Numerical modeling of the generation of long waves by a dynamic seismic source and their propagation in the Black Sea

R. Kh. Mazova, and E. A. Tresvyatskaya

Nizhniy Novgorod Technical University, Nizhniy Novgorod, Russia

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[1] Numerical modeling of generation and propagation of tsunami waves caused by underwater earthquakes in the Black Sea basin is carried out using the model of dynamic seismic source. A number of historical tsunamis are considered as well as possible catastrophic tsunami with large magnitudes from the sources whose location is close to the historical events considered here. The process of tsunami source formation and propagation of tsunami waves in the entire basin of the sea up to 10-meter isobath was considered. Kinematic vertical motion of key-blocks, into which the source of the earthquake is divided, was used to model the seismic source. The obtained results were compared with the data of pressure gauges and results of other authors. The distribution of maximal heights of tsunami waves along the entire Russian coast of the Black Sea was obtained for each calculation. Pressure gauge records were plotted for a number of points at the eastern coast located close to eight Russian cities such as Anapa, where the probability of earthquakes and tsunami is high in the nearest future. *INDEX TERMS:* 3025 Marine Geology and Geophysics: Marine seismics; 3285 Mathematical Geophysics: Wave propagation; 4255 Oceanography: General: Numerical modeling; 4564 Oceanography: Physical: Tsunamis and storm surges; 7209 Seismology: Earthquake dynamics; *KEYWORDS:* tsunami danger evaluation, seismic danger, region tectonics, shelf zone and continental slope zone, dynamic seismic source.

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Introduction

[2] Numerical modeling of tsunami at the coast of the Black Sea including the estimate of tsunami hazard and seismic hazard of the Russian coast (see, for example, [*Garagash and Lobkovsky,* 2000; *Solovieva and Kuzin,* 2005]) is a pressing objective of research in the last decades. High industrial potential of the region (large ports, terminals of gas and oil pipelines), and the largest recreation zone that exists here determine the importance of this problem. The urgency of such calculations is related, in particular, to the problem of operation of the marine part of gas pipeline Russia-Turkey (the "Blue Flow" project) connecting the territories of these countries over the bottom of the Black Sea, which should operate in the conditions of increased seismic and landslide hazard of the Russian and Turkish slopes of the Black Sea [*Garagash and Lobkovsky,* 2000; *Solovieva and Kuzin,* 2005].

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[3] Although seismicity of the Caucasus and Crimea coasts is considered moderate (see, for example, [*Solovieva and Kuzin,* 2005]), according to the chart of the maximal vibrations over the territory of North Caucasus, the coast of the Black Sea from Anapa to Sochi falls within the zone of seventh grade of intensity, which approximately corresponds to magnitude 6 and horizontal velocities from 0.1 to 0.2 m/s [*Lobkovsky and Baranov,* 1984; *Solovieva and Kuzin,* 2005]. Even more, detailed seismological observations using bottom stations of high sensitivity in the Jubga region where the terminal of the gas pipeline Russia-Turkey is located, revealed a very high level of seismic activity at the level of micro- and weak earthquakes. Such seismicity is caused by the regional tectonics since the Black Sea is located in the boundary region of the interaction between the Arabian and Eurasian tectonic plates, which results in the fact that in the northeastern part of the Black Sea Depression, significant stresses are formed in the Earth's crust, which later relax in the form of earthquakes in the zones of shelf and continental slope as well as in the fractures of the costal zone [*Solovieva and Kuzin,* 2005].

[4] In addition to the seismic displacements of the sea bot-

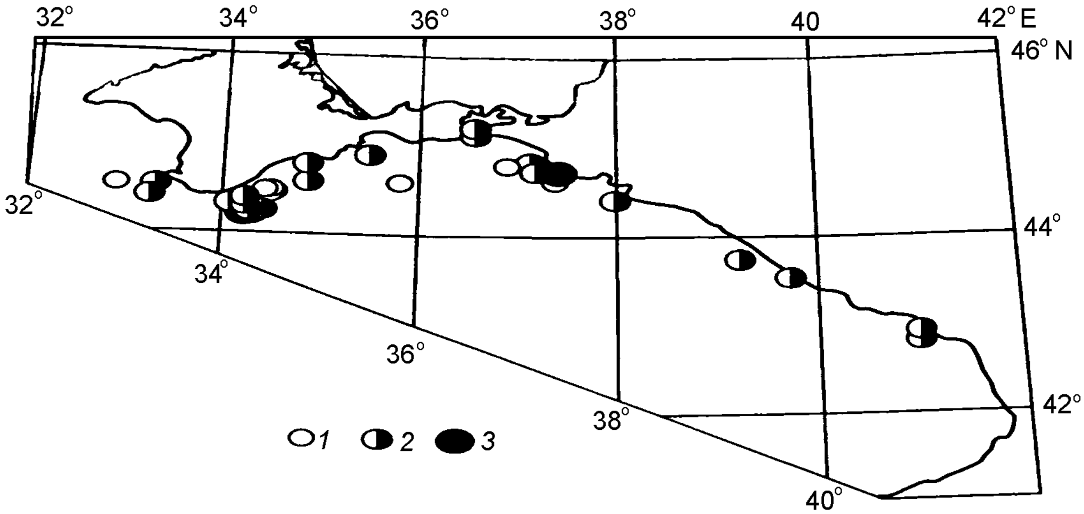

Figure 1. Distribution of epicenters of earthquakes (see [*Solovieva and Kuzin,* 2005]).

tom, development of large landslide displacements of large blocks of sedimentary formations are possible over the underwater slopes in their upper parts induced by seismicity of the bottom [*Garagash and Lobkovsky,* 2000; *Lobkovsky and Baranov,* 1984]. Such landslides can also be the sources of tsunamis (cf. with [*Garder et al.,* 1993; *Gusyakov V.K.,* 1978; *Novikova and Ostrovsky,* 1978]), which were mentioned in historical tsunami data in this region (between Sochi and Tuapse in 1909 [*Solovieva and Kuzin,* 2005; *Zaitsev et al.,* 2002]).

[5] As was mentioned in [*Solovieva and Kuzin,* 2005], the peculiarity of tsunami propagation in the basin of the Black Sea is trapping of wave energy in the zone of the shelf and continental slope, which results in the fact that for the sources in the western part of the Black Sea the wave energy is almost not transferred to the eastern part of the sea, and on the contrary, tsunamis generated in the eastern part of the sea are strongly attenuated when the waves approach its western coast.

[6] The Anapa region is one of the seismic active regions at the Russian coast of the Black Sea. Underwater earthquakes repeatedly occurred and tsunamis were recorded here. The recurrence period of tsunami is approximately 40 years [*Solovieva and Kuzin,* 2005]. The last of the recorded earthquakes and tsunamis in this region occurred in July 1966, thus numerical modeling of the possible tsunami in the nearest time at the coast of the Black Sea based on the new model of seismic source and characteristic of tsunami at the coast in the Anapa region, where the well known recreation center for children is located, seems were actual.

[7] The objective of this work is numerical modeling of a number of historical events (earthquakes accompanied by tsunami) and possible hypothetical events using the model of dynamic seismic source [*Lobkovsky, Baranov,* 1984] (cf. with [*Yanushauskas,* 1978]), which generates tsunamis. We consider propagation of tsunami waves over the entire basin of the Black Sea. The peculiarity of our calculations for several historical tsunamis (generated by seismic sources with known locations and pressure gauge records, and field data), which distinguishes them from the calculations of other authors is application of the keyboard model for the calculation of tsunami waves generation by a seismic source. Although in our calculations of the historical events we consider only a seismic source consisting of one key of the keyboard, wave generation occurs not by instantaneous rising of this key as in piston model, but by its rising with the previously calculated velocity. One of the important peculiarities of this work is calculation of possible tsunami at a hypothetical source located in a seismic active region (see Figure 1). We considered six versions of the seismic source conserving its size and displacement in the source to analyze the consequences of such event. The orientation of the seismic source with respect to the coast line and the sequence of the motion of key-blocks in this source were changed. The calculation of tsunami wave propagation was performed up to a 10-meter isobath for the entire coast of the Black Sea. At some points, we modeled the run-up of the waves and gave the estimates of the errors in the calculation of maximal values of inundation and maximal wave heights at 10-meter isobath.

Formulation of the Problem

[8] We consider a problem of long wave generation by a dynamic source and their propagation with account for real bathymetry of the Black Sea in two-dimensional formulation. Spatial variables are x, y, and z, the Ox axis is directed to the shore (Figure 2). The system of coordinates is oriented so that axis Oz is directed vertically upwards, and

non-perturbed sea level coincides with yOx plane.

[9] Here, $u(x,t)$ is horizontal velocity component; $\eta(x,y,t)$ is perturbation of the free surface; H is maximal depth of the basin; $B(x,y,t)$ is variation in the bottom of the basin; H^* is depth at the 10-meter isobath.

[10] Dynamic seismic source in the form of key-blocks, which can rise (or descend) to a given distance with different velocity, was used for tsunami wave generation [*Lobkovsky and Baranov,* 1984]. At the initial time moment, parameters of dynamic seismic source (coordinates, velocity of the vertical motion of key-block) are specified in the calculation area. The boundaries are located either in the land regions or the water surface.

Numerical Modeling of Generation and Propagation of Tsunami Waves

Equations of Motion

[11] We shall consider generation of tsunami waves in the shallow water approximation (see, e.g. [*Gusyakov V.K.,* 1978; *Pelinovsky,* 1982]. We consider nonlinear equations (1), where function $B(x,y,t)$ describes the vertical motion of key-blocks in the seismic source. The law of the motion of key-blocks changes depending on the version of the calculation. This dynamic model allows us to model various variations of the sea bottom without significant complication of the algorithm.

$$\begin{cases} \dfrac{\partial \eta}{\partial t} + \dfrac{\partial}{\partial x}\big((H+\eta-B)u\big) + \dfrac{\partial}{\partial y}\big((H+\eta-B)v\big) = \dfrac{\partial B}{\partial t} \\ \dfrac{\partial u}{\partial t} + g\dfrac{\partial \eta}{\partial x} = 0 \\ \dfrac{\partial v}{\partial t} + g\dfrac{\partial \eta}{\partial y} = 0 \ , \end{cases} \qquad (1)$$

where x, y are spatial coordinates, t is time, $u(x,t),\ v(y,t)$ are horizontal components of velocity, $\eta(x,y,t)$ is perturbation of the free surface with respect to its level at rest, H is maximal depth of the basin, B is variation in the sea bottom (the account for the characteristics of dynamic seismic source), g is acceleration due to gravity.

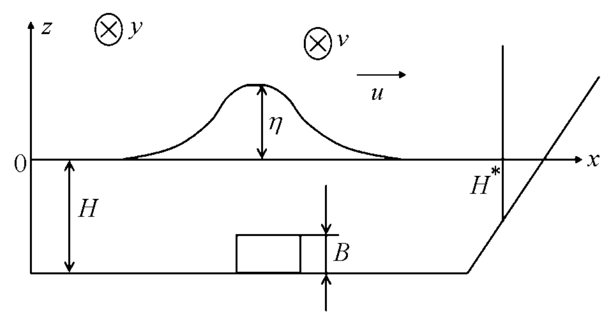

Figure 2. Scheme of the formulation of the problem.

Initial and Boundary Conditions

[12] Boundary conditions in the problems of tsunami wave propagation differ depending on the peculiarity of the problems considered in the study. For example, if propagation of tsunami waves is considered in the basin of the sea, it is possible to specify the condition of complete reflection (specifying zero normal components of velocity u_{n}, v_{n}, and derivative η_{n}) or to specify "free" boundary conditions. In the latter case, the wave passes through the boundary without distortions. However, a more complete description of the interaction between the wave and coast is needed in the solution of the problems of tsunami wave propagation in the shelf zone [*Pelinovsky,* 1982; *Pelinovsky and Mazova,* 1992].

[13] We consider that before the generation, the fluid that fills the region with initial form of the bottom is at rest, i.e. the velocity and perturbation of the free surface are zero:

$$\eta(x,y,t) = u(x,0) = v(y,0) = 0 \ .$$

Boundary conditions (full reflection) at 10-meter isobath are written as:

$$\begin{cases} u_{\mathrm{b}} = 0; \\ v_{\mathrm{b}} = 0 \ . \end{cases} \qquad (2)$$

The conditions of free passing wave are written as

$$\begin{cases} u_{\mathrm{b}}^{n+1} = c\eta_{\mathrm{b}}^{n+1} / \left(H + \eta_{\mathrm{b}}^{n+1}\right), \\ v_{\mathrm{b}}^{n+1} = c\eta_{\mathrm{b}}^{n+1} / \left(H + \eta_{\mathrm{b}}^{n+1}\right), \\ \eta_{\mathrm{b}}^{n+1} = \eta_{\mathrm{b}}^{n+1} \pm \dfrac{c\Delta t}{\Delta x}\left(\eta_{\mathrm{b}}^{n} - \eta_{\mathrm{b}-1}^{n}\right) \ . \end{cases} \qquad (3)$$

where $n+1$ denotes the time layer following layer n, and $c = \sqrt{g(H+\eta)}$.

[14] This model makes possible to correlate the wave with the generating source taking into account the characteristics of displacements and velocities at each point of variable sea bottom. The method allows us to combine the processes of numerical modeling of the generation and propagation of tsunami waves taking into account the effects of real basin bathymetry residual variations in bottom topography and superposition of subsequent perturbations on the wave propagating in the ocean. The seismic characteristics of the earthquake source influence the wave only by means of function $B(x,y,t)$.

[15] The numerical scheme described in and adjusted for the solution of the problems with dynamic source [*Garagash et al.,* 2003] was used to calculate the generation and propagation of tsunami waves.

[16] Bathymetry of the Black Sea with a resolution of 1.5 km was used in the modeling. The number of nodes in the numerical scheme is equal to 505×781=394,405. Modeling was carried out with a time step of 1 s (taking into account the tests for convergence and stability, see e.g. [*Garagash*

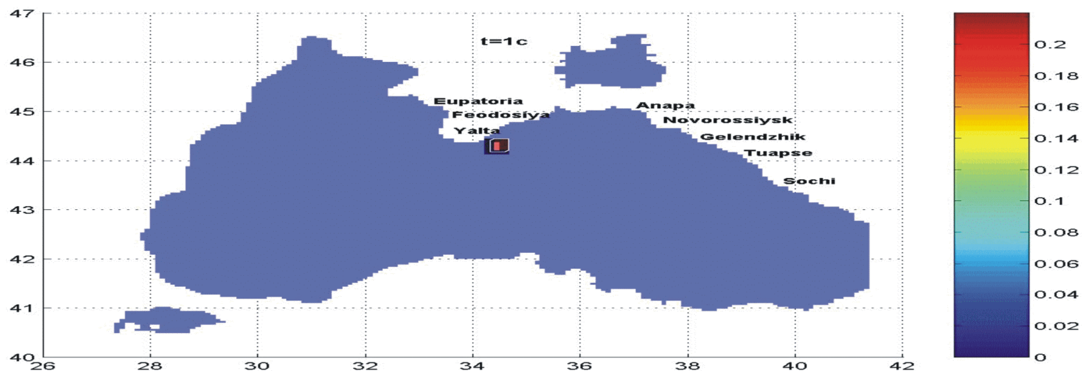

Figure 3. Location of the earthquake source on 26 June 1927.

et al., 2003]). Condition of full reflection (vertical wall) was specified at the last point of the sea region at a depth of 10 m.

Results of Numerical Modeling

Calculation of Historical Tsunami

[17] *Solovieva and Kuzin,* [2005] considered the main earthquakes and tsunamis at the Russian coast of the Black Sea. Events were selected from these data, for which the dates of earthquakes, coordinates of the earthquake epicenters, and run-up data were known. This makes possible adequate modeling of the past events for analyzing possible dynamic displacements within the seismic source. The results of the calculations were checked with the data of observations on run-up at the coast for each event and with the results of calculations performed by other authors [*Solovieva and Kuzin,* 2005; *Zaitsev et al.,* 2002]. Thus, we selected three seismic events on 26 June 1927; 12 September 1927; and 12 July 1966 with coordinates of the sources 34.4°E, 44.4°N; 34.5°E, 44.5°N; and 37.3°E, 44.7°N, respectively (see Table 1).

[18] We obtained approximate sizes of tsunami source and altitude, at which water could be displaced in the source using Iida relation (see, for example [*Pelinovsky,* 1982]) for estimating the parameters of tsunami source at given magnitude of the earthquake M.

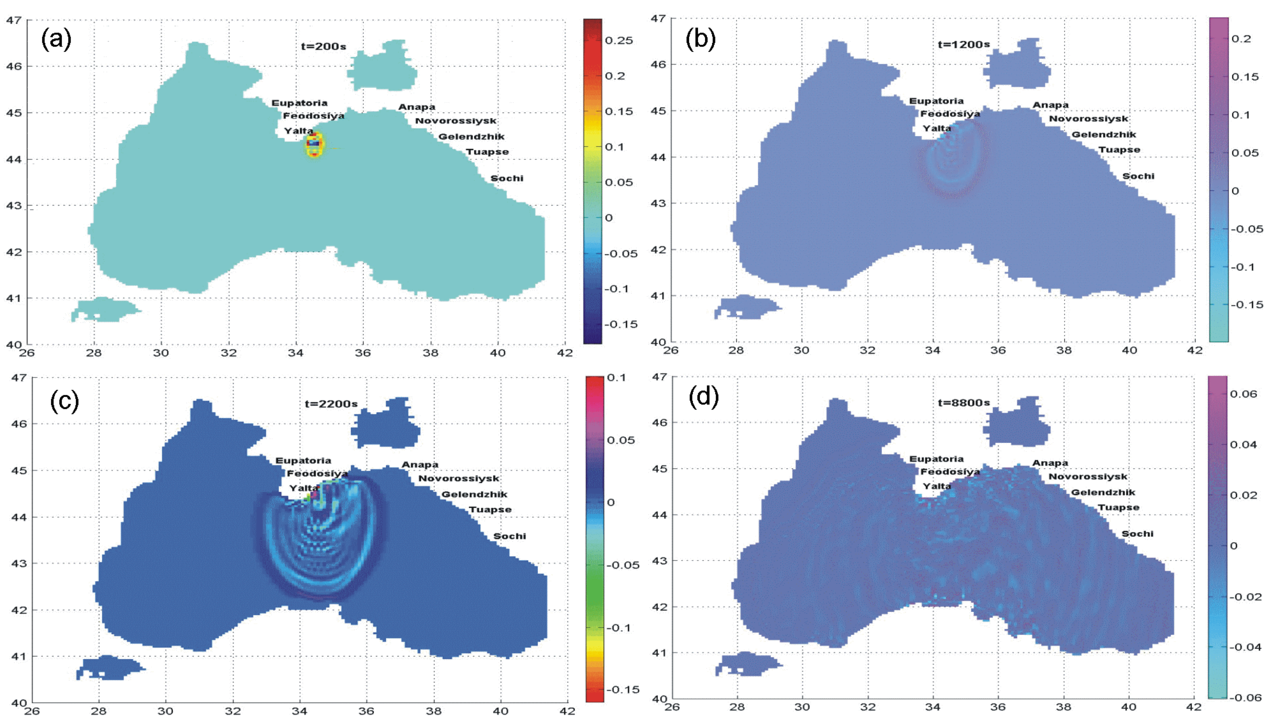

Figure 4. Locations of tsunami wave fronts and distribution of sea level at four time moments: t = 200 s, t = 1200 s, t = 2200 s, t = 8800 s.

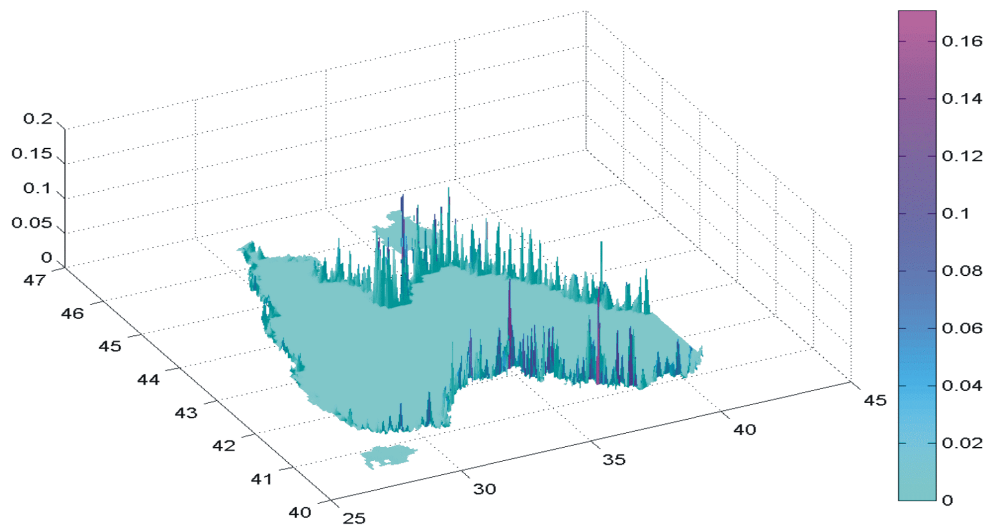

Figure 5. Distribution of maximal wave heights at 10-meter isobath during the earthquake on 26 June 1927.

$$\begin{aligned} \lg(R(\mathrm{km})) &= 0.5M - 2.1 \\ \lg(\eta(\mathrm{m})) &= 0.8M - 5.6 \ , \end{aligned} \qquad (4)$$

where R is radius of the source, and η is displacement of water over the seismic source. It is noteworthy that owing to incompressibility of the fluid, the displacement at the surface would repeat exactly the bottom displacement in the seismic source. Thus, formation of the tsunami source would occur during the time of dynamic displacements in the seismic source, in our case, during t seconds of the rising of the block. The size of the tsunami source R allows us to specify the approximate size of the block (or blocks) comprising the seismic source, while the displacement of the wave surface over the seismic source would allow us to calculate the altitude of the elevation of the block (or blocks) in the seismic source.

[19] **Calculation 1.** Let us consider earthquake on 26 June 1927 (M = 5.8) with coordinates of the epicenter: 34.4°E, 44.4°N. Using relations (4) we get that the radius of the source is $R = 6.3$ km, and the altitude of the displacement of water surface is $\eta = 0.12$ m.

[20] Thus, we assume that approximate parameters of the seismic source are: $D = 12.6$ km is the size of the key-block; $B = 0.2$ m is the altitude of the key-block.

[21] The location of the earthquake source on 26 June 1927 is schematically shown in Figure 3.

[22] Patterns of the locations of wave fronts for four time moments are shown in Figures 4a–d: in 200 s after the beginning of tsunami wave generation by the seismic source, after 1200 s, after 2200 s, and after 8800 s. It is clearly seen that after 20 min (1200 s) the wave front reached Yalta and Feodosiya, and approximately after 40 min, the wave front reached the Turkish coast of the Black Sea. Almost in two and a half hours, the wave reached all points at the Black Sea coast.

[23] The distribution of maximal wave heights at 10-meter isobath is shown in Figure 5. It is seen well that the maximal wave heights at this isobath do not exceed 20 cm, which

Table 1.

Date of earthquake	Coordinates of the source	City at 10-m isobath	Height, m	Height, m (from [*Solovieva and Kuzin,* 2005; *Zaitsev et al.,* 2002]
6 June 1927	34.4°E 44.4°S	1. Eupatoria	0.09	0.14
		2. Yalta	0.15	0.16
		3. Feodosiya	0.08	0.08
		4. Novorossiysk	0.06	0.08
		5. Tuapse	0.06	0.08
12 September 1927	34.5°E 44.5°S	1. Yalta	0.32	0.37
		2. Novorossiysk	0.15	0.19
		3. Tuapse	0.1	0.1
12 July 1966	37.3°E 44.7°S	1. Feodosiya	0.08	0.1
		2. Anapa	0.36	0.42
		3. Gelendzhik	0.4	0.42

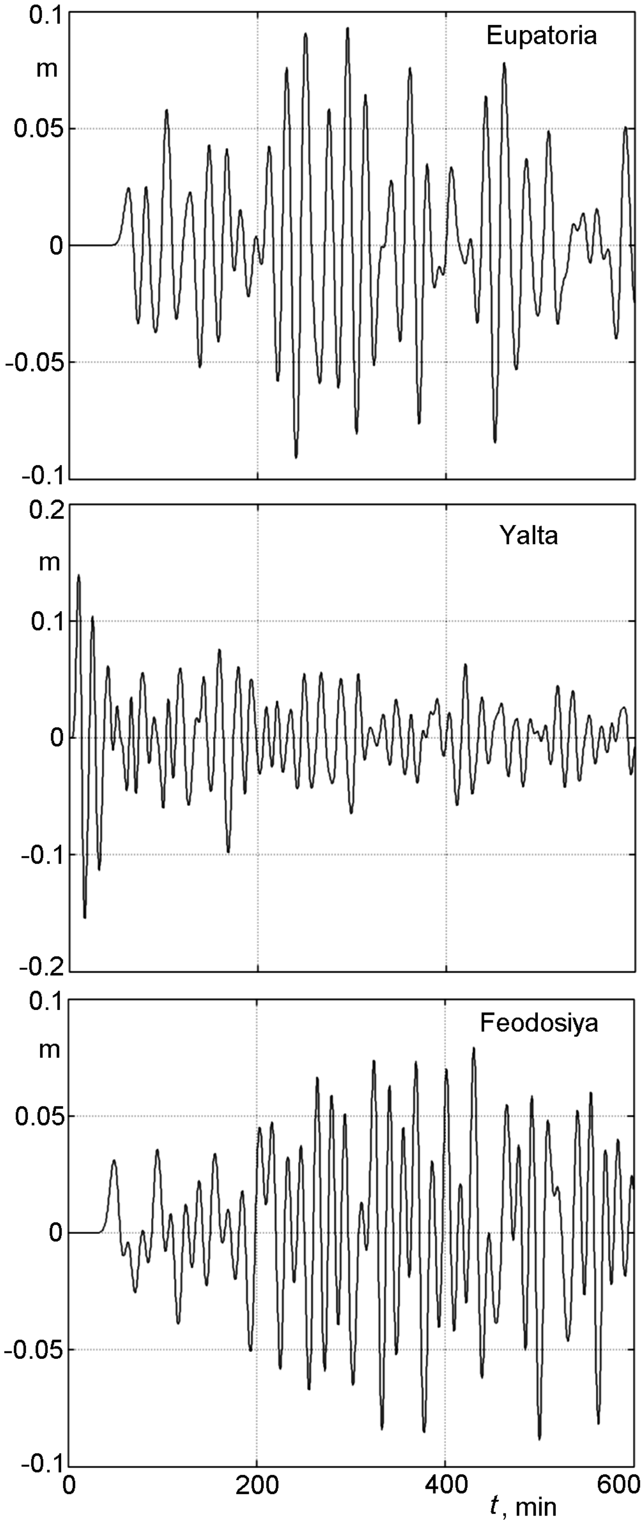

Figure 6. Pressure gauge series or the first version of calculation in Eupatoria, Yalta, and Feodosiya.

agrees well with the results of calculation of other authors [*Solovieva and Kuzin,* 2005; *Zaitsev et al.*, 2002].

[24] Pressure gauge series calculated at three points of the Black Sea coast for the first 500 s of the tsunami wave generation and propagation are shown in Figure 6.

[25] It is clearly seen from the pressure gauge series that at each of the three points, tsunami started with sea level rise. For example, in Eupatoria, the first sea level rise was 2 cm, and only the fifth wave caused a rise of 9 cm. Fluctuations of the sea level continued for a long time and ranged from −8 to 9 cm. In Yalta, the height of the first wave was 8 cm, while the second was already equal to 15 cm. After this, the fluctuations of the sea level decreased and continued for a long time ranging from −7 to 8 cm. In Feodosiya, the height of the first wave was 4 cm, and for a long time the fluctuations of the level ranged from −10 to 8 cm. It is clearly seen that the distribution of maximal wave heights along the Russian coast of the Black Sea has a small scatter (Figures 5, 6).

[26] **Calculation 2.** The earthquake on 12 September 1927 (M = 6) corresponds to the following coordinates of the epicenter: 34.5°E, 44.4°N. The coordinates of the source are close to the case considered above, however, the recorded magnitude of the earthquake was higher (M = 6). The parameters of the tsunami source calculated from relations (4) are the following: radius of the tsunami source is $R = 7.9$ km, while the elevation of water at the source is $\eta = 0.18$ m.

[27] Thus, we assume approximate parameters of the seismic source: $D = 15.8$ km is the size of the key-block; $B = 0.3$ m is the altitude of the key-block.

[28] Localization of the source for this earthquake is shown in Figure 7.

[29] Locations of tsunami wave fronts at four time moments: after 220 s, after 2200 s, after 3550 s, and after 7100 s are shown in Figure 8.

[30] It is clearly seen that less than in one hour the wave reaches Anapa, Novorossiysk, and Gelendzhik. Although the arrival time of waves from this source to specific points

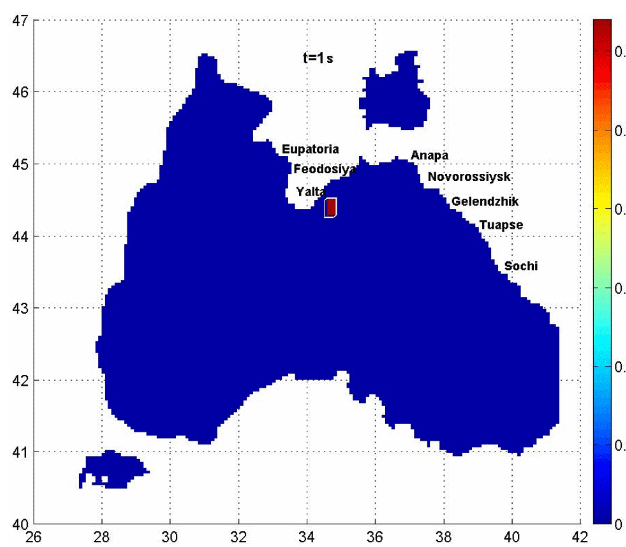

Figure 7. Location of the source of earthquake on 12 September 1927.

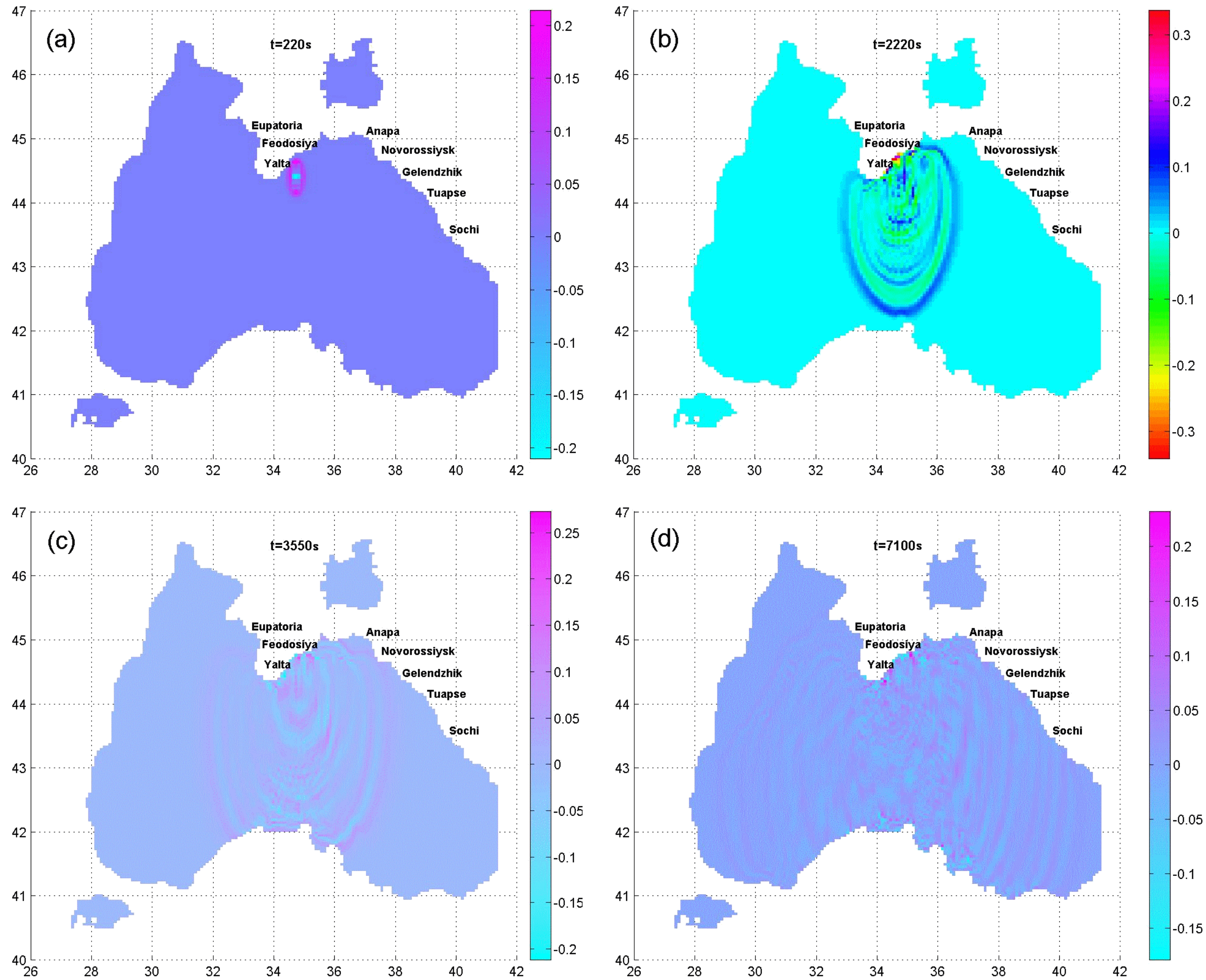

Figure 8. Locations of tsunami wave fronts and distribution of sea level at four time moments.

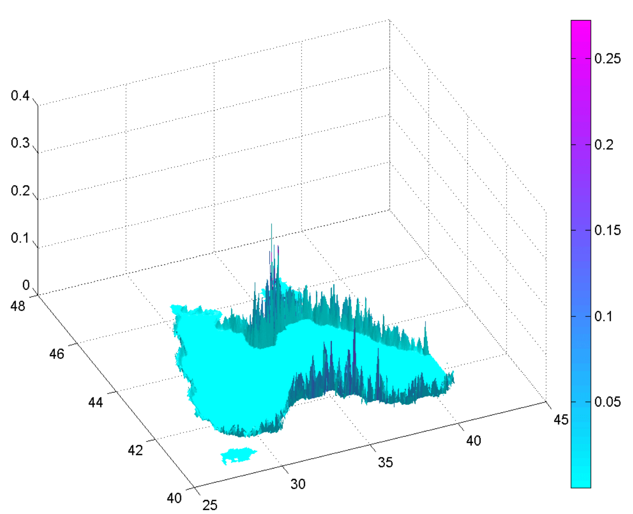

Figure 9. Distribution of maximal wave heights at 10-meter isobath for the earthquake on 12 September 1927.

at the coast is practically the same as in the previous case (localization of the sources is close) but the distribution of wave heights in the second case is different (see Figure 9, Figure 10). The greatest wave heights are observed in Yalta, Feodosiya, and Eupatoria, which agrees well with the available data.

[31] Pressure gauge series calculated at three points of the Black Sea coast: Yalta, Novorossiysk, and Tuapse are shown in Figure 10. The choice of the towns is related to the possibility of testing the results of the calculations on the basis of the available data of measurements and calculations.

[32] **Calculation 3.** The earthquake on 12 July 1966 (M = 5.8) corresponds to the following coordinates of the epicenter: 37.3°E, 44.7°N. The parameters of the tsunami source calculated from relations (4) are the following: radius of the tsunami source is $R = 6.3$ km, while the elevation of water at the source is $\eta = 0.12$ m.

[33] Thus, we assume approximate parameters of the seismic source: $D = 12.6$ km is the size of the key-block; $B = 0.22$ m is the altitude of the key-block.

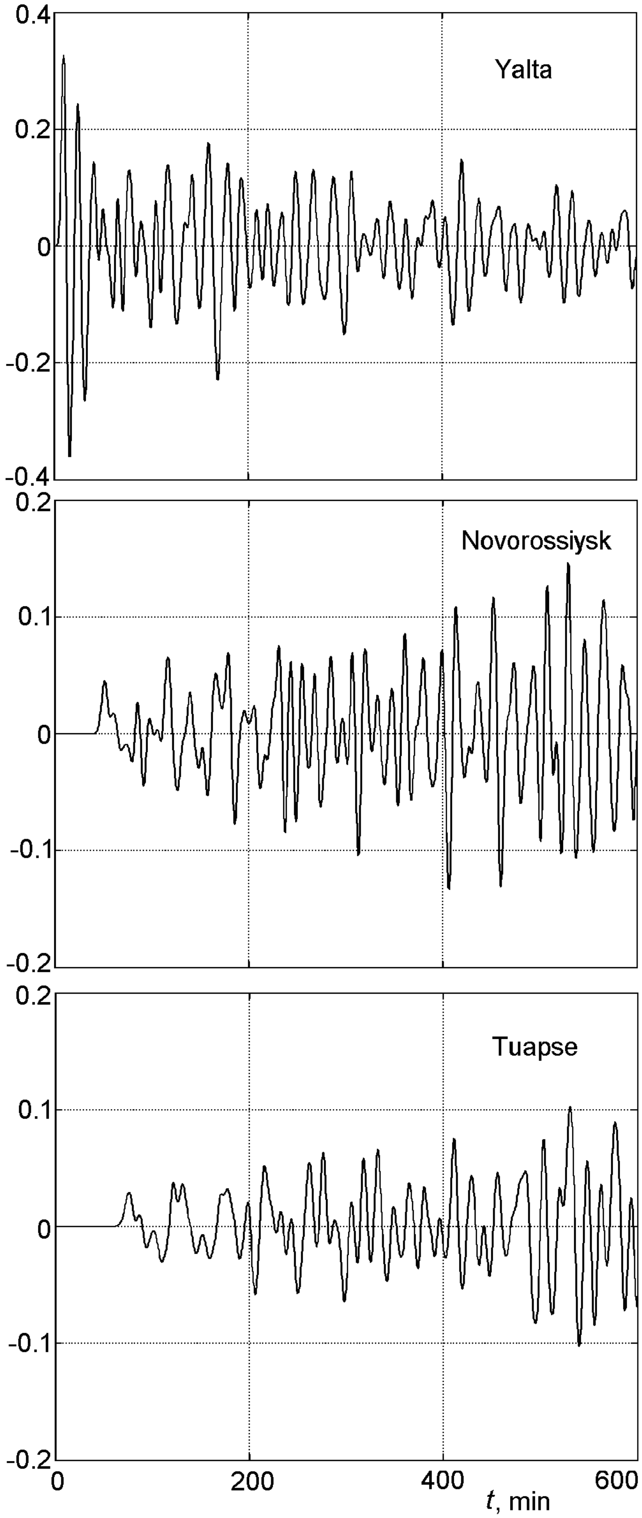

Figure 10. Pressure gauge series in Yalta, Novorossiysk, and Tuapse for the earthquake on 12 September 1927.

[34] The location of the source of this earthquake is shown in Figure 11.

[35] Locations of tsunami wave fronts and spatial distribution of sea level at four time moments after wave propagation from this source are shown in Figure 12: after 310 s, after 1200 s, after 3500 s, and after 9100 s. It is clearly seen that already in 20 min after the earthquake, the waves would reach Anapa, Novorossiysk, and Gelendzhik. In half an hour, the waves would reach Tuapse, and in 40 min they would reach Sochi. Less than one hour would be necessary for the waves to reach the Turkish coast of the Black Sea (see Figures 12a–d).

[36] The distribution of maximal wave heights at 10-meter isobath over the entire perimeter of the Black Sea for this earthquake is shown in Figure 13. It is clearly seen that unlike the previous cases, when the distribution of maximal heights was localized in the region of Yalta, in the third case, the distribution is localized in the region of Anapa-Gelendzhik (see Figures 13, 14).

[37] One can see that localization of the earthquake source near Anapa yields in a peak of maximal wave heights at the coast in the region of Anapa, Novorossiysk, and Gelendzhik. The greatest heights reach 42 cm in Gelendzhik (see Figure 15a, and Table 1).

[38] It is clearly seen that the results obtained by numerical modeling using the dynamic keyboard model of subduction [*Zaitsev et al.,* 2002] agree well with the data of field observations and calculations of other authors almost at all points. However, to our opinion, a certain difference from the calculations made by other authors for the earthquakes on 26 June 1927 in Eupatoria and on 12 September 1927 in Yalta is related to a better physical basis of the earthquake source model.

Calculation of Possible Catastrophic Tsunami at the Black Sea Coast Generated at Hypothetical Seismic Sources

[39] Let us consider generation and propagation of a tsunami wave over the basin of the Black Sea for six sources with equal size, the same localization, and assume that in

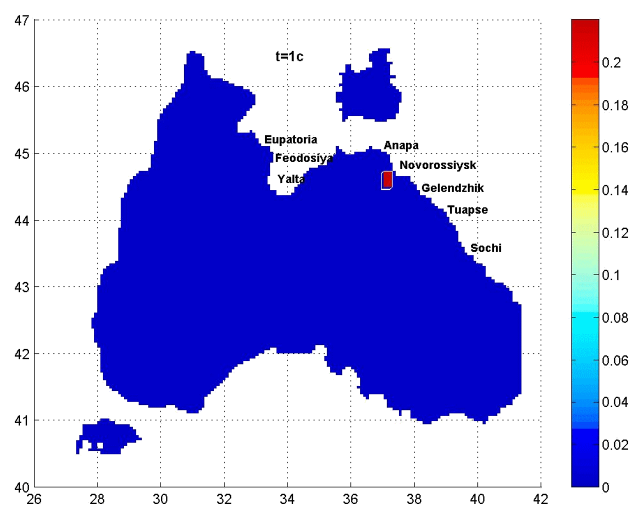

Figure 11. Location of the source of earthquake on 12 July 1966.

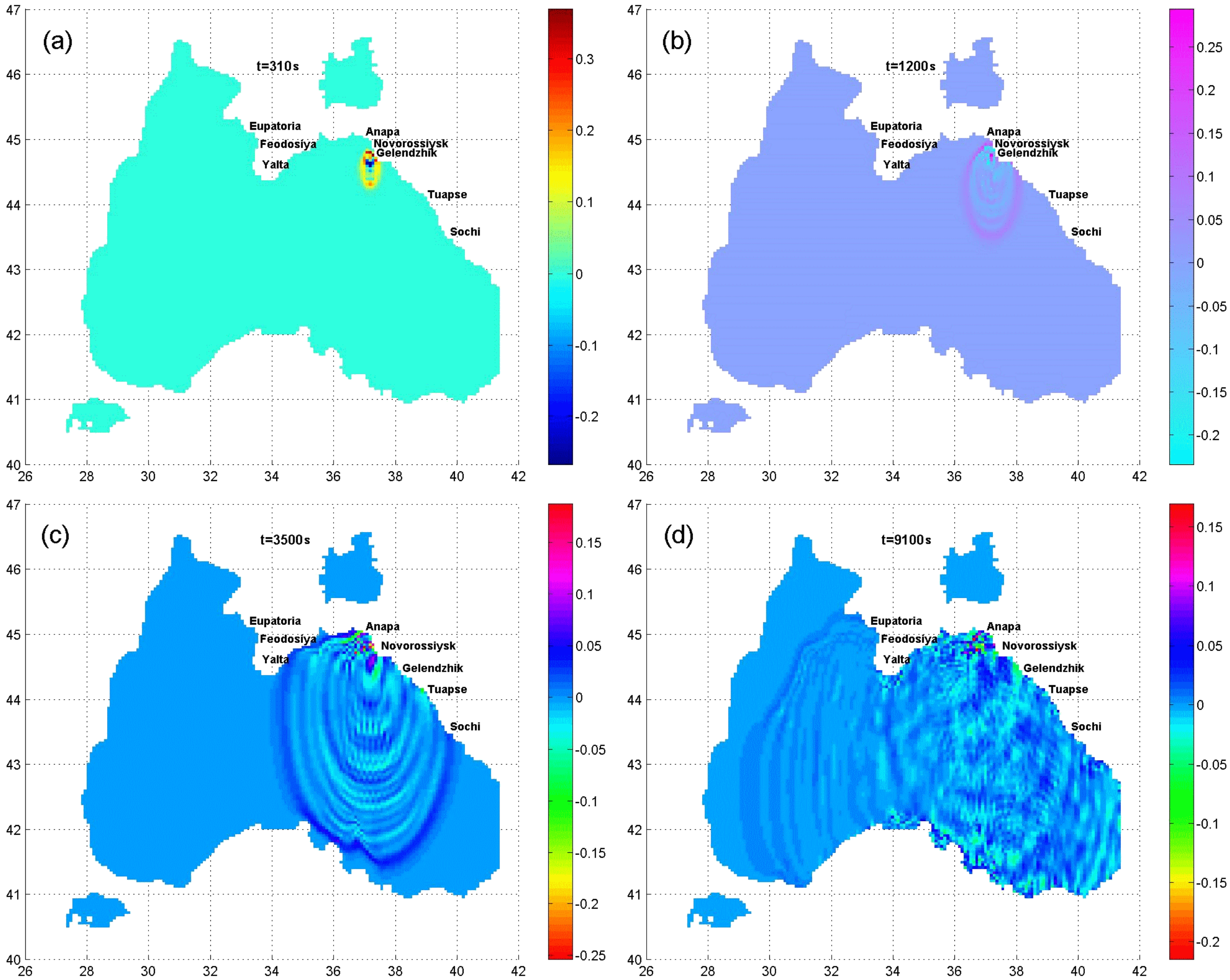

Figure 12. Locations of tsunami wave fronts and distribution of sea level at four time moments: t = 310 s, t = 1200 s, t = 3500 s, t = 9100 s.

all six cases (scenarios) the magnitude of the possible catastrophic earthquake is M = 8.5. The motion of blocks in the source is considered with the same velocity 0.54 km h^{-1}. The displacement is the same: up or down. The location of the source corresponds to the coordinates of the earthquake on 26 June 1927: 34.4°E–33.6°E; 44.3°N–43.5°N. From relations (4) we get the size of the tsunami source $R = 141.2$ km and height of water displacement at the tsunami source $\eta = 2.5$ m. Rising of block (blocks) in the seismic source occurs during 30 s, then the recalculated elevation of the block at the bottom would be equal to 4.5 m. We assume that the size of the seismic source is approximately $D = 282$ km.

[40] Let us consider possible scenarios of the block motion in the seismic source (Figure 16):

[41] 1. The source consists of one block moving upwards (Figure 16a);

[42] 2. The source consists of one block moving downwards (Figure 16b);

[43] 3. The source consists of two blocks simultaneously moving upwards and downwards and the negative motion in the source is oriented to the sea side (Figures 16c,d);

[44] 4. The source consists of two blocks simultaneously moving upwards and downwards and the negative motion in the source is oriented to the coast side (Figures 16e,f).

[45] **Calculation 1.** Let us, first, consider the motion of the block as a whole (Figure 16a). We shall consider propagation of waves in the basin of the Black Sea. Distribution of maximal wave heights at 10-meter isobath for the entire Black Sea coast of Russia for this calculation is shown in Figure 15a.

[46] Since we consider local tsunamis, the maximal wave heights are found at small distances from the sources, i.e. in Yalta, Feodosiya, and Eupatoria, which is clearly seen in Figure 17, where pressure gauge series are shown at eight points of the Russian Black Sea coast

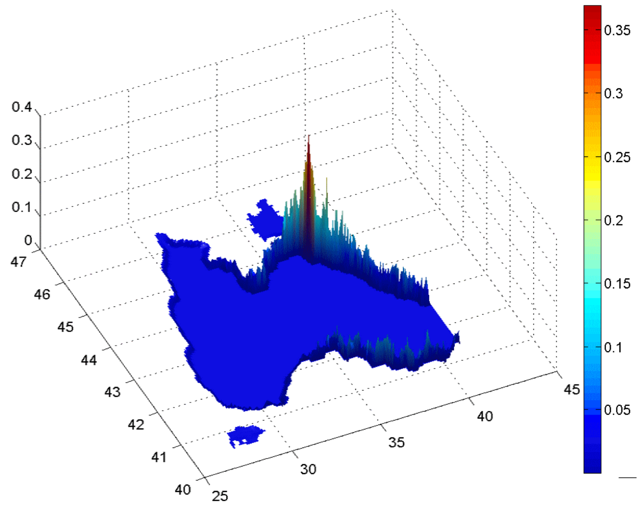

Figure 13. Distribution of maximal wave heights at 10-meter isobath during the earthquake on 12 July 1966.

[47] Analysis of pressure gauge series indicates that at all points the wave would reach the coast in 15–50 minutes, and only in Yalta, the first front would be observed almost instantaneously, in 3–5 m. after the beginning of the seismic process. The greatest values of run-up and run-down in Yalta would be equal almost to three meters, after this the amplitudes would decrease but however, for a long time the maxima of the approaching wave trains would remain within 1.7–1.2 m. In Feodosiya and Eupatoria, the wave heights would reach 1.5–1.8 m, while the maximal run-down values would reach 1.5 m. In Gelendzhik, Novorossiysk, Tuapse, and Sochi, the first maximal waves of run-up and run-down would be in the interval 0.5–1 m. It is worth noting that since we consider only local tsunamis and the source is located close to the coast, the first wave that reaches the coast (10-meter isobath), would be a run-up wave at all points of the coast.

[48] **Calculation 2.** Let us consider the same formulation of the problem, but the block as a whole moves downwards (Figure 16b). Distribution of maximal wave heights at 10-meter isobath for the entire Black Sea coast of Russia for this calculation is shown in Figure 15b.

[49] It is clearly seen in Figure 18 that at all points, tsunami starts with a run-down motion, i.e. water flows off the coast. The distributions of maximal and minimal run-up values along the Russian coast of the Black Sea for the first and second calculations are shown in Figure 19.

[50] It is interesting to note that it follows from the comparison of Figures 19a and 19b that the patterns of the distribution of wave heights for the maximal and minimal values calculated along the coast are overturned. It is seen well that maximal values of run-up and run-down are observed in the region left of Yalta.

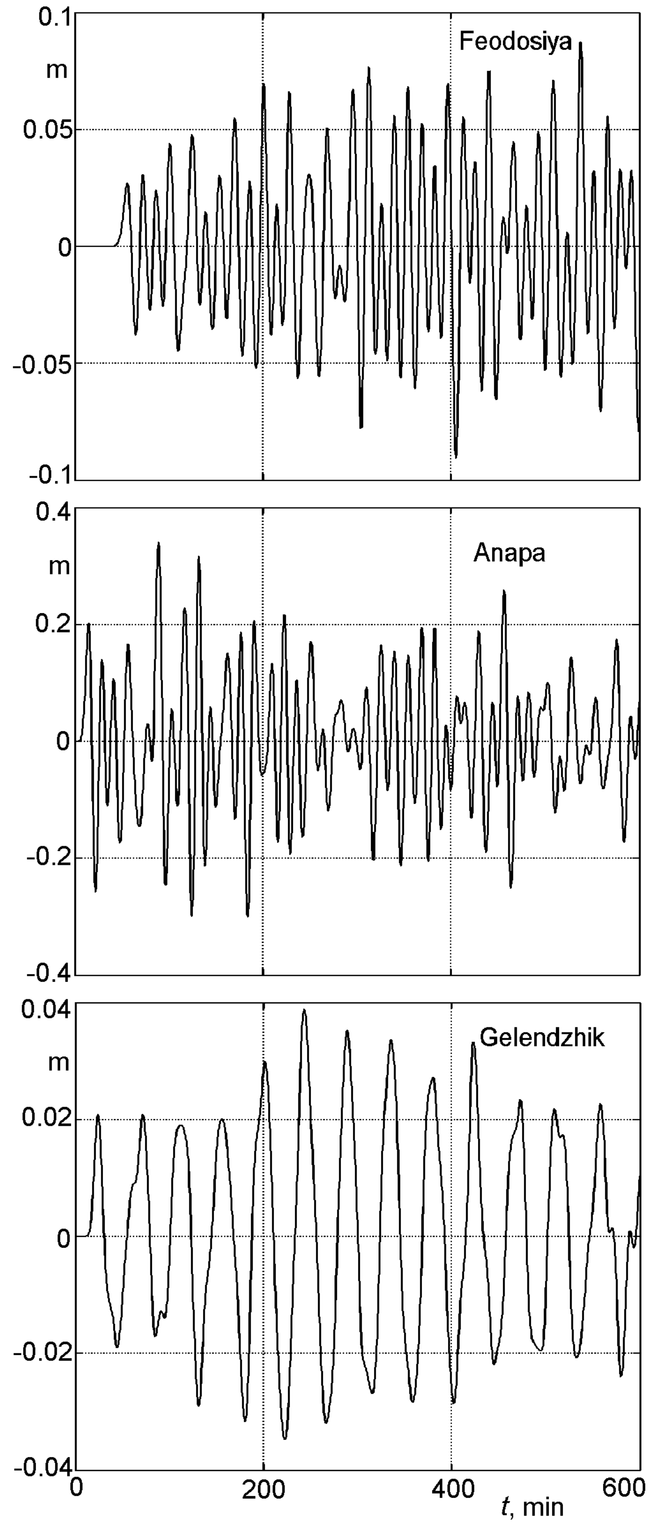

Figure 14. Pressure gauge series at three points: Feodosiya, Anapa, and Gelendzhik.

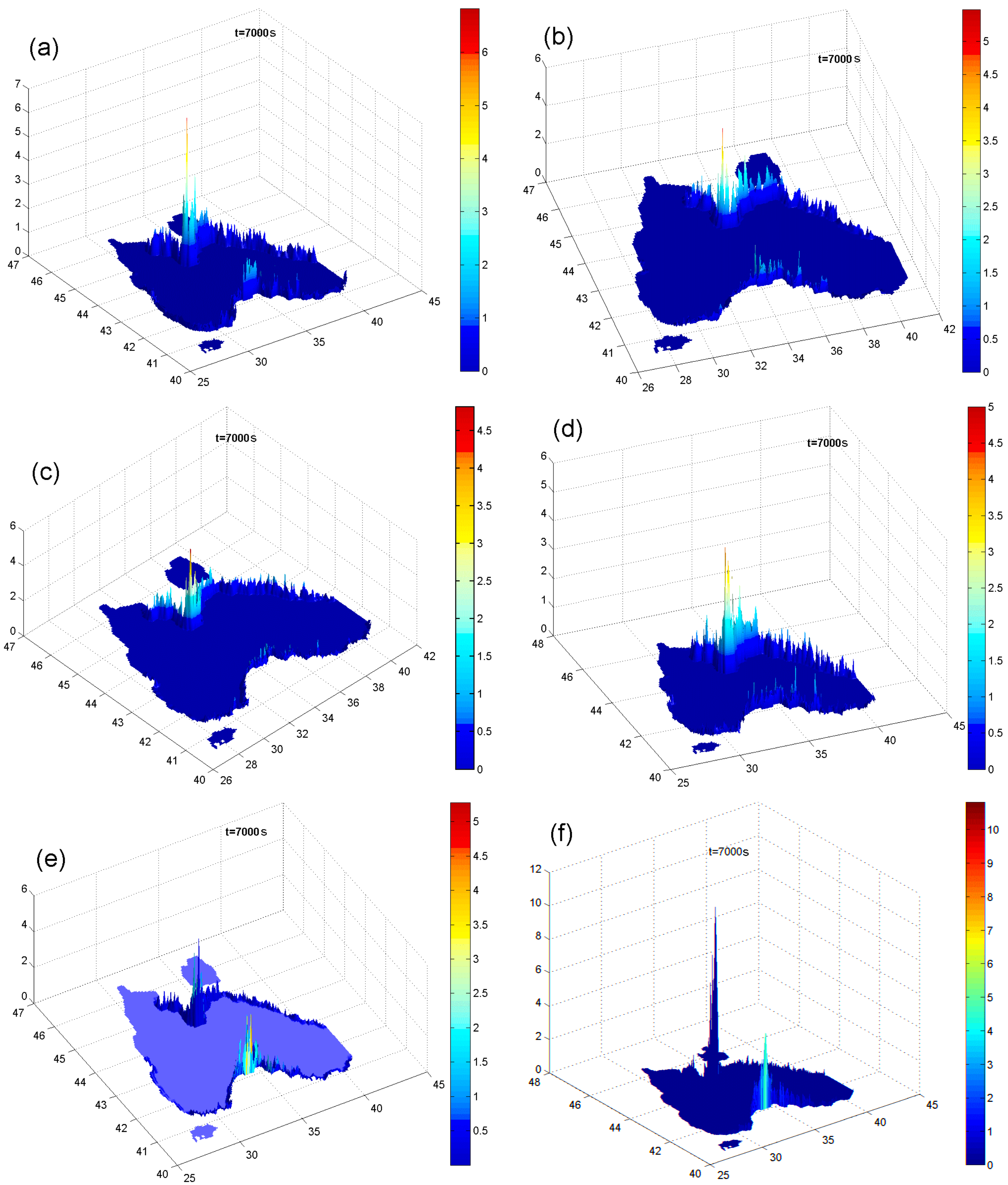

Figure 15. Distributions of maximal wave heights at 10-meter isobath for the first (a), second (b), third (c), fourth (d), fifth (e), and sixth (f) scenarios.

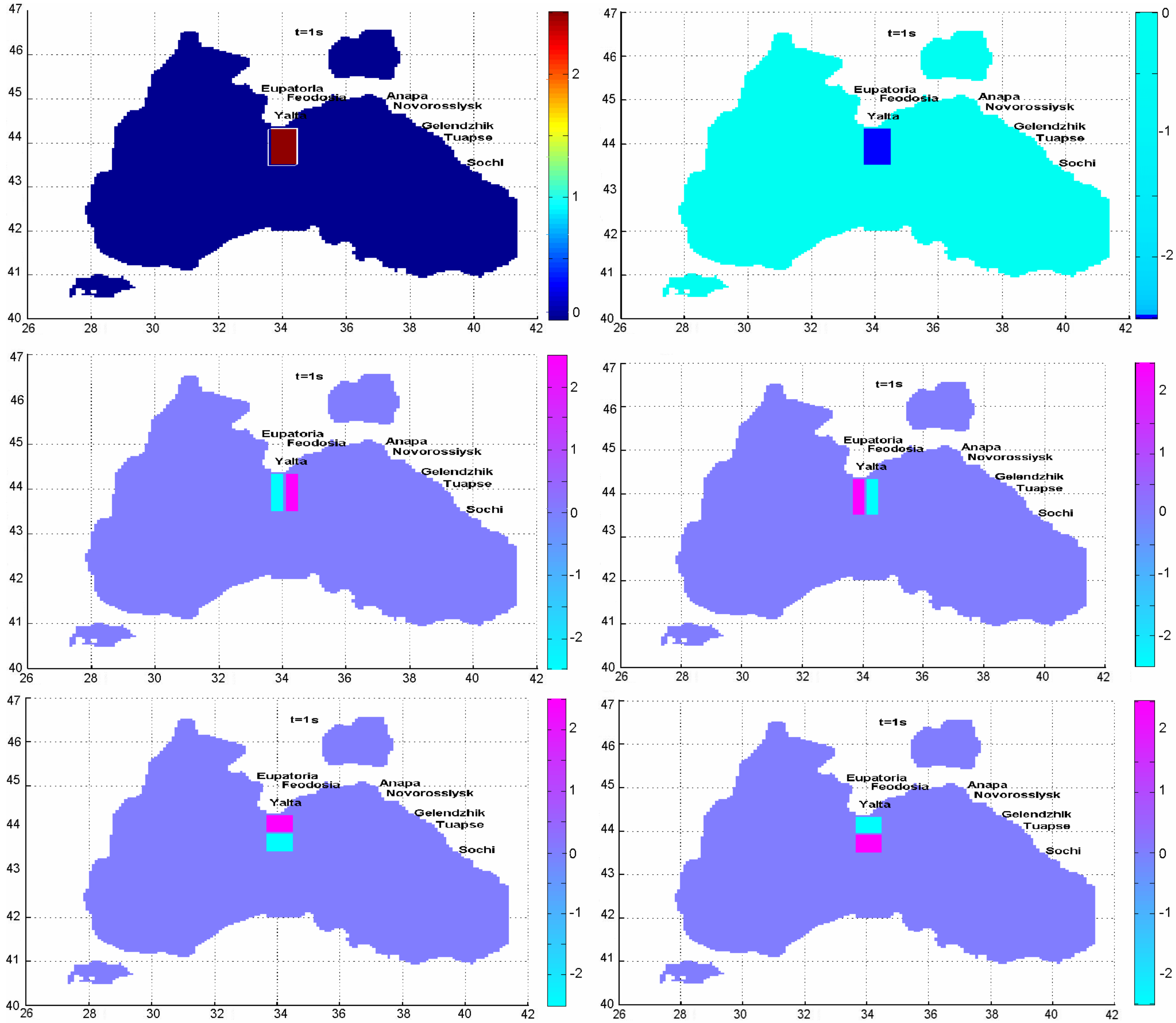

Figure 16. Locations of hypothetical earthquake sources: (a) the source consists of one block moving upwards; (b) the source consists of one block moving downwards; (c–f) the source consists of two differently oriented blocks simultaneously moving upwards (pink color) and downwards (blue color).

[51] **Calculation 3.** Let us consider a seismic source (Figure 16c) consisting of two blocks of equal size. The blocks move simultaneously upwards and downwards with equal speed of 0.54 km h^{-1}. The calculated values of vertical displacement of blocks are equal to 4.5 m and -4.5 m, respectively.

[52] The distributions of maximal wave heights at 10-meter isobath along the entire Russian coast of the Black Sea for this calculation are shown in Figure 15c.

[53] A comparison of Figure 15b and Figure 15c clearly demonstrates a significant difference in the distribution of wave heights along the coast. In Anapa and Gelendzhik, the run-up and run-down values are significantly smaller, in Yalta, the run-up is approximately the same, but the run-down is significantly greater, while in Novorossiysk, in the third scenario the run-up and run-down values are much greater (Figure 20).

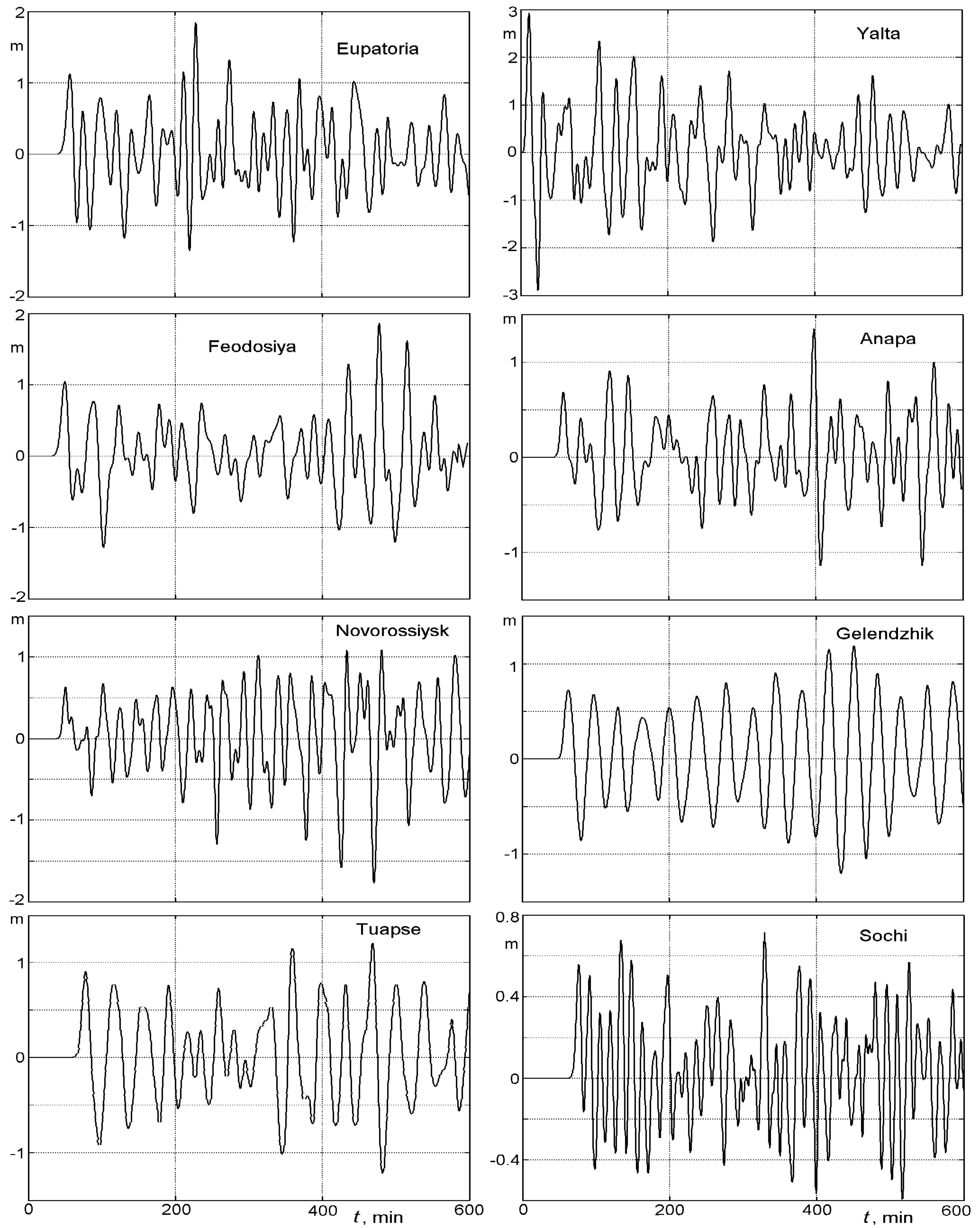

Figure 17. Pressure gauge series in Anapa, Eupatoria, Feodosiya, Gelendzhik, Novorossiysk, Tuapse, and Yalta for the first version of calculations.

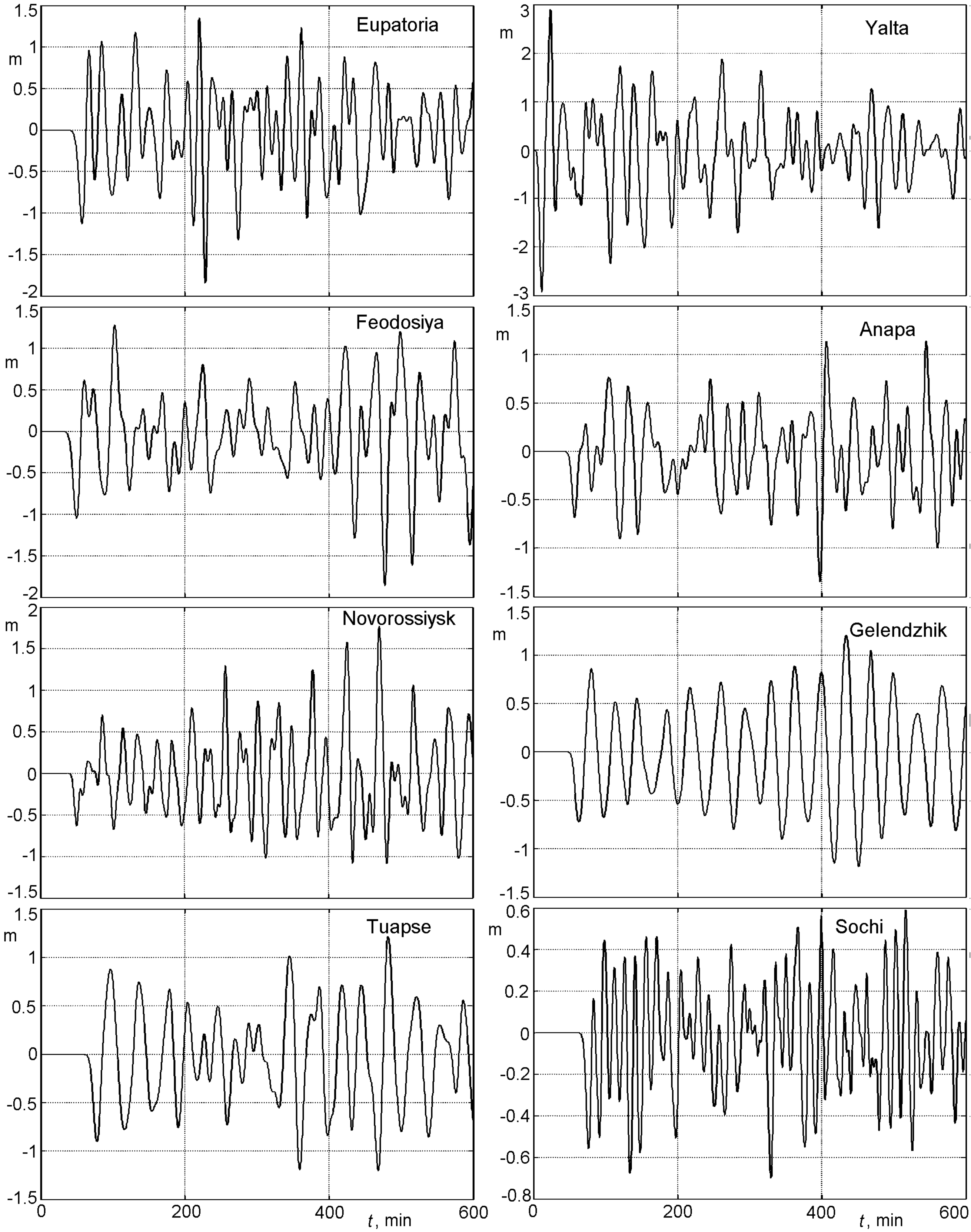

Figure 18. Pressure gauge series in eight towns of the coast: Eupatoria, Yalta, Feodosiya, Anapa, Novorossiysk, Gelendzhik, Tuapse, and Sochi for the second version of calculations.

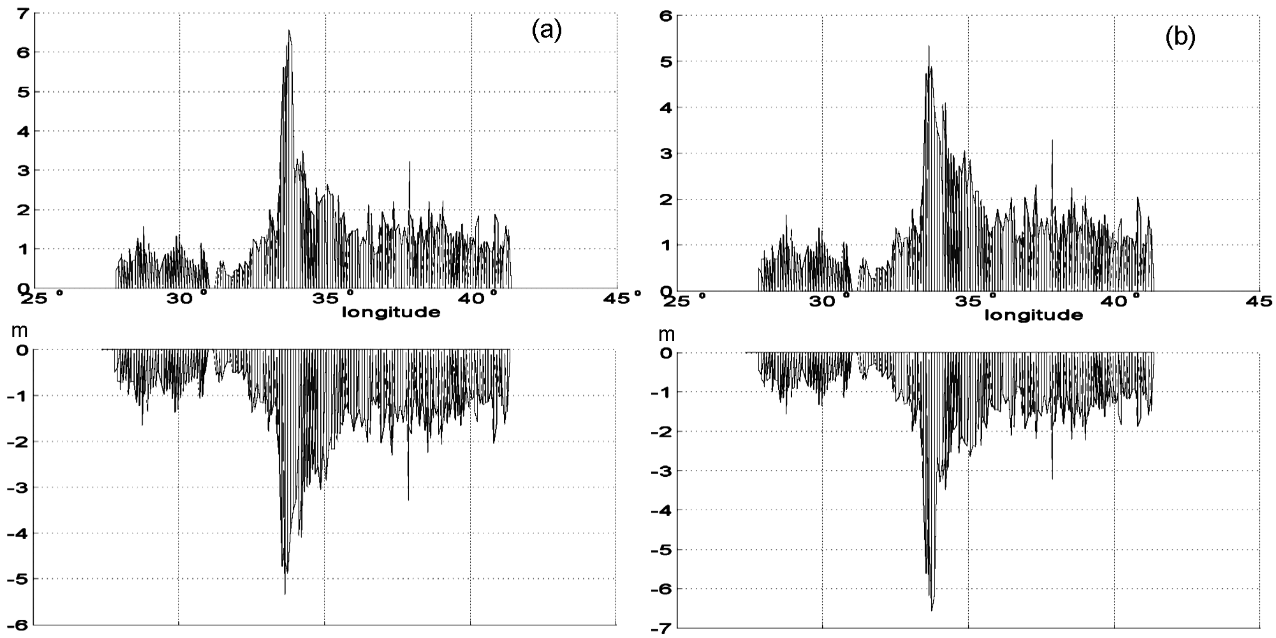

Figure 19. Histograms of the distribution of maximal wave heights for the first and second calculations.

[54] It is clearly seen that the wave arrived to Eupatoria with a negative height, i.e. the water, first, flowed off the coast (60 cm in the vertical direction), and then returned with a height of 1.3 m. At all other points, tsunami started with run-up. The maximal run-up reaching 3.5 m is possible in Yalta.

[55] **Calculation 4.** In this calculation we consider an "overturned" seismic source (relative to Calculation 3) oriented as shown in Figure 16d. Negative displacement is oriented in the region of Gelendzhik, Tuapse, and Sochi. The blocks move simultaneously upwards and downwards with equal speed of 0.54 km h^{-1}. The calculated values of vertical displacement of blocks are equal to 4.5 m and −4.5 m, respectively.

[56] It is clearly seen in Figures 15d, 21, and 22 that unlike Calculation 1 (simple elevation of the block over the bottom) at all points except for Eupatoria, tsunami starts with run-down while the maximal values of run-up are significantly greater than in the first scenario of calculations. A consideration of more complex seismic source, in which displacements are oriented not only upwards but also downwards, yield in another pattern of the arrival of the first wave as well as in the other pattern of the distribution of maximal and minimal heights along the coast.

[57] **Calculation 5.** In this calculation, in the source of the earthquake of the same size as in the previous calculations the negative displacement is oriented into the open sea (Figure 16e). The blocks move simultaneously upwards and downwards with equal velocity of 0.54 km h^{-1}. The displacement of the blocks is the same with the same velocity.

[58] Distribution of maximal wave heights at 10-meter isobath is shown in Figure 15e.

[59] The analysis of the distribution shown here demonstrates that in this version of calculation the values of run-up at the Russian coast of the Black Sea are relatively small. In Gelendzhik, Tuapse, and Sochi (Figure 23) tsunami starts with a run-down flow, but the run-up waves, which arrive later, are not high. They would not exceed a few tens of centimeters. However, in Yalta, the height of the first wave would reach 2.6 m; it will be followed by a strong run-down, whose value along the vertical would reach 5.5 m. The second run-up as expected would be significantly greater and reach 4 m.

[60] **Calculation 6.** In this calculation, the source is similar to the previous one; however, the negative displacement is oriented to the coast (Figure 16f). The blocks move simultaneously upwards and downwards with equal velocity of 0.54 km h^{-1}. The displacement of the blocks is the same with the same velocity as in the previous calculation. Localization of the source and magnitude of the earthquake M = 8.5 is the same as in the previous calculations (see Figure 15f).

[61] Pressure gauge series in eight towns of the coast are shown in Figure 24. It is seen well that in Yalta and Feodosiya, tsunami starts with run-down. In Yalta, the first wave is maximal (of the order of 4 m). The waves arrive at

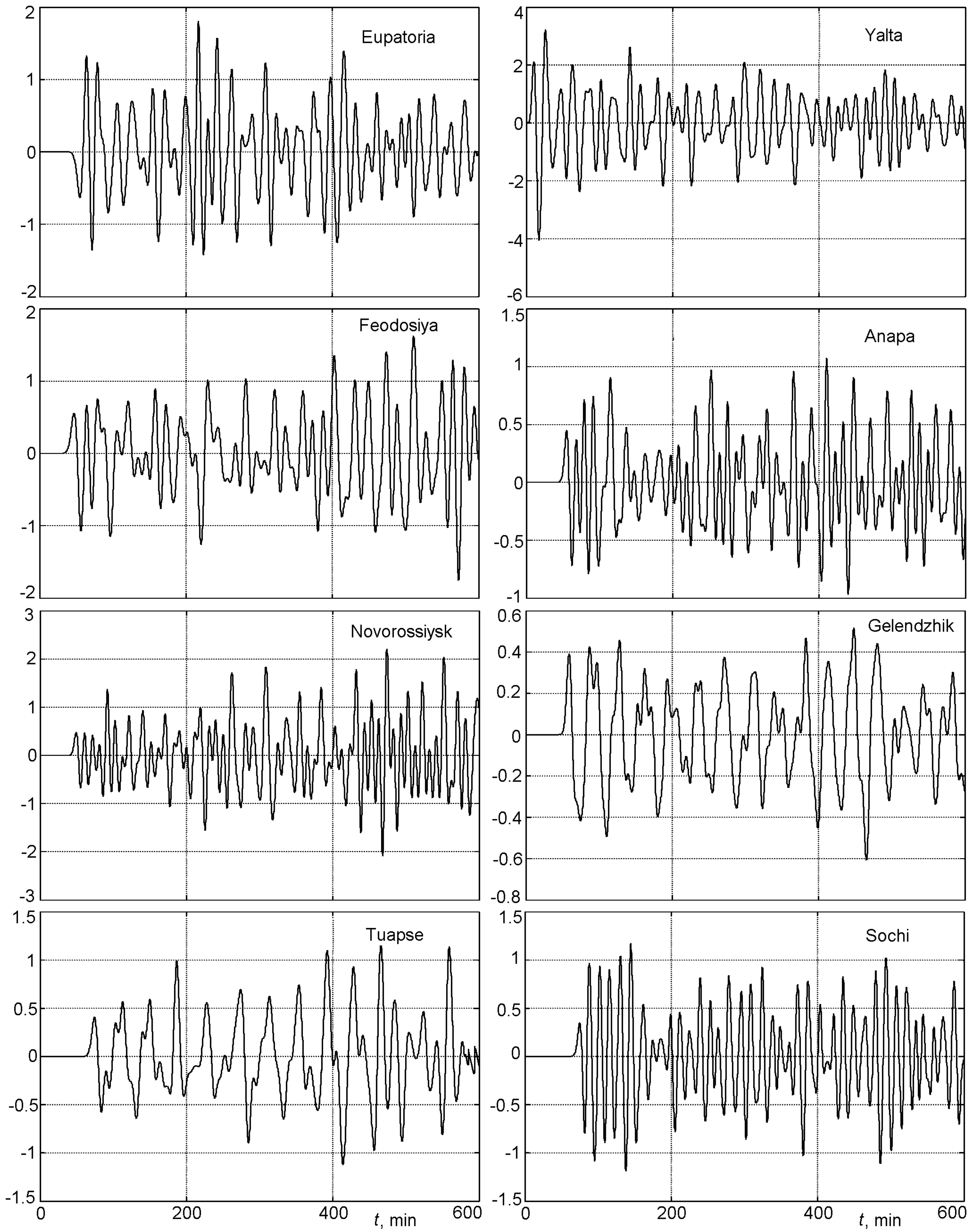

Figure 20. Pressure gauge series in eight towns of the coast: Eupatoria, Yalta, Feodosiya, Anapa, Novorossiysk, Gelendzhik, Tuapse, and Sochi for the third version of calculations.

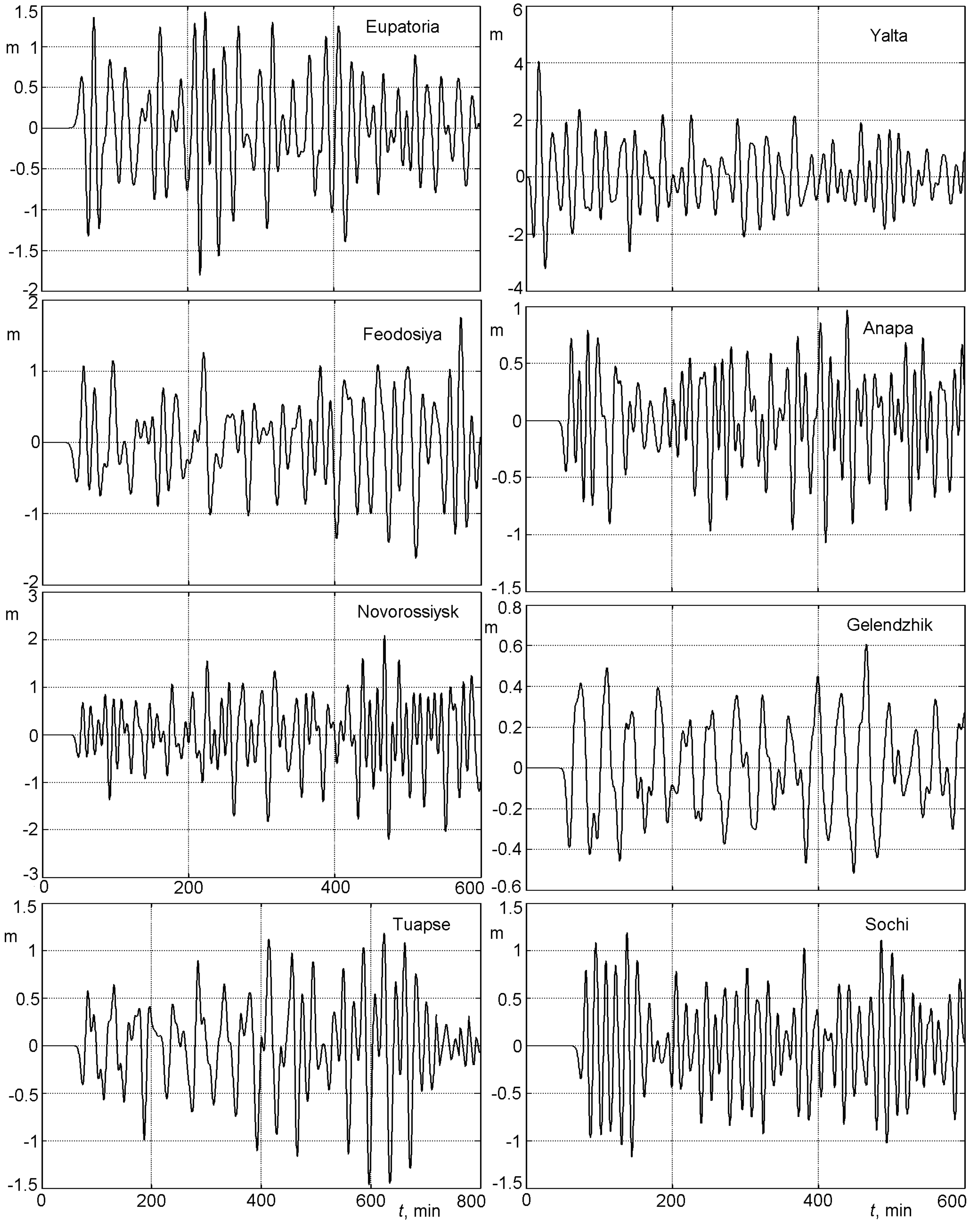

Figure 21. Pressure gauge series in eight towns of the coast: Eupatoria, Yalta, Feodosiya, Anapa, Novorossiysk, Gelendzhik, Tuapse, and Sochi for the fourth version of calculations.

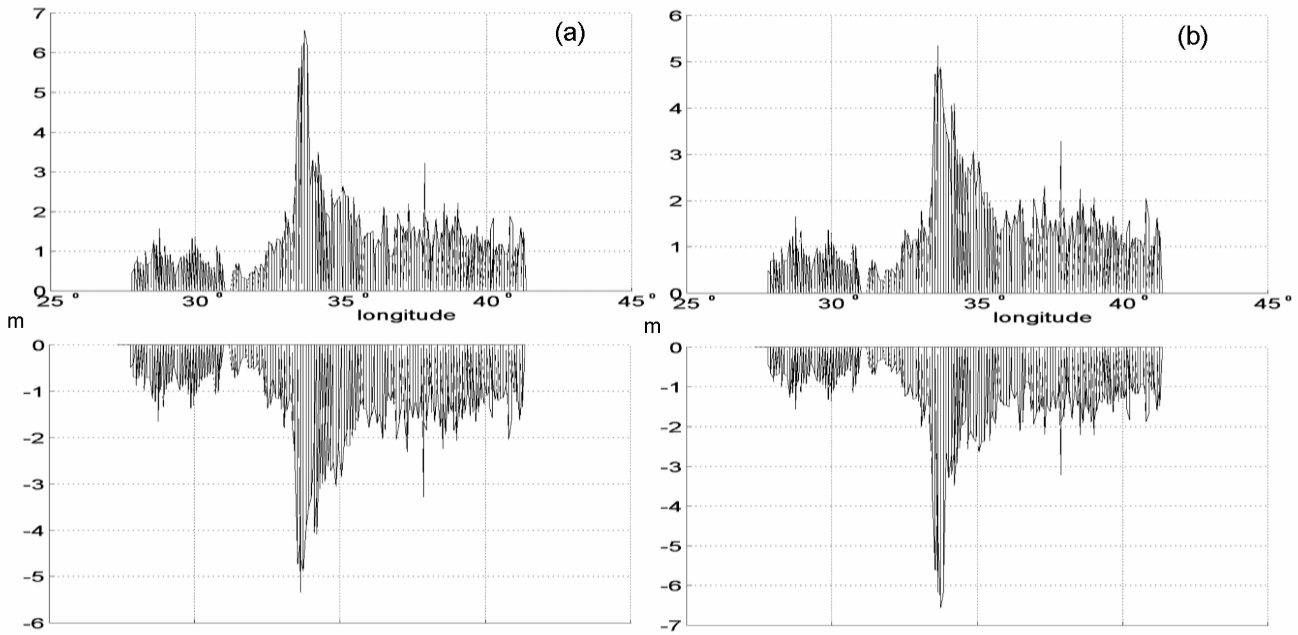

Figure 22. Distribution of maximal and minimal wave heights along the Russian coast for the third and fourth scenarios.

the Russian coast with a positive phase of run-up, and the maximal values of the run-up are of the order of 1 m.

[62] Distributions of maximal and minimal wave heights along the Russian coast of the Black Sea are shown in Figure 25. It is seen well that distributions (a) and (b) differ significantly from each other. In scenario (b) the values of maximal run-up heights reach 10 meters, and minimal run-down values reach 7 m, while in case (a) the values of maximal run-up heights reach 5 meters, and minimal run-down values reach 9.5 m.

[63] A histogram of the distribution of maximal wave heights for all six calculations of tsunamis from a hypothetical source is shown in Figure 26. It is clearly seen that the maximal values of wave heights up to 10 m are observed in the region left of Yalta. The greatest waves are generated in the realization of the sixth scenario, when the negative displacement in the seismic source is oriented to the coast. This agrees well with the results of paper [*Pelinovsky and Mazova,* 1992], in which the authors speak about possible increase in tsunami wave height at the coast in the case of a local source with negative displacement in the source oriented to the coast. The next peak of maximal values is located in the region of Novorossiysk for scenarios 3 and 4. The Gelendzhik and Sochi regions appeared the safest. The maximal wave heights are of the order of 40 cm and 70 cm, respectively.

Conclusion

[64] In this work, we carried out numerical modeling of the generation of long gravity waves in water by a dynamic seismic source and their propagation for the specific historical events in the Black Sea. It was shown that for a given magnitude of earthquake the source provides a good agreement with the data of pressure gauges recorded for the given event. The performed calculation of possible catastrophic tsunami at the Black Sea coast from hypothetical seismic sources showed that if the source is localized in the region with coordinates 34.4°E–33.6°E; 44.3°N–43.5°N, the regions of Yalta and Novorossiysk would be subjected to greatest hazard, while the regions of Sochi and Gelendzhik would rest in the calm zone.

[65] The analysis demonstrated that for local tsunamis at the same earthquake magnitude and conservation of the source parameters and its localization the possible values of tsunami run-up and run-down at the coast depend significantly in the sequence of the motion of key-blocks in the seismic source.

[66] It is clear that the performed analysis is only an example of using the dynamic keyboard model for calculating possible consequences after earthquakes with magnitude M = 8.5. Complete analysis of the possible catastrophic con-

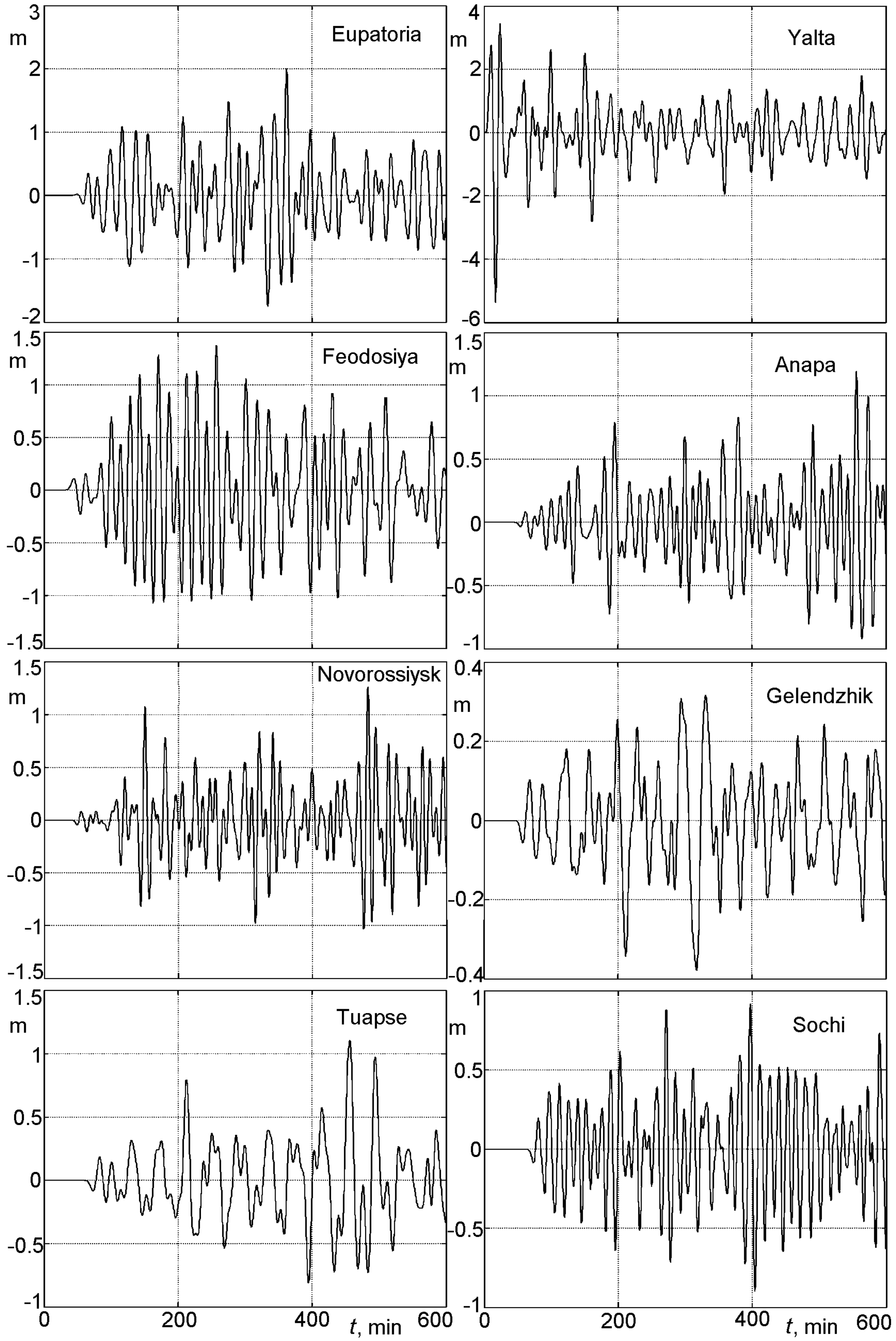

Figure 23. Pressure gauge series in Anapa, Eupatoria, Feodosiya, Gelendzhik, Novorossiysk, Tuapse, Yalta, and Sochi for the fifth version of calculations.

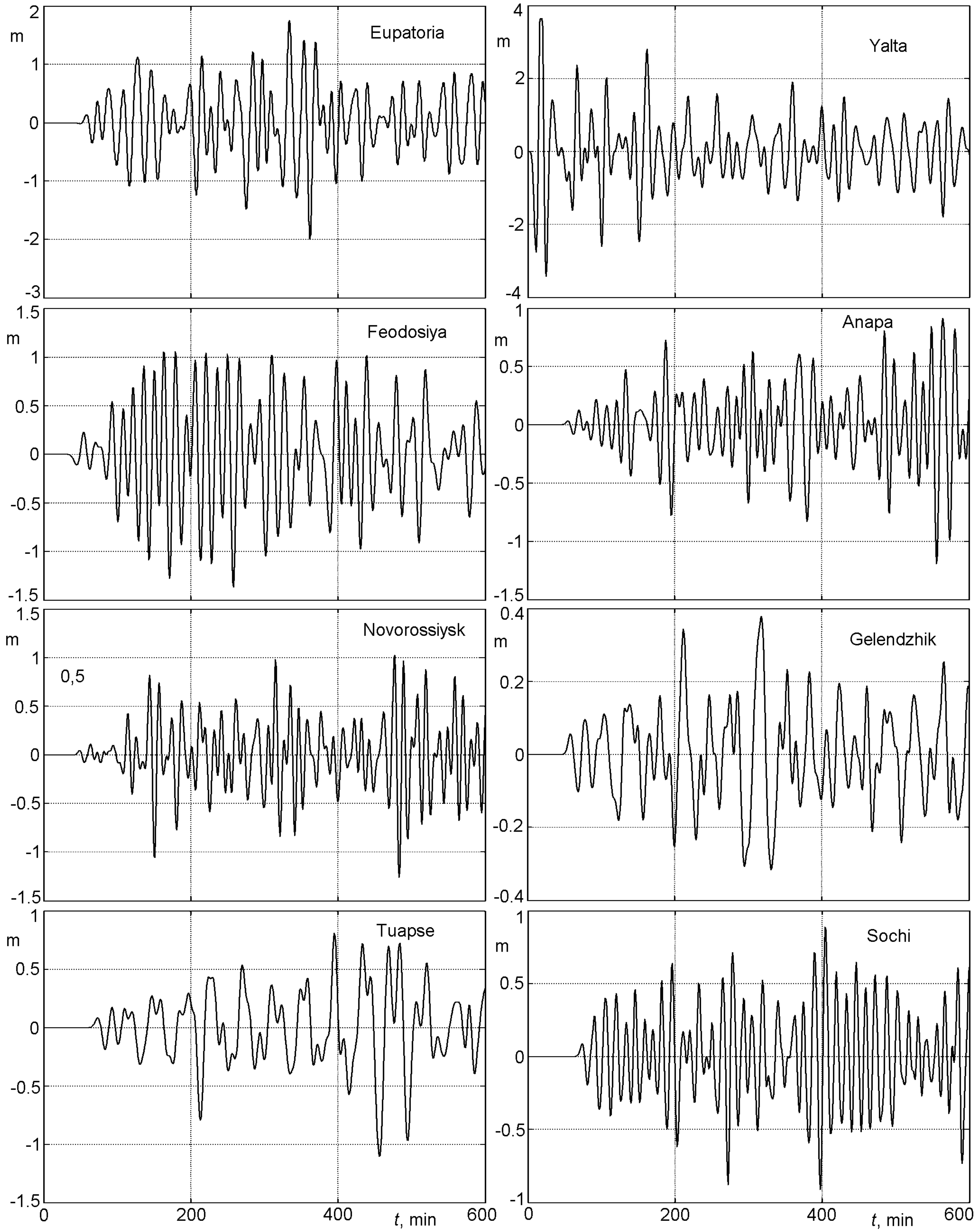

Figure 24. Pressure gauge series in eight towns of the coast for the sixth version of calculations: Anapa, Eupatoria, Feodosiya, Anapa, Gelendzhik, Novorossiysk, Tuapse, Yalta, and Sochi.

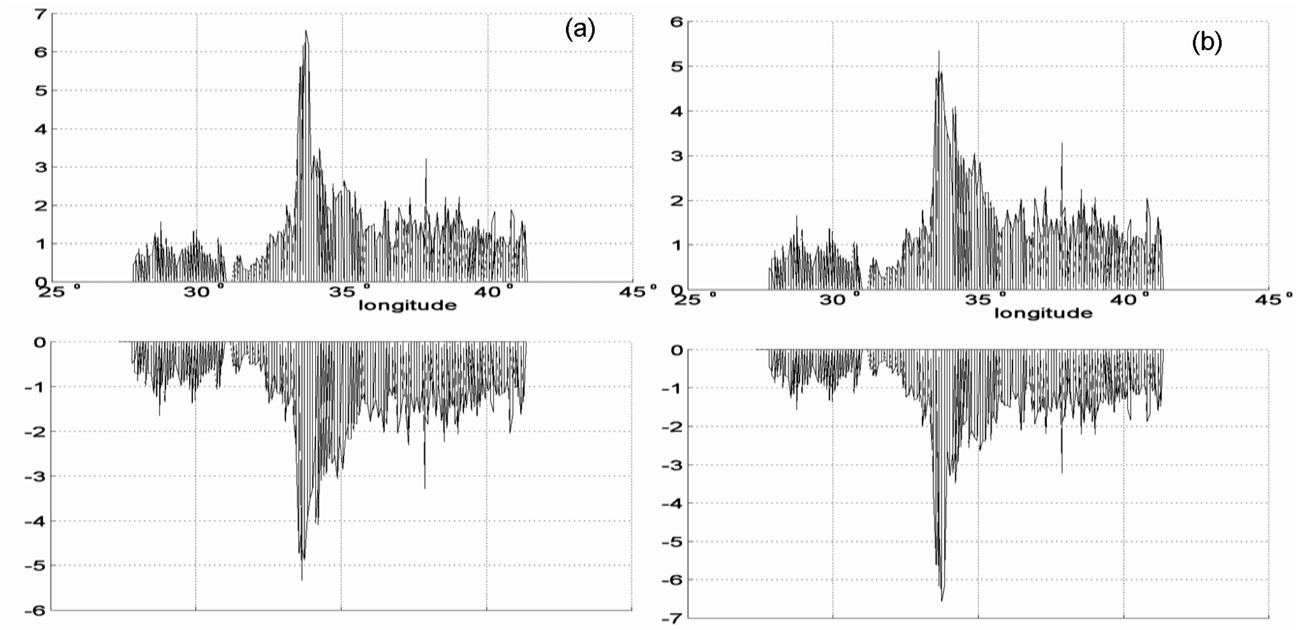

Figure 25. Distributions of maximal and minimal wave heights along the Russian coast for the fifth and sixth scenarios.

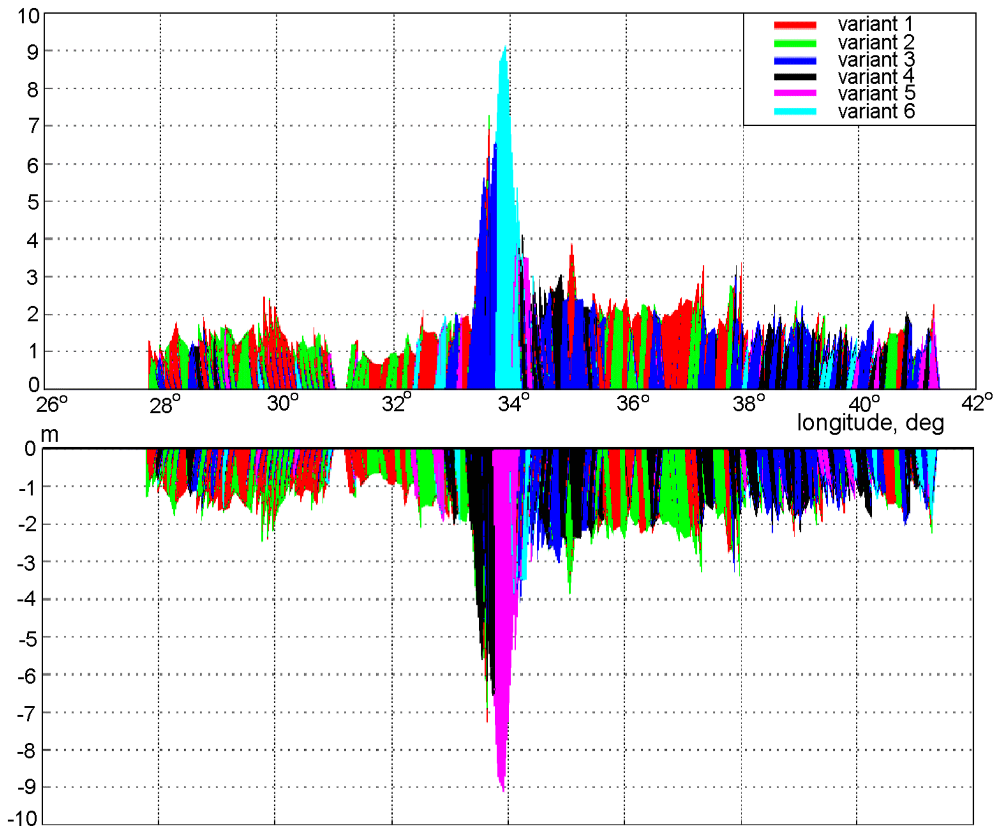

Figure 26. Histogram of the distribution of wave heights along the Russian coast of the Black Sea for hypothetical tsunami with M = 8.5. Coordinates of the source are 34.4°E–33.6°E; 44.3°N–43.5°N.

sequences of tsunami wave impact caused by strong earthquakes requires numerical modeling of the generation and propagation of tsunami waves at the location of the earthquake source in the most dangerous zones of fractures of tectonic plates, which will be studied in our future work.

[67] **Acknowledgments.** This work was supported by Russian Foundation for Basic Research no. 05-05-64685 and EU Project 502247 (COMSHELFRISKS).

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R. Kh. Mazova, E.A. Tresvyatskaya, Nizhniy Novgorod Technical University, Nizhniy Novgorod, 603600 Russia