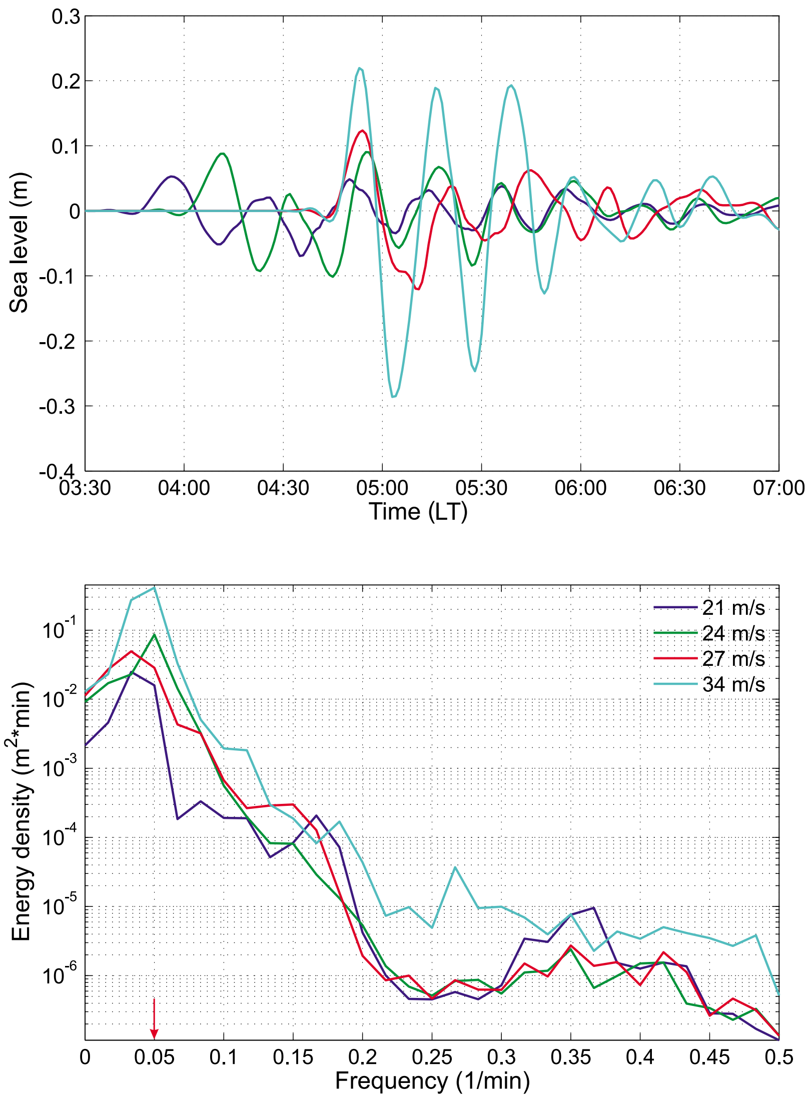

Figure 13. (top) Sea levels and (bottom) corresponding energy density spectra calculated for a point in front of the Vela Luka Bay mouth by assuming that the direction of the air pressure perturbation is fixed (γ = 56°) but that its speed may vary (c = 21, 24, 27 or 34 m/s). The relative offset of the four time series in Figure 13 (top) is related to the way the model time was transformed to the LT and reflects the fact that the maximum sea level inside Vela Luka Bay lags behind the first incoming wave when the speed is small, whereas the maximum coincides with the first wave when the speed is large. The red arrow in Figure 13 (bottom) marks the period of the fundamental mode of Vela Luka Bay (20.0 min), empirically determined by *Pasarić and Orlić* [2007].

by *Vilibić* [2005] as a byproduct of a modeling study focusing on some of the other Adriatic bays, but their positions and strengths were different than those simulated herein. This is probably due to a different air pressure forcing as well as to the fact that only a part of the Adriatic Sea was modeled in the paper, and therefore a radiation condition had to be imposed at the open boundary located close to Vela Luka Bay. In order to interpret the present finding, we plotted in Figure 13 the sea levels and corresponding energy density spectra calculated for a point in front of the mouth of Vela Luka Bay by assuming that $\gamma = 56°$ and that $c = 21$, 24, 27, and 34 m/s; the four speeds were selected to correspond with the primary maximum (34 m/s), the secondary maximum (24 m/s), and the two minima (21 and 27 m/s) of the response depicted in Figure 11. Careful consideration of the spectra reveals that for speeds of 24 and 34 m/s, sea level variability peaks at the period of 20 min with the latter peak being stronger, and that for speeds of 21 and 27 m/s, the variability peaks at a longer period with the latter peak surpassing the former one. As the observed period of the fundamental mode of Vela Luka Bay is 20.0 min [*Pasarić and Orlić*, 2007], this suggests that the response of the bay to the air pressure forcing depends not only on the Proudman resonance in the open Adriatic but also on the harbor resonance in the bay itself [*Miles and Munk*, 1961]. The sea level variability in the bay is largest when the wave packet in front of Vela Luka Bay is characterized by large amplitudes and periods close to 20 min (c = 34 m/s). The variability is still pronounced when the amplitudes are

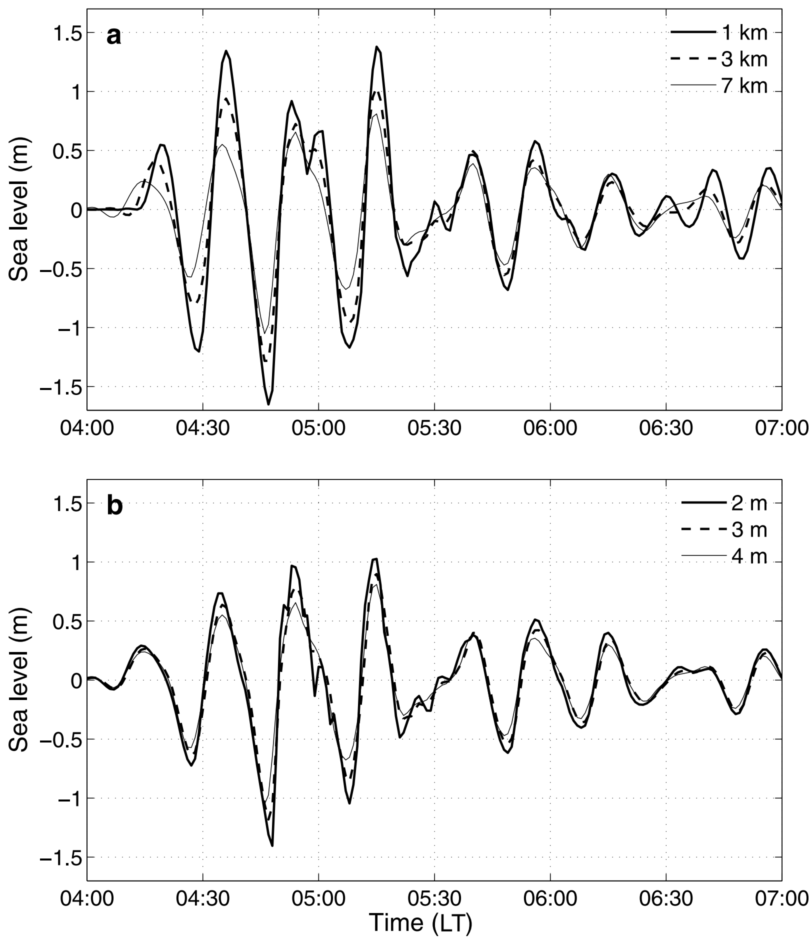

Figure 14. Sea levels computed for the head of Vela Luka Bay by assuming that the speed of the air pressure perturbation is 24 m/s and that its direction is 56° and (a) improving the grid resolution in the open sea from 7 via 3 to 1 km and (b) reducing the minimum bottom depth of the bay from 4 via 3 to 2 m. In Figure 14a, the minimum bottom depth was maintained at 4 m; in Figure 14b, the original grid resolution of 7 km was retained in the open sea.

smaller because c differs from v, if the periods are close to 20 min (c = 24 m/s). The variability is smaller when the periods differ from 20 min, even if the open sea amplitudes are relatively large because c is close to v (c = 27 m/s). Of course, the variability is at a minimum when the amplitudes are small, due to c being much smaller than v, and when the periods differ from 20 min (c = 21 m/s). To summarize, for the excitation of Vela Luka Bay, it is important not only how the forced wave amplifies in the open Adriatic, which is controlled by the Proudman resonance mechanism, but also how the wave packet is formed there. The latter process depends on the duration of air pressure forcing as well as on the effect of the Italian coastline and the scattering supported by variable bathymetry; the atmospheric disturbance lasting 10 min could, for some speeds of propagation, produce the wave packet in front of Vela Luka Bay characterized by a 20 min period. When the wave packet enters the bay from the open Adriatic, its final amplification is regulated by the harbor resonance mechanism.

[25] It is interesting that the speed and direction of the air pressure disturbance that crossed the Adriatic in the morning hours of 21 June 1978 correspond to the secondary maximum in Figure 11 and not with the primary maximum, which implies that the surge could have been even worse if the speed of the atmospheric perturbation was larger. On the other hand, for the observed speed and direction, our model provides a trough-to-crest height of 2 m rather than the 6 m that were actually observed. The discrepancy is most likely due to some limitations of the oceanographic modeling: rather coarse sampling of the air pressure forcing and resulting waves in the open sea and the inability to reproduce flooding and drying of the interior part of Vela Luka Bay. Due to the large number of simulations needed, the best grid resolution we could afford in the open sea was about 7 km. Furthermore, since the model became unstable when the sea level variability was comparable with the bottom depth, we had to restrict the minimum bottom depth to 4 m. In order to illustrate how sensitive the model results could be to the changing grid resolution and minimum bottom depth, we present in Figure 14 sea levels computed for Vela Luka with the air pressure disturbance traveling at c = 24 m/s and γ = 56° upon (a) improving the grid resolution in the open sea to 3 and 1 km and (b) reducing the minimum bottom depth to 3 and 2 m. Figure 14 illustrates that there is a 70% increase in the sea level range when the grid resolution is improved and a 30% increase if the minimum bottom depth is reduced (with the latter being potentially even

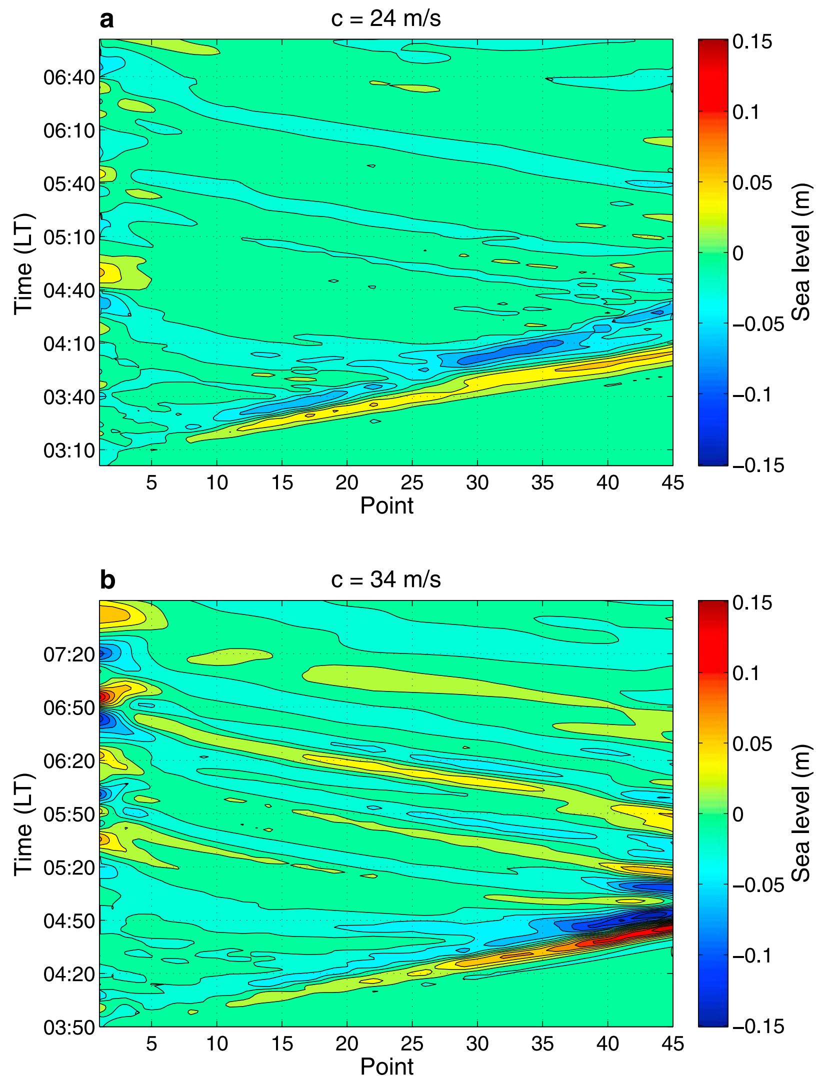

Figure 15. Sea level as a function of distance from the Italian coast (point 1) to the vicinity of Vela Luka (point 45) and time. Positions of the points are indicated in Figure 12. (a) Illustration obtained by forcing the Adriatic model with the boxcar air pressure disturbance having a speed of 24 m/s and a direction of 56°, and (b) illustration resulting from the simulation allowing for a speed of 34 m/s and again a direction of 56°.

larger if flooding and drying were taken into account). This strongly suggests that a finer-scale modeling could bring the simulations closer to reality. Unfortunately, such modeling was not feasible in the scope of this paper, which aimed at elucidating the resonant atmosphere-sea coupling via a large number of simulations.

[26] As already pointed out, the Adriatic surge of 21 June 1978 impacted not only Vela Luka but also, to a smaller extent, a number of places along both the Croatian and Italian coasts. In order to interpret these empirical findings, it is instructive to consider our modeling results for a wider area. To begin with, Figure 15 shows sea levels computed for a line connecting the Italian coast (point 1) with the vicinity of Vela Luka Bay (point 45) by applying the previously described air pressure perturbation and assuming that $\gamma = 56°$ and that c = 24 and 34 m/s. Several processes are clearly illustrated by Figure 15. A sea level low is driven by the air pressure perturbation from the Italian coast to Vela Luka and is amplified on its way, due to the Proudman resonance. The low is preceded by a sea level high, presumably signaling the influence of the boundary condition imposed at the Italian coast, and is followed by a series of highs and lows, most likely resulting from scattering due to the variable bathymetry. Figure 15 also dramatically illustrates how the scattering and the reflection from the Croatian coast result in waves that return towards the Italian coast and, with a delay, support considerable sea level activity there. Equally significant is the difference between the speed of waves approaching the Croatian coast and the speed of waves arriving at the Italian coast; the former is nearly constant since it is primarily defined by the speed of the air pressure disturbance (c), and the latter decreases towards the coast as it is equal to the speed of shallow water waves (v).

[27] Figure 16 illustrates conditions in a wider middle and south Adriatic area by depicting the difference between the maximum and minimum sea levels obtained during a run (wave height) as well as the time of the maximum sea level achieved during a simulation (onset time). Again, the air

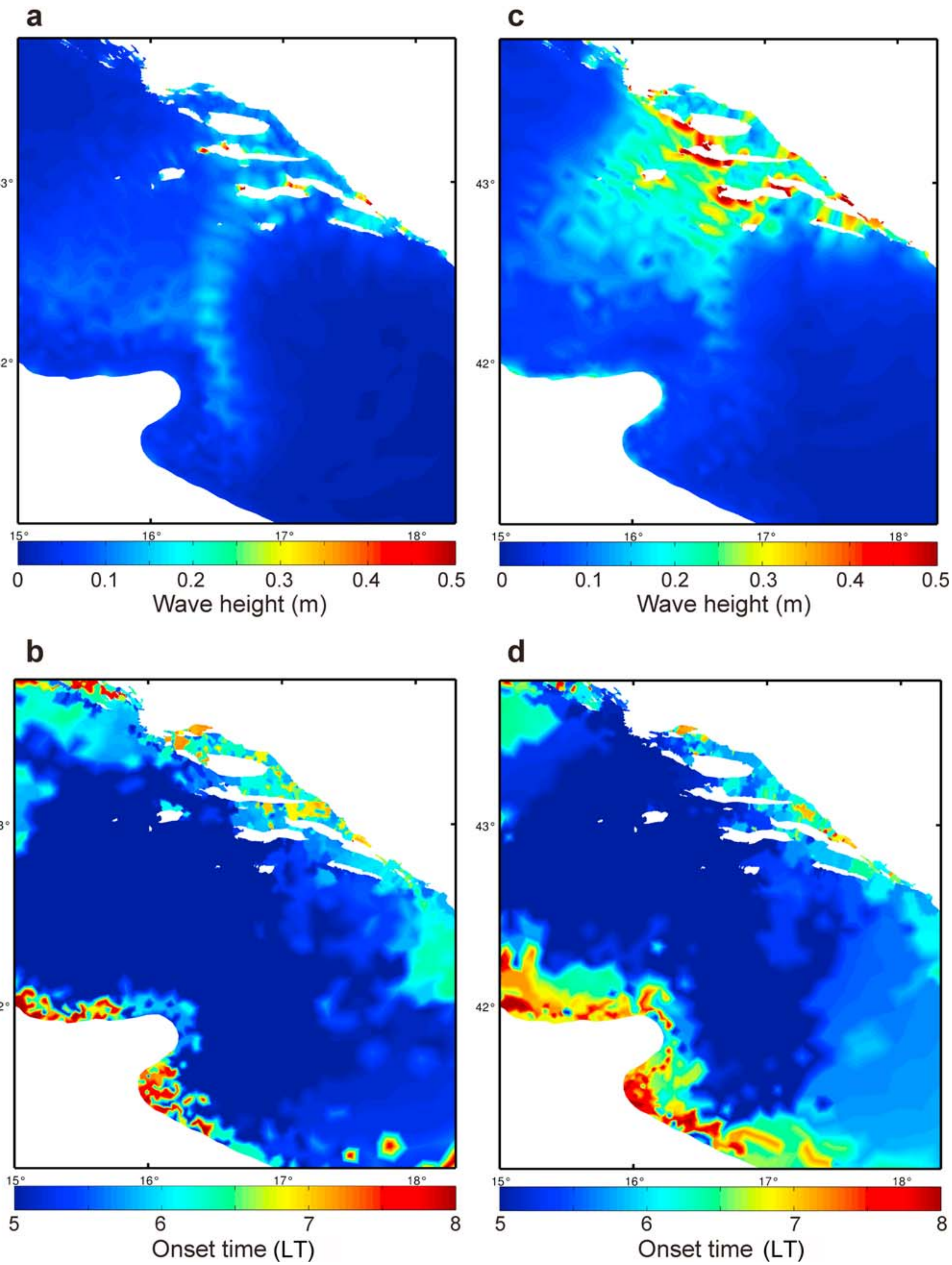

Figure 16. (a and c) Wave heights and (b and d) onset times obtained by subjecting the Adriatic model to the boxcar air pressure disturbance traveling at a direction equal to 56° and at speeds of 24 m/s (Figures 16a and 16b) and 34 m/s (Figures 16c and 16d).

pressure perturbation is assumed to be characterized by γ = 56° and by c = 24 and 34 m/s. The wave heights are larger along the Croatian than along the Italian coast, and their extremes appear to be highly localized since, as already pointed out, they are controlled not only by the Proudman resonance in the open sea but also by the shoaling in front of the coasts and by the harbor resonance in the coastal basins. It is now easy to understand why the extremes were missed by a small number of tide gauges operating in the Adriatic in 1978. As for the onset times, they clearly show the lag of a large part of the Croatian coast and an even greater lag of the whole Italian coast behind Vela Luka. Visual inspection of the individual time series (not shown), obtained for stations inside the middle Adriatic archipelago (e.g., Split Harbor) and outside it (e.g., Dubrovnik), reveals that the pronounced sea level activity lasted about two times longer at the former stations than at the latter stations. Obviously, the persistent ringing after the initial impulse is due to the wave energy being trapped among the islands, whereas the perturbation is short-lived when the wave energy spreads over a wider sea area. This qualitatively explains the difference between the tide gauge records shown in Figure 2 and commented upon in the second section.

[28] Finally, it is tempting to compare Figure 16, in particular the wave heights and the onset times related to the atmospheric perturbation traveling at a speed of 24 m/s, with Figure 3. It should be stressed that the modeled heights and times are not entirely comparable with the observed and measured values. In particular, if more than one wave packet occurred in the Adriatic area on 21 June 1978 because more than one air pressure disturbance passed above the sea (I. Vilibić, personal communication, 2008), one may not be sure that the empirical heights and times are related to the first wave packet modeled herein. Moreover, the time of the maximum sea level simulated over a 12 h interval does not necessarily correspond with the time that was recorded by the eyewitnesses since they could easily remember the first maximum that flooded their town even if it was not the largest one. Despite these difficulties, the results of the correlation and regression analysis of the empirical and modeled heights and times are surprisingly good (Figure 17). Admittedly, the correlation coefficient may be questioned for the wave heights because the Vela Luka (i.e., station 19) heights far surpass the other heights, but it turns out to be even higher if Vela Luka is excluded from the analysis. The correlation coefficient is high for the onset times. The modeled heights underestimate the empirical heights, most likely because the form of air pressure disturbance applied to the oceanographic model was not completely realistic, and the resolution of oceanographic modeling had to be limited. The modeled times agree well with the empirical times, possibly signaling that the timing of waves traveling towards the Croatian coast and then towards the Italian coast is not sensitively dependent on the exact form of the forcing air pressure perturbation.

5. Discussion

[29] Early on 21 June 1978, pronounced, high-frequency, sea level oscillations were observed in Vela Luka Bay on the Island of Korčula and in a wider middle and south Adriatic east coastal area and, with some delay, along the west coast. The trough-to-crest height was largest at Vela Luka, and with a height of 6 m this was the most pronounced such event observed in the Adriatic in the 20th century. In order to interpret the event, four different hypotheses have been put forward, without any of them being supported by an in-depth, dynamical analysis. In this paper, one of the hypotheses, that which related the event to a mesoscale air pressure disturbance traveling above the Adriatic at the time of surging, is reconsidered by using all the available data as well as state-of-the-art meteorological and oceanographic models. Careful analysis of the sea level observations and measurements reveals that the sea level heights at the east Adriatic coast were much larger than at the west coast and that the west coast oscillations mostly lagged behind the east coast variability. A fresh look at the air pressure data confirms the finding by *Orlić* [1980], according to which a mesoscale atmospheric disturbance propagated at about 22 m/s in a northeastward direction above the area affected by surging, and it also enables various timing errors in the barograph records to be taken into account. Additionally, analysis of a simultaneous wind record reveals that the disturbance lasted about 10 min. The meteorological model employed (WRF-ARW) proved unable to reproduce the mesoscale disturbance coinciding with the surge, but it showed that the background atmospheric conditions were favorable for the development of such disturbances. The oceanographic model ADCIRC-2DDI, forced by the air pressure disturbance characterized by a 3 mbar increase, the shape of a boxcar function, and the other parameters as stated above, successfully reproduced sea level variability in Vela Luka Bay, reaching a few meters and thus surpassing the inverted barometer response by two orders of magnitude. The model also illustrates how the scattering due to the variable bathymetry and the reflection from the east coast resulted in waves that returned towards the west coast and generated considerable sea level activity there. Comparison of the empirical sea levels with the modeled values carried out for the whole area strongly supports the rather weak mesoscale atmospheric disturbance as an adequate forcing agent.

[30] It is of interest to consider in some detail the dynamics behind the numerical simulations, and thus presumably behind the 1978 Adriatic surging event. It appears that the sea level variability in Vela Luka Bay of O (1 m) develops from the air pressure forcing of O (1 mbar) during a process that has four phases.

[31] 1. An air pressure disturbance travels from the west Adriatic coast to the mouth of Vela Luka Bay and generates a wave packet in the sea. In order to illustrate the basic phenomenon, let us assume that the x axis originates at the west coast with the bay mouth being positioned at $x = L$, that the depth is constant along the line, and that the forcing is defined via the so-called equilibrium elevation

$$\bar{\xi} = -\frac{p_a}{g\rho_o} = f\left(t - \frac{x}{c}\right).$$

The sea surface elevation at the bay mouth is then given by [*Proudman*, 1929, 1953]

$$\xi_m = F_1\left[f\left(t - \frac{L}{c}\right) - \frac{c}{v}f\left(t - \frac{L}{v}\right)\right], \quad F_1 = \frac{1}{1 - \frac{c^2}{v^2}}, \qquad (5)$$

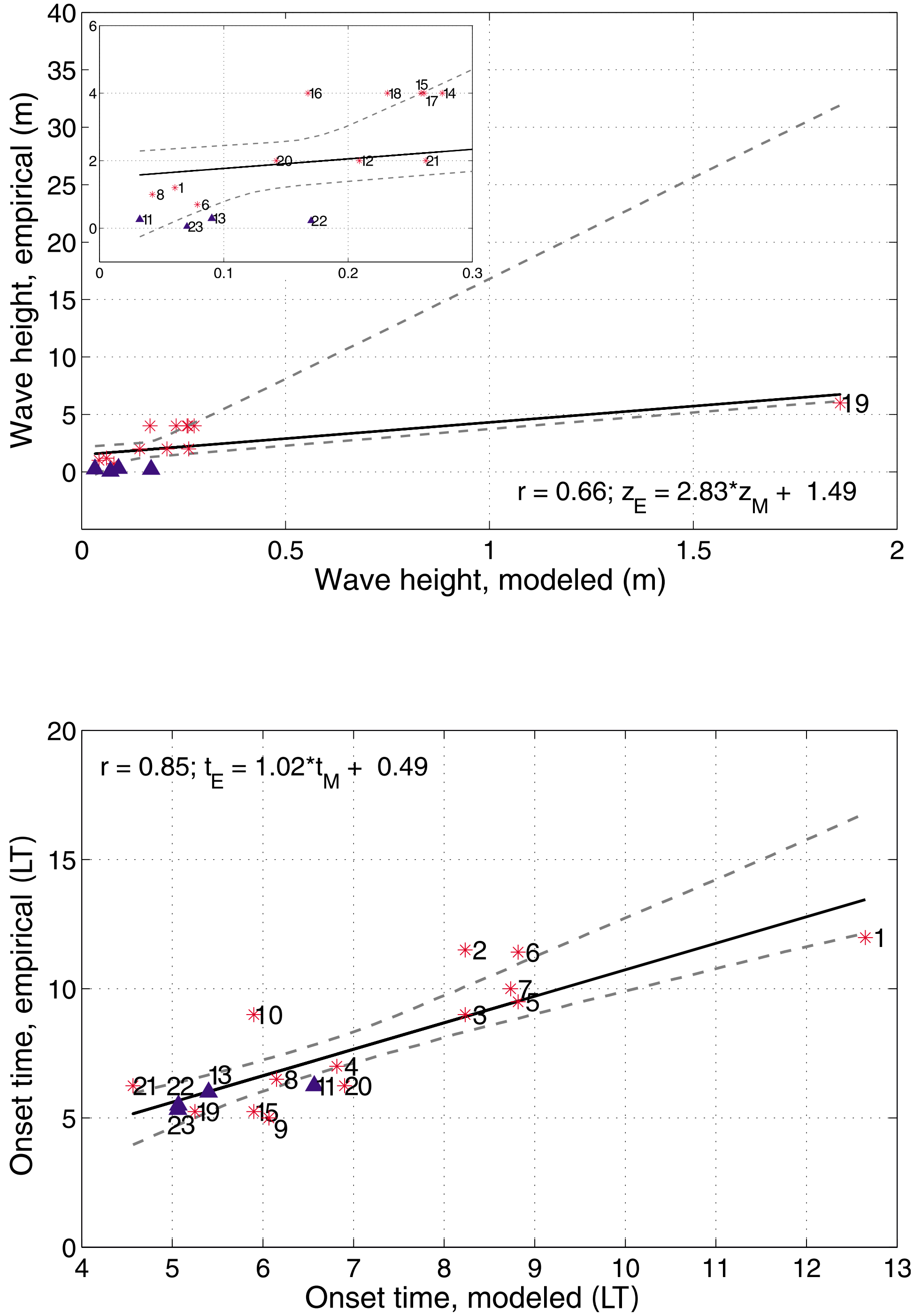

Figure 17. Comparison of the empirical and the modeled (top) wave heights and (bottom) onset times. The empirical values are those reported in Figure 3. The modeled values were obtained by subjecting the Adriatic model to the air pressure disturbance traveling at a speed of 24 m/s and a direction of 56° (Figures 16a and 16b). Stars relate visual observations to modeling results, and triangles connect instrumental measurements with modeling results. Numbers 1–10 refer to the stations distributed along the west coast, and numbers 11–23 refer to the east coast stations; the positions of all the stations are shown in Figure 3. Dashed lines indicate 95% confidence intervals obtained by a bootstrap procedure with 1000 samples.

where subscript m denotes the mouth of the basin, whereas the other symbols follow the notation previously introduced. It is obvious that two waves arrive at the bay mouth: a wave driven by the air pressure disturbance (first term in the square bracket) and a shallow water wave traveling away from the west coast (second term). When $c < v$ the free wave arrives before the forced wave and *vice versa*. With $c = 24$ m/s and $v \approx 30$ m/s, the factor F_1 is close to 2.8. Of course, under realistic conditions the process is more complicated because variable bathymetry supports scattering and formation of the wave packets that are comprised of more than two waves. The scattering at the step was theoretically explored by *Garrett* [1970], whereas the waves emanating from the ridge were analytically and numerically considered by *Vennell* [2007]. The overall effect of all of these processes is that during this phase, the wave driven by the air pressure perturbation is amplified in the open Adriatic due to the Proudman resonance, and also that the wave packet is formed due to the effects of the coastline and bathymetry. Both phenomena are relevant for the way the sea level is eventually perturbed in Vela Luka Bay.

[32] 2. The waves enter Vela Luka Bay and are amplified while propagating from the mouth to the head due to the funnel-shaped form of the basin. The sea surface elevation at the head of the bay may be estimated from Green's law [e.g., *Lamb*, 1932]

$$\xi_h' = F_2 \xi_m, \quad F_2 = \left(\frac{b_m}{b_h}\right)^{1/2} \left(\frac{h_m}{h_h}\right)^{1/4}, \tag{6}$$

where b is the breadth and h is the depth of the basin, and subscripts m and h denote the mouth and head of the basin, respectively. With $b_m = 5600$ m, $b_h = 300$ m, $h_m = 70$ m, and $h_h = 5$ m, the factor F_2 equals 8.4.

[33] 3. The waves are reflected at the bay head. This leads to their further amplification, according to the well-known relationship [e.g., *Lamb*, 1932]

$$\xi_h'' = F_3 \xi_h', \tag{7}$$

where $F_3 = 2$.

[34] 4. The waves return to the bay mouth, are partially reflected there, and are, under suitable conditions, constructively superimposed on the waves entering the bay from the open sea. The effect of the ensuing harbor resonance [*Miles and Munk*, 1961] depends on the matching of the period of the incoming waves and the period of the normal modes of the basin as well as on some other factors like the decay of the normal modes and the relative duration of the forcing. It is straightforward to show from the general theory of resonantly forced oscillations started from a state of rest and subjected to damping that the following is valid:

$$\xi_h''' = F_4 \xi_h'', \quad F_4 = \frac{1 - \exp\left[-\frac{2(1-R)}{T_o} t_e\right]}{1 - R}, \tag{8}$$

where T_o is the period of the fundamental bay mode, t_e is the time elapsed from the moment the bay began to be excited, and R is the reflection coefficient at the bay mouth (with $R = 0$ implying maximum damping, and $R = 1$ implying no loss of energy). The reflection coefficient may be estimated from the so-called quality factor or, alternatively, from [*Cerovečki et al.*, 1997]

$$R = \exp\left(-\frac{T_o}{2\tau_0}\right),$$

with τ_o being the decay time of the fundamental mode. In order to determine the reflection coefficient from the above formula, we have imposed on our Adriatic model a linear increase in the sea level between the mouth and the head of Vela Luka Bay and have analyzed the resulting free oscillations in the bay. The period of the fundamental mode turned out to be close to the 20.0 min observed by *Pasarić and Orlić* [2007], thus suggesting that the bay is well resolved by the numerical grid used, whereas the corresponding decay time ranged between 30 and 40 min. This gave $R \approx 0.75$, implying that a surprisingly small amount of energy leaks from the bay to the open sea. Application of (8) then results in the factor $F_4 = 1.6$, for $t_e = 20$ min defined by the speed of the forced and free waves and the distance, O(100 km), covered by these waves in the open sea. Thus, a phenomenon that occurs during the first phase of the process considered influences how the last phase develops.

[35] To summarize, the total amplification factor resulting from the four-phase process is $F = F_1 \times F_2 \times F_3 \times F_4 = 2.8 \times 8.4 \times 2 \times 1.6 = 75.3$, and therefore a 3 mbar air pressure forcing, corresponding to a 3 cm inverted barometer effect, may be expected to produce a 226 cm sea level amplitude inside Vela Luka Bay. The estimate of the amplification via simple analytical solutions is realistic, but it exceeds the estimation resulting from numerical modeling, either because the air pressure forcing tends to be underestimated by the numerical modeling or because the open sea and coastal area are being grossly simplified while applying the analytical solutions. Even if the paper-and-pencil approach is to blame for the discrepancy, it serves the purpose of illustrating the process of amplification in simple terms. It may be tempting to express the contributions of the four phases to the total amplification as percentages, but this would not be justified since, as mentioned above, the four phases are not independent. Because the process sensitively depends on the main bathymetry features characterized by large scales in the open sea and by small scales in the coastal basin, it is crucial for the success of numerical modeling that the finite element model is used, as in this paper, or that nested modeling is employed.

[36] Let it be stressed again that the combination of forced and free waves, leading to the flooding of the east Adriatic coast, differs from the purely free waves, which were responsible for the sea level activity along the west coast. This difference between the local and remote forcing is also visible in studies performed elsewhere in the world. Thus, for example, sea level variability locally corresponding to a traveling air pressure disturbance was considered at the following sites: the English Channel [*Douglas*, 1929], the coastal waters off of New York [*Donn and Balachandran*, 1969], Nagasaki Bay [*Hibiya and Kajiura*, 1982], the Balearic Islands [*Gomis et al.*, 1993; *Garcies et al.*, 1996], Sicily Strait [*Candela et al.*, 1999], and the Buenos Aires coastal area [*Dragani et al.*, 2002]. On the other hand, the variability due to the free waves excited by a remote air pressure perturbation was observed in Lake Michigan [*Ewing et al.*, 1954; *Platzman*, 1958], in Lakes Huron and Erie [*Donn*, 1959], in the Newfoundland coastal area [*Mercer et al.*, 2002], and at the east coast of New Zealand [*Vennell*, 2007]. It may be useful to stress the difference between the two processes via the use of appropriate terminology, analogous to the distinction being made between wind waves and swell at somewhat higher frequencies. The term meteotsunami, introduced by *Nomitsu* [1935] and used more recently by *Defant* [1961] and by *Monserrat et al.* [2006], appears to be perfectly suitable for the free waves generated away from

the area they inundate. For the combination of forced and free waves and the surging that directly corresponds to a passing air pressure disturbance, an adequate term could be "abiki," following the practice of adopting such terms from the Japanese language and honoring the fact that an influential analysis of the process was performed by *Hibiya and Kajiura* [1982] in Nagasaki Bay where this is the local term. Allowing for the two distinct terms, it would be simple to characterize the phenomenon observed in the early morning of 21 June 1978 at the east Adriatic coast as abiki and the phenomenon observed a few hours later at the west Adriatic coast as meteotsunami. Of course, the use of specific terms in the scientific literature will not change the local terms already adopted. In the Croatian part of the Adriatic Sea, the local term is "šćiga," and, as may be expected, it allows for no distinction between the local and remote generation or even between the impulsive and extended atmospheric forcing.

[37] The data, the numerical models, and especially the data-to-model comparison presented in this paper strongly support the hypothesis originally proposed by *Orlić* [1980] according to which the great Adriatic surge of 21 June 1978 was generated by a mesoscale atmospheric disturbance. The finding implies that the remaining three hypotheses, if they are to stay viable, should be tested by employing a methodology similar to the one applied herein. For each hypothesis, there are some obvious questions that have to be answered if the hypothesis is to pass the test. Thus, the interpretation relating the Adriatic surge to the earthquake-related bottom movement in the Aegean Sea area [*Zore-Armanda*, 1979] is challenged by the fact that the time needed for the shallow water waves generated close to Thessaloniki to reach Vela Luka would be 3.6 h, i.e., much less than the observed time of about 8 h, and also by the fact that if the waves are coming from the Otranto Strait, a rather small phase shift may be expected between the variability induced at the east and west Adriatic coasts. In order to model the influence of a landslide on the Adriatic sea level, one would have to first specify the location, time, and form of the landslide, and if the landslide occurred off the middle Adriatic coast of Italy [*Bedosti*, 1980], it would have to be shown how such an initial condition could support sea level activity at the Italian coast lagging behind that at the Croatian coast. Finally, the hypothesis attributing the Adriatic surge to a synoptic atmospheric perturbation [*Hodžić*, 1979, 1988] requires that the generation of the shallow water waves of O (10 km, 10 min) by a cyclone of O (1000 km, 1 day) be explained and also that the west-to-east coast differences be reconciled with the changing forcing field.

6. Conclusion

[38] The central result of this paper is the comparison of the empirical wave heights and onset times with the corresponding modeled values. As already stressed above, the correlation coefficients obtained are high. The results of the regression analysis show that the modeled heights underestimate the empirical heights due to the exact form of the forcing air pressure perturbation being unknown and the resolution of the oceanographic model being limited. While the second of these shortcomings may be eliminated in future modeling work, the first will most likely persist; due to the low sensitivity of the barographs used in the Adriatic area in 1978, the perturbation was not adequately recorded and, of course, experiments cannot be repeated in geophysics. Future measurements, with better instruments, will enable forthcoming events to be explained with more confidence, but the interpretation of the exceptional 1978 surge will most likely always remain subject to the basic caveat. While the results of regression analysis of the wave heights leave some space for doubt, the corresponding results for the onset times strongly point to the mesoscale atmospheric disturbance as the cause of the 1978 Adriatic surge. The onset times thus prove to be of crucial importance for the analysis, suggesting that they should be carefully considered by future researchers.

[39] Our study shows that, at present, the meteorological models are not able to simulate the mesoscale disturbances in a way that would enable the oceanographic models to produce an adequate forecast of the surging events. This implies that the forecasts, if attempted, should be based on (a) the data documenting the situation in the atmosphere rather than the atmospheric model forecasts and (b) the modeling that reproduces processes in the sea. The same combination of meteorological data and oceanographic modeling could be used to study the problem of permanent protection of the most endangered areas, e.g., Vela Luka Bay. If such a study is undertaken, it should be done with the utmost care; since the surging is obviously controlled by a fine resonant tuning, an intervention in a coastal basin aimed at shifting the basin away from one of the resonance peaks should not bring it closer to another peak.

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