THE PROBABILITY OF TSUNAMIS OCCURRENCE GENERATED BY THE ISTANBUL SEISMIC AREA

RALUCA PARTHENIU[1], ANDREEA CRAIU[1], MIHAIL DIACONESCU[1], DUMITRU IOANE[2], IREN-ADELINA MOLDOVAN[1]

[1] *National Institute of Research and Development for Earth Physics, 12, Călugăreni St., Măgurele, Romania, partheniu_raluca@yahoo.com*
[2] *University of Bucharest, Faculty of Geology and Geophysics, Department of Geophysics, 6, Traian Vuia St., 020956 Bucharest, Romania*

Previous studies have shown that the Black Sea was subject to tsunami waves generation in the past (Altinok, 1999), with a total of twenty-two events generated. According to recent studies of Diaconescu *et al.* (2008), the Black Sea is divided in nine seismic sources. A more recent approach structures the area in ten different seismic sources, given by Moldovan *et al.* (2016, 2017). This study focuses mostly on the Istanbul seismic source, which triggered in the past high magnitude earthquakes followed by tsunami waves.

The most recent event generated in the Black Sea was on 15th of October 2016, with a magnitude Mw = 5.1, at a depth of 10 km, with the following location: Latitude 42.19° N, Longitude 30.68° E. The focal mechanism determined through the moment tensor inversion (U.S. Geological Survey – USGS) indicates a reverse faulting type. For this event, few tsunami modeling scenarios were run. When using the exact parameters of the earthquake (Mw = 5.3), the simulations show no results. More simulations were computed, increasing the magnitude with steps of 0.2, from 7.0 up to 7.8. The modeling was accomplished using the Tsunami Analysis Tool (TAT), software provided by the Joint Research Center (JRC) from Ispra, Italy.

The results of these tsunami simulations show low wave heights for a magnitude of 7.2, of maximum 0.42 m in Eregli (Turkey), 0.36 m in Zonguldak Eregli (Turkey), and 0.32 m in Kilimli (Turkey). For a magnitude of 7.6, the maximum wave heights are higher, considered to be moderate, of 1.59 m in Zonguldak Eregli (Turkey), 1.21 m in Eregli (Turkey). Moreover, there are three locations from the Romanian shoreline affected, as follows: 0.83 m in Mangalia, 0.5 m in Techirghiol and 0.39 m in Constanţa.

In order to obtain a correlation of these simulations to real events of high magnitude, we will compare them with two past earthquakes from the Istanbul seismic area, generated on 12th of November 1999 (Mw = 7.2) and 17th of August 1999 (Mw = 7.6). Due to their location inland, the results for these two earthquakes display very low wave heights, of maximum 0.18 m. These events were also modeled using the same software, same methodology, considering as location an offshore position of the earthquakes, assumed as being generated on similar faults. The results were compared to the modeling output of the 2016 earthquake from October.

For a better evaluation of the tsunami waves possibility of occurrence in the Istanbul seismic area, more information regarding the parameters of high magnitude earthquakes, their location and focal mechanism type, are necessary.

Key words: earthquake, Black Sea, tsunami modelling.

1. INTRODUCTION

The Black Sea was subject to tsunami waves generation in the past, with a total of 22 events generated, according to different sources and papers (Altinok, 1999; Yalciner *et al.*, 2004; Papadopoulos *et al.*, 2011).

According to previous studies provided by Diaconescu *et al.* (2008), the Black Sea is divided in nine seismic sources. A more recent approach structures the area in ten different seismic sources, given by Moldovan *et al.* (2016, 2017).

This study focuses mostly on the Istanbul seismic source, which triggered in the past high magnitude earthquakes. Some of these events were followed by tsunami waves generation.

The Istanbul seismic source is defined considering both onshore and offshore past earthquakes (Hancilar, 2012; Kalkan *et al.*, 2008; Moldovan, 2016), being situated along the intersection between the southern part of the West Black Sea fault and faults associated to the North Anatolian fault.

A short description of the past high magnitude earthquakes was given, along with

the most recent event generated in the Black Sea, on 15th of October 2016, with an initial magnitude Mw = 5.3 (final magnitude of 5.1), at a depth of 10 km.

For a good evaluation of the tsunamis occurrence generated by the Istanbul seismic source, few tsunami modeling scenarios were accomplished, using the parameters of the most recent event from 15th of October 2016. The modeling was accomplished using the Tsunami Analysis Tool (TAT), software provided by the Joint Research Center (JRC) from Ispra, Italy. Same software was used for tsunami waves modeling for two past earthquakes from the Istanbul seismic area, generated on 12th of November 1999 (Mw = 7.2) and 17th of August 1999 (Mw = 7.6).

2. SHORT DESCRIPTION OF THE ISTANBUL SEISMIC AREA

The continental maximum observed Magnitude was Mw = 7.6 for an earthquake generated on 17th of August 1999 (U.S. Geological Survey – USGS).

The seismic activity is considered to be the number of seismic events per number of years. In this case, for the Istanbul seismic area, the estimated seismic activity is 0,44 events / year, considering all the events with a minimum magnitude of Mw = 3.

The average depth of the earthquakes generated in this area is 22,1 km. Taking into account previous studies of Yalciner *et al.* (2004), most of the past events have a shallow depth.

The Istanbul seismic area contains both onshore and offshore sectors, from the Sea of Marmara (South of Istanbul) and the Black Sea (North of Istanbul). The area is located along the intersection between the southern part of the West Black Sea Fault (Eurasian Plate) and faults associated to the North Anatolian fault (Anatolian Block), as displayed in Figures 1a and 1b (Sosson *et al.*, 2010).

The distribution of epicentres which characterize the Istanbul seismic area mark the flections of the structural lines belonging to the North Anatolian faults system. The faults from Istanbul source have an ample development, the active sectors being of hundreds of km. The fault plain solutions highlight mostly a strike slip character (European–Mediterranean Seismological Centre – CSEM–EMSC).

3. PAST AND RECENT EVENTS

The past earthquakes generated in the Istanbul seismic area are displayed in Figure 2 (CSEM-EMSC), with the most recent event evidenced by a red star.

Two documented events of high magnitude were generated in the past in Istanbul area, one on 12th of November 1999 (Mw = 7.2), with the following parameters: latitude 40.75°, longitude 31.16°, depth 10 km, and the other one on 17th of August 1999 (Mw = 7.6) with the location: latitude 40.74°, longitude 29.86°, at a depth of 17 km (Fig. 2).

The most recent earthquake generated in the Black Sea (represented by a red star in Fig. 2), was on 15th of October 2016, with an initial magnitude Mw 5.3 (final magnitude Mw 5.1), at a depth of 10 km, and having the following coordinates: latitude 42.19°, longitude 30.68° (according to CSEM–EMSC). The focal mechanism determined through the moment tensor inversion (3 sources: USGS, German Research Centre for Geosciences – GFZ, Kandilli Observatory and Earthquake Research Institute – KAN) indicates a reverse faulting type for this earthquake and is displayed in Figure 3. The earthquake's parameters, including the fault plane solution, are displayed in Table 1.

4. DATA AND RESULTS

Different tsunami modeling scenarios were accomplished for the most recent event generated in the Black Sea on 15th of October 2016, using the earthquakes parameters (coordinates, depth and fault plane solution – Table 1). For a magnitude of Mw = 5.3 the

modeling gives no results. The magnitude was further increased with steps of 0.2, from 7.0 up to 7.8. The modeling was accomplished using the Tsunami Analysis Tool (TAT), software provided and developed by the Joint Research Center (JRC) (Annunziato, 2007). The software is used worldwide for the purpose of assisting the operator from a tsunami warning centre in decision making in case of an event which could generate a tsunami. TAT contains a database with processed simulations, which will be compared with real data, in order to rapidly estimate the effects of an earthquake. Moreover, real time modeling is generated, in case of an event of high magnitude. The software collects the information from different websites and Agencies (USGS, CSEM–EMSC), and sends messages to its users, for any worldwide earthquake with Mw ≥ 4.5. It was also used in the recent years in the framework of numerous national and international projects.

In the present paper, only some examples of tsunami simulations are displayed, a paper with more results will be written in the near future. Two examples are for magnitudes of 7.2 and 7.6, and also a correlation with the simulations of real past events will be made.

The first example is for a simulation of an earthquake using the location of 15th of October earthquake (Mw 5.1), modifying the magnitude of the event (for a magnitude lower than 7, the simulations give no results). The exact parameters used in the modeling simulation are: latitude 42.19°, longitude 30.68°, magnitude 7.2, depth 10 km; the fault parameters are: strike = 224, dip = 28, rake = 80, fault width = 16 km, fault length = 60 km. The maximum wave heights and travel times for this scenario are displayed in Figure 4.

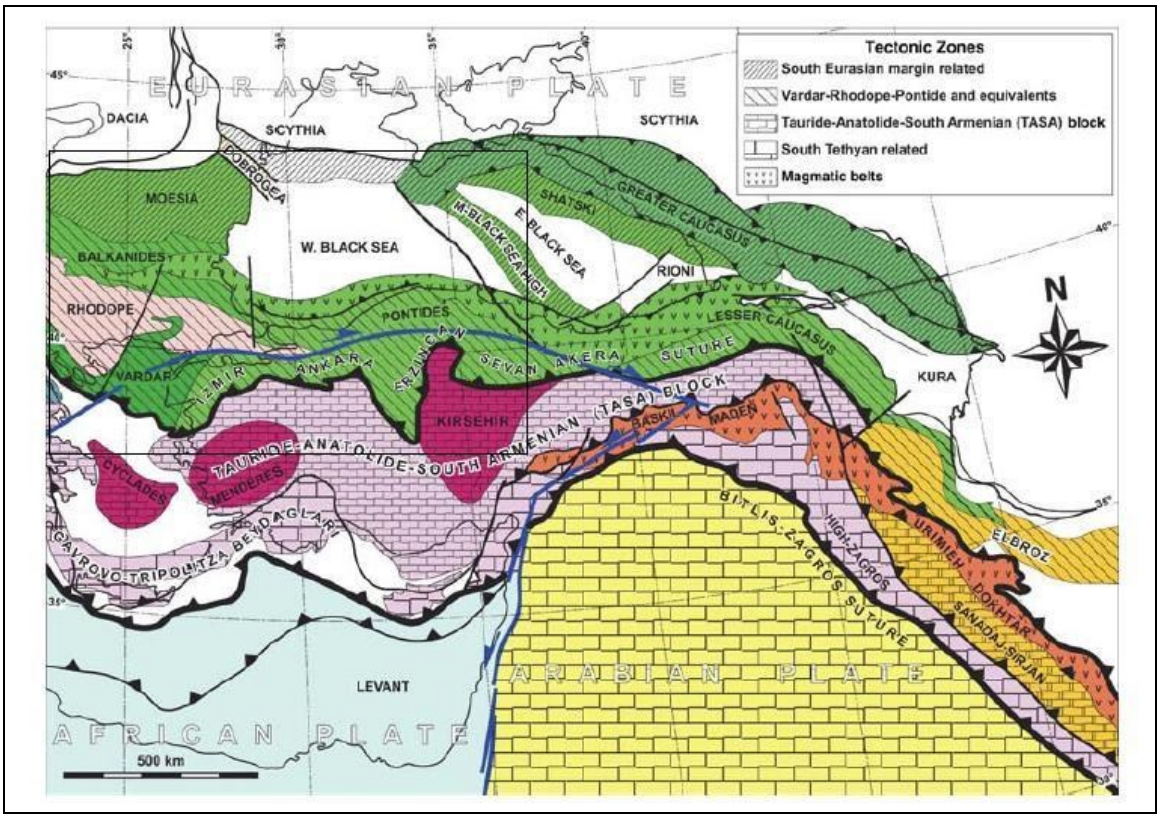

Fig. 1a – Tectonic setting of the Black Sea area – general view (Sosson *et al.*, 2010).

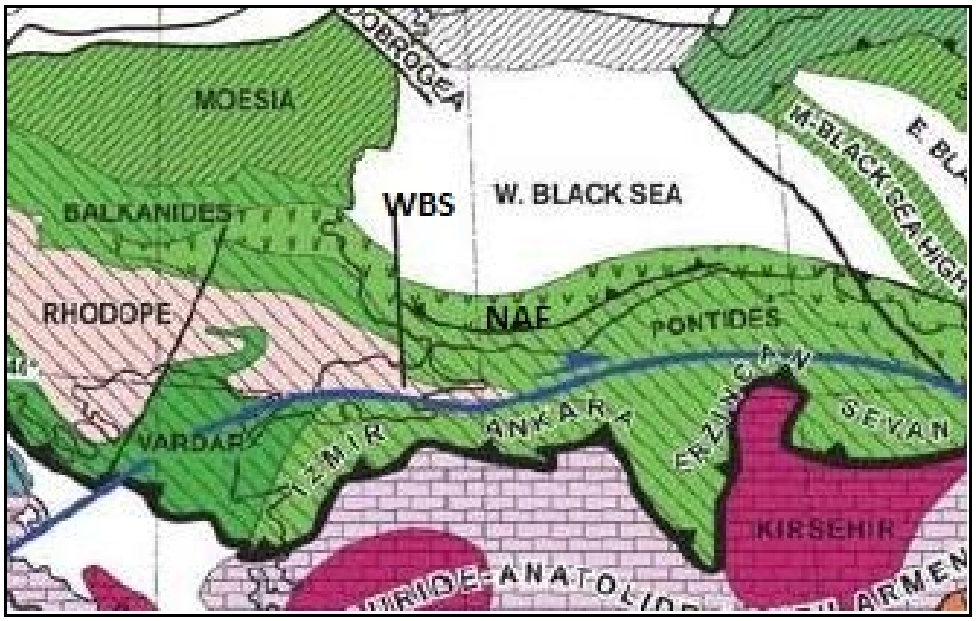

Fig. 1b – Tectonic setting of the Black Sea area – detailed view (Sosson *et al.*, 2010); (WBS – Western Black Sea fault, NAF – North Anatolian fault).

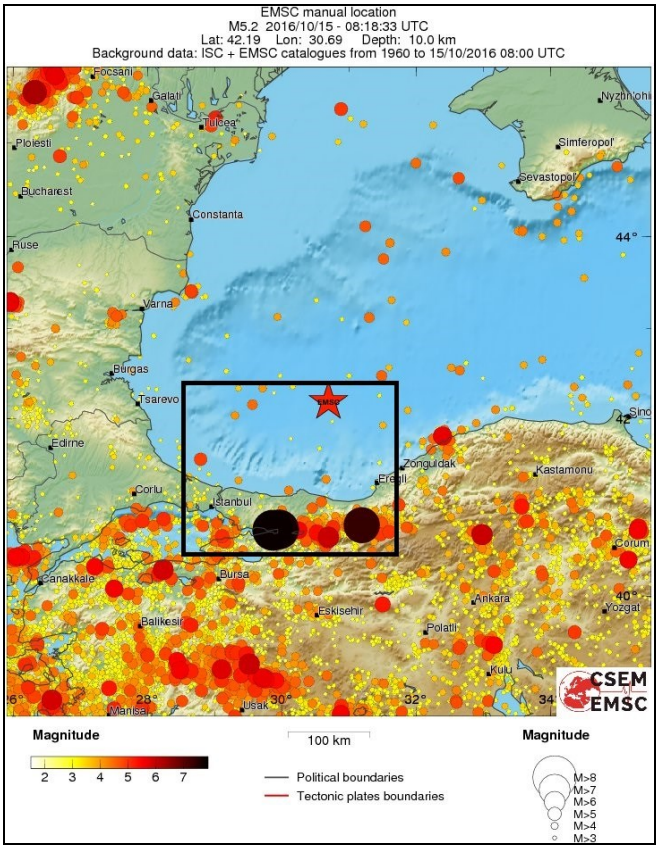

Fig. 2 – Past earthquakes generated in the Istanbul seismic area (source: CSEM-EMSC). The black dots represent past high magnitude earthquakes.

Table 1

Final parameters of the earthquake from 15th of October 2016 (source: USGS)

Date and Time UTC	**Mag.**	**Latitude**	**Longitude**	**Depth** km	**Plane**	**Strike**	**Dip**	**Rake**
2016-10-15 08:18:32	5.1	42.19°N	30.68°E	6.4	**NP1**	55°	62°	95°
					NP2	224°	28°	80°

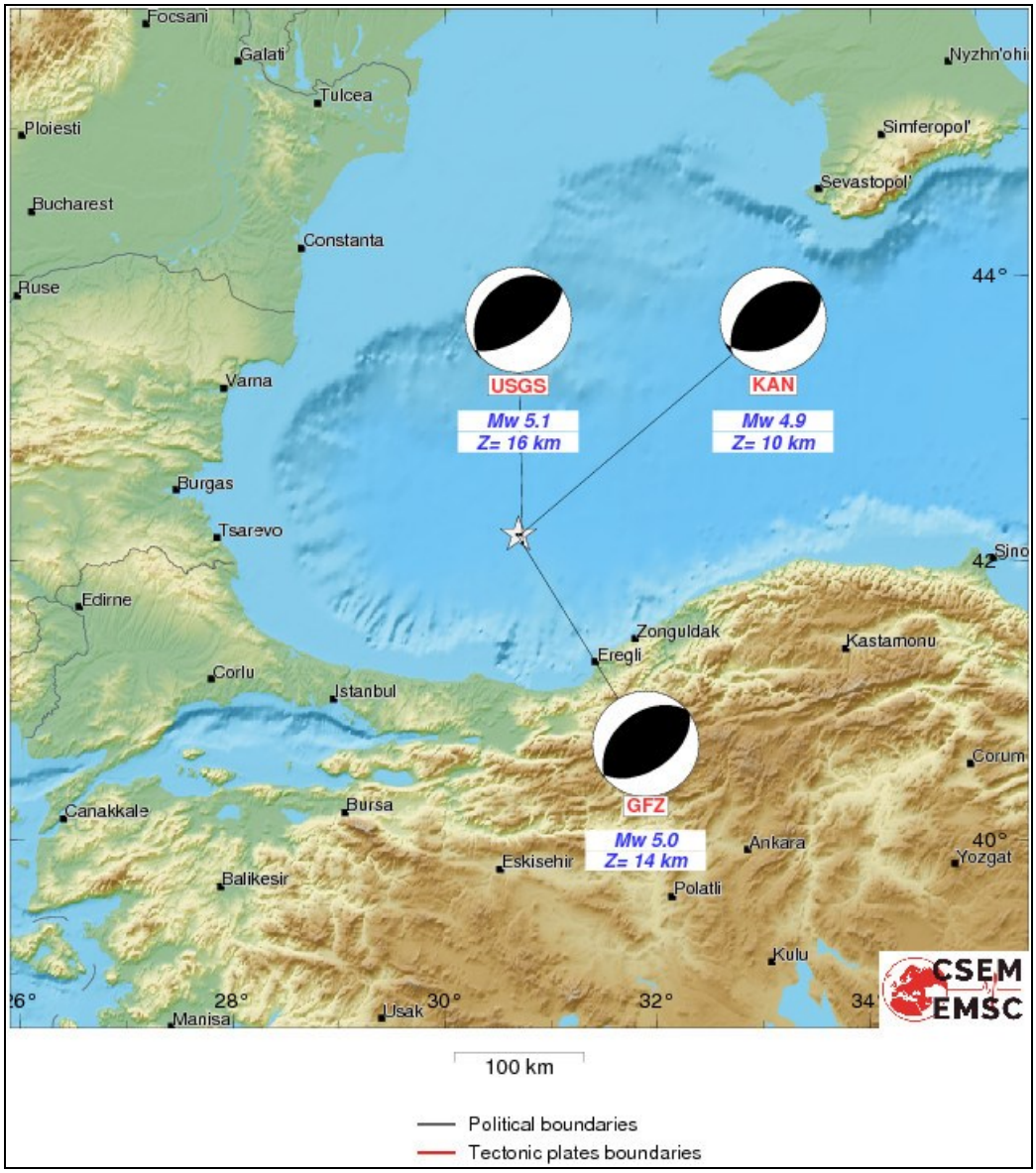

Fig. 3 – The focal mechanism of the initial magnitude Mw 5.3 earthquake, determined by different sources (source: CSEM-EMSC).

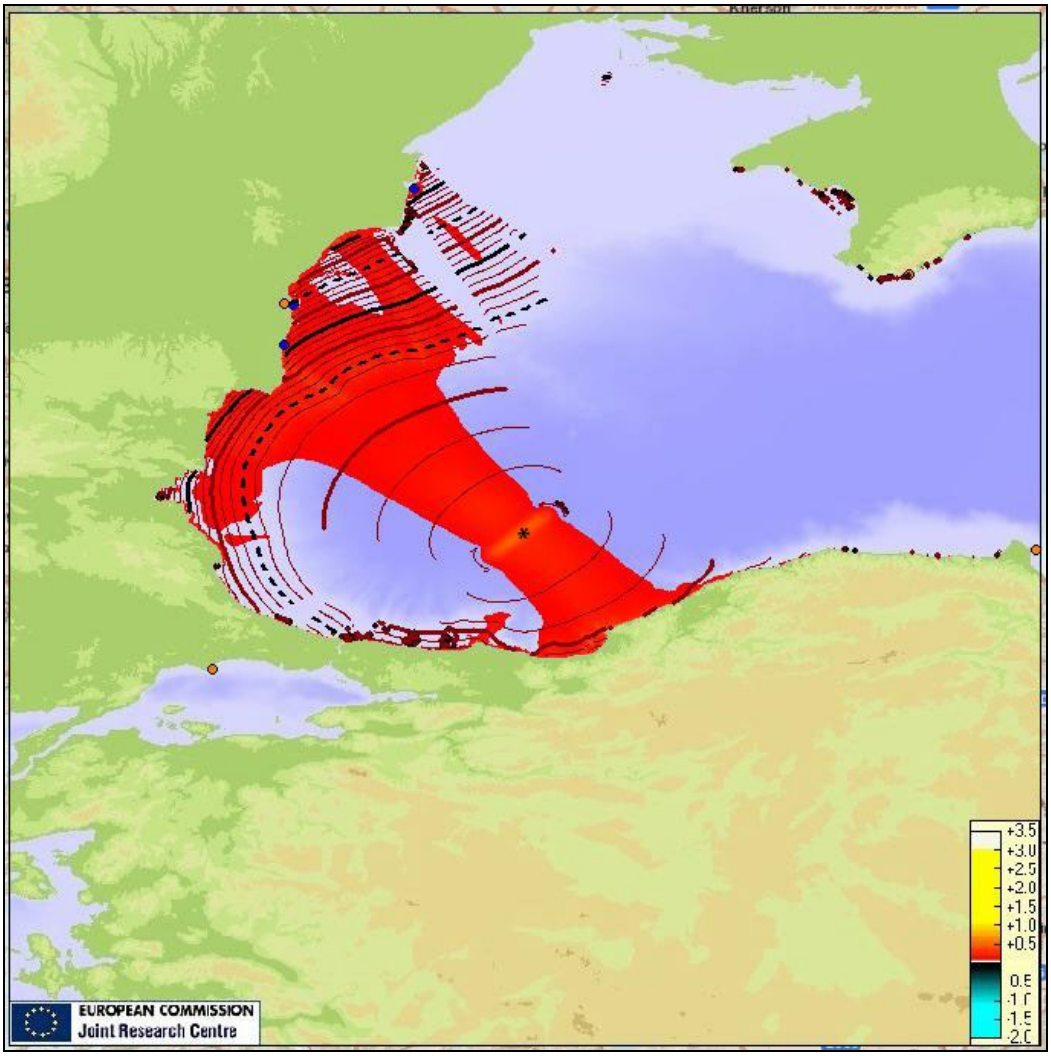

Fig. 4 – Maximum wave heights and travel times for the simulation of an earthquake of magnitude 7.2, generated in offshore Istanbul (source: TAT Software).

The results show low wave heights for a magnitude of 7.2, of maximum 0.42 m in Eregli (Turkey), 0.36 m in Zonguldak Eregli (Turkey), and 0.32 m in Kilimli (Turkey). There are two locations affected from the Romanian shore, Techirghiol with 0.14 m and Constanta with 0.11 m (Table 2). The tsunami waves propagate from the epicentral area to these locations with a travel time of 1 hour and 20 minutes for Techirghiol and 1 hours and 28 minutes for Constanta (Table 2).

The second example is a simulation of an earthquake with the following parameters: latitude 42.19°, longitude 30.68°, magnitude 7.6, depth 10 km, having the fault parameters: strike = 224, dip = 28, rake = 80, width = 19 km, length = 118,5 km. The maximum wave heights and travel times are displayed in Figure 5.

For this modeling scenario, the results show higher maximum wave heights, of 1.59 m in Zonguldak Eregli (Turkey), 1.21 m in Eregli (Turkey) (Table 4). There are 3 locations affected, from the Romanian shore as follows: 0.83 m in Mangalia, 0.5 m in Techirghiol and 0.39 m in Constanta (Table 3). The tsunami waves propagate from the epicentral area to these locations with a travel time of 58 minutes for Mangalia, 1 hour and 14 minutes for Techirghiol and 1 hours and 26 minutes for Constanta (Table 4).

Table 2

Affected locations resulted from the simulation of an earthquake of magnitude 7.2, generated offshore Istanbul (source: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height	ID	
00:40 (Max: 00:44)	15 Oct 2016 09:02	Turkey	Karacakoy	0.07	41.43	28.46
00:50 (Max: 00:52)	15 Oct 2016 09:10	Turkey	Kirklareli_Igneada_(	0.07	41.89	28.02
00:22 (Max: 01:28)	15 Oct 2016 09:46	Turkey	Istanbul_Sile_(m)	0.08	41.18	29.60
01:08 (Max: 01:10)	15 Oct 2016 09:28	Bulgaria	Chernomorets	0.09	42.45	27.64
00:50 (Max: 00:54)	15 Oct 2016 09:12	Bulgaria	Akhtopol	0.11	42.10	27.94
01:28 (Max: 02:38)	15 Oct 2016 10:56	Romania	Constanta	0.11	44.19	28.66
00:14 (Max: 00:16)	15 Oct 2016 08:34	Turkey	Sakarya_Ihsaniye	0.12	41.13	30.65
00:22 (Max: 00:26)	15 Oct 2016 08:44	Turkey	Kocaeli_Kefken	0.12	41.17	30.22
00:54 (Max: 00:58)	15 Oct 2016 09:16	Bulgaria	Michurin	0.13	42.18	27.85
01:20 (Max: 01:44)	15 Oct 2016 10:02	Romania	Techirghiol	0.14	44.07	28.65
00:16 (Max: 00:34)	15 Oct 2016 08:52	Turkey	Amasra_(m)	0.15	41.75	32.39
01:08 (Max: 01:10)	15 Oct 2016 09:28	Bulgaria	Varna	0.15	43.20	27.93
00:20 (Max: 00:58)	15 Oct 2016 09:16	Turkey	Duzce_Akcakoca	0.18	41.10	31.12
00:14 (Max: 00:22)	15 Oct 2016 08:40	Turkey	Catalagzi	0.25	41.53	31.91
00:14 (Max: 00:16)	15 Oct 2016 08:34	Turkey	Kozlu	0.3	41.45	31.75
00:14 (Max: 00:26)	15 Oct 2016 08:44	Turkey	Zonguldak	0.3	41.46	31.78
00:14 (Max: 00:42)	15 Oct 2016 09:00	Turkey	Kilimli	0.32	41.50	31.85
00:16 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Zonguldak_Eregli	0.36	41.25	31.40
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Eregli	0.42	41.32	31.41

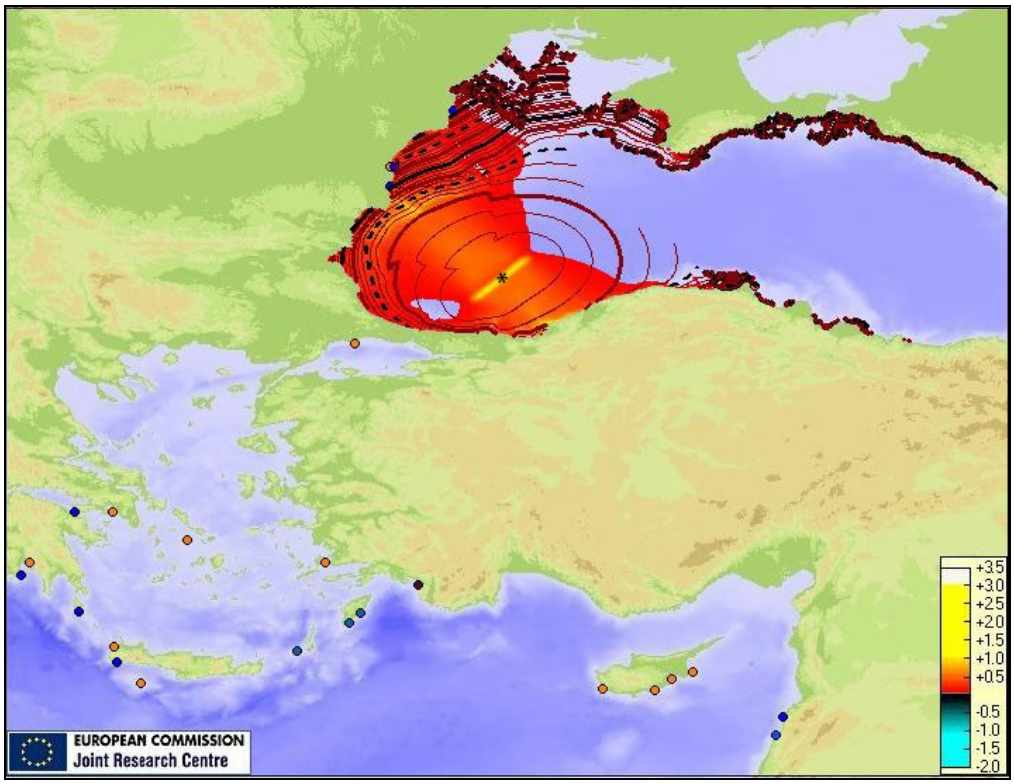

Fig. 5 – Maximum wave heights and travel times for the simulation of an earthquake of magnitude 7.6, generated offshore Istanbul (source: TAT Software).

Table 3

Affected locations resulted from the simulation of an earthquake of magnitude 7.6, generated offshore Istanbul (source: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height		ID	
01:22 (Max: 02:50)	15 Oct 2016 11:08	Russia	Arkhipo-Osipovka	0.07		44.35	38.52
01:22 (Max: 03:12)	15 Oct 2016 11:30	Russia	Tuapse	0.07		44.10	39.06
01:44 (Max: 03:28)	15 Oct 2016 11:46	Russia	Kabardinka	0.07		44.65	37.92
02:12 (Max: 03:20)	15 Oct 2016 11:38	Russia	Anapa	0.07		44.90	37.31
03:08 (Max: 03:16)	15 Oct 2016 11:34	Turkey	Ordu	0.07		40.99	37.92
01:04 (Max: 02:40)	15 Oct 2016 10:58	Turkey	Sinop_(m)	0.08		42.02	35.15
00:30 (Max: 03:44)	15 Oct 2016 12:02	Turkey	Kastamonu_Inebolu	0.09		41.98	33.77
00:42 (Max: 01:56)	15 Oct 2016 10:14	Ukraine	Sevastopol'	0.1		44.49	33.60
01:04 (Max: 01:08)	15 Oct 2016 09:26	Bulgaria	Pomorie	0.21		42.57	27.64
00:32 (Max: 00:46)	15 Oct 2016 09:04	Turkey	Sariyer	0.25		41.16	29.05
00:38 (Max: 00:46)	15 Oct 2016 09:04	Turkey	Uskudak	0.25		41.11	29.09
00:38 (Max: 00:46)	15 Oct 2016 09:04	Turkey	Beykoz	0.25		41.12	29.09
01:04 (Max: 01:08)	15 Oct 2016 09:26	Bulgaria	Chernomorets	0.26		42.45	27.64
00:36 (Max: 00:42)	15 Oct 2016 09:00	Turkey	Karacakoy	0.29		41.43	28.46
00:16 (Max: 01:24)	15 Oct 2016 09:42	Turkey	Istanbul_Sile_(m)	0.35		41.18	29.60
00:44 (Max: 00:48)	15 Oct 2016 09:06	Bulgaria	Akhtopol	0.37		42.10	27.94
00:48 (Max: 00:54)	15 Oct 2016 09:12	Bulgaria	Michurin	0.37		42.18	27.85
01:26 (Max: 01:56)	15 Oct 2016 10:14	Romania	Constanta	0.39		44.19	28.66
01:04 (Max: 01:20)	15 Oct 2016 09:38	Bulgaria	Varna	0.42		43.20	27.93
00:56 (Max: 01:12)	15 Oct 2016 09:30	Bulgaria	Balchik	0.49		43.40	28.16
00:12 (Max: 00:20)	15 Oct 2016 08:38	Turkey	Sakarya_Ihsaniye	0.51		41.13	30.65
00:46 (Max: 00:50)	15 Oct 2016 09:08	Turkey	Kirklareli_Igneada_(	0.52		41.89	28.02
01:14 (Max: 01:36)	15 Oct 2016 09:54	Romania	Techirghiol	0.55		44.07	28.65
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Catalagzi	0.57		41.53	31.91
00:46 (Max: 00:58)	15 Oct 2016 09:16	Bulgaria	Kavarna	0.57		43.41	28.33
00:16 (Max: 00:22)	15 Oct 2016 08:40	Turkey	Amasra_(m)	0.62		41.75	32.39
00:18 (Max: 00:24)	15 Oct 2016 08:42	Turkey	Kocaeli_Kefken	0.62		41.17	30.22
00:18 (Max: 00:26)	15 Oct 2016 08:44	Turkey	Duzce_Akcakoca	0.73		41.10	31.12
00:58 (Max: 01:12)	15 Oct 2016 09:30	Romania	Mangalia	0.83		43.81	28.59
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Kozlu	0.86		41.45	31.75
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Kilimli	0.89		41.50	31.85
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Zonguldak	0.9		41.46	31.78
00:16 (Max: 00:24)	15 Oct 2016 08:42	Turkey	Zonguldak_Eregli	1.21		41.25	31.40
00:14 (Max: 00:18)	15 Oct 2016 08:36	Turkey	Eregli	1.59		41.32	31.41

Table 4

Affected locations from the Romanian shoreline, resulted from the simulation of an earthquake of magnitude 7.6, generated offshore Istanbul (source: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height		ID	
00:58 (Max: 01:12)	15 Oct 2016 09:30	Romania	Mangalia	0.83		43.81	28.59
01:14 (Max: 01:36)	15 Oct 2016 09:54	Romania	Techirghiol	0.55		44.07	28.65
01:26 (Max: 01:56)	15 Oct 2016 10:14	Romania	Constanta	0.39		44.19	28.66

Table 5

Affected locations resulted from the simulation of the earthquake of magnitude 7.2, generated on 12th of November 1999 (offshore location) (source: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height		ID	
01:20 (Max: 02:32)	12 Nov 1999 19:29	Bulgaria	Pomorie	0.06		42.57	27.64
00:12 (Max: 01:30)	12 Nov 1999 18:27	Turkey	Kozlu	0.07		41.45	31.75
00:12 (Max: 01:30)	12 Nov 1999 18:27	Turkey	Zonguldak	0.07		41.46	31.78
00:14 (Max: 01:04)	12 Nov 1999 18:01	Turkey	Kilimli	0.08		41.50	31.85
00:36 (Max: 01:16)	12 Nov 1999 18:13	Turkey	Amasra_(m)	0.08		41.75	32.39
00:56 (Max: 01:06)	12 Nov 1999 18:03	Turkey	Kirklareli_Igneada_(	0.08		41.89	28.02
00:58 (Max: 01:00)	12 Nov 1999 17:57	Bulgaria	Akhtopol	0.09		42.10	27.94
01:02 (Max: 03:04)	12 Nov 1999 20:01	Bulgaria	Michurin	0.09		42.18	27.85
00:48 (Max: 02:50)	12 Nov 1999 19:47	Turkey	Karacakoy	0.13		41.43	28.46
00:08 (Max: 01:08)	12 Nov 1999 18:05	Turkey	Eregli	0.16		41.32	31.41
00:10 (Max: 01:10)	12 Nov 1999 18:07	Turkey	Zonguldak_Eregli	0.24		41.25	31.40
00:14 (Max: 00:42)	12 Nov 1999 17:39	Turkey	Kocaeli_Kefken	0.3		41.17	30.22
00:10 (Max: 01:14)	12 Nov 1999 18:11	Turkey	Duzce_Akcakoca	0.31		41.10	31.12
00:02 (Max: 00:04)	12 Nov 1999 17:01	Turkey	Sakarya_Ihsaniye	0.37		41.13	30.65
00:26 (Max: 01:22)	12 Nov 1999 18:19	Turkey	Istanbul_Sile_(m)	0.4		41.18	29.60

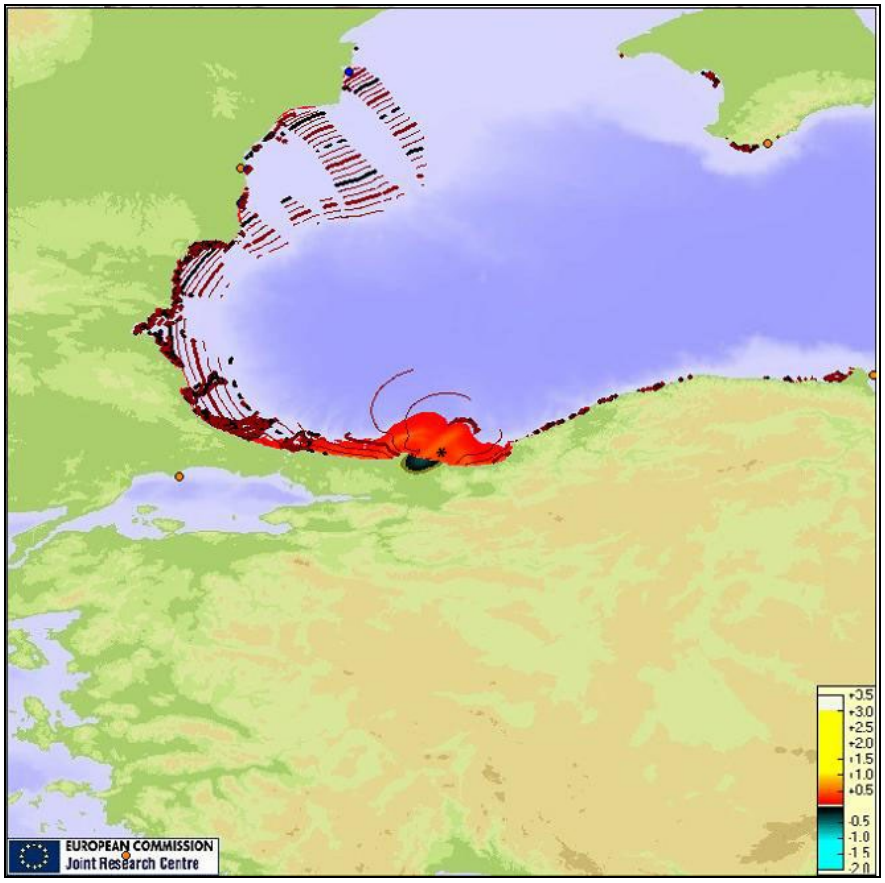

Fig. 6 – Maximum wave heights and travel times for the simulation of the earthquake of magnitude 7.2, generated on 12th of November 1999 (offshore location) (source: TAT Software).

Table 6
Parameters of the earthquake from 17th of August 1999 and tsunami maximum waves evaluation
(source: *https://www.ngdc.noaa.gov/hazard/tsu_db.shtml*)

Date and Time	Tsunami cause	Earthquake magnitude	Country, area	Latitude	Longitude	Max. Water Height (m)	Number of run-ups
17.08.1999 00:01:39	Earthquake	7.6	Turkey, Kocaeli	40.76	29.97	2.52	26

In order to obtain a comparison of these simulations to real events of high magnitude, we correlated them with two past earthquakes from the Istanbul seismic area, generated on 12th of November 1999 (Mw = 7.2) and 17th of August 1999 (Mw = 7.6). These events were modeled using the same software and methodology and also same input earthquake parameters (coordinates, depth and fault parameters), but due to their location inland or close to inland, a new location was given in the Southern Black Sea area.

For the event of magnitude 7.2, generated on 12th of November 1999, the parameters of the earthquake used for the tsunami simulation are the following: latitude 40.75°, longitude 31.16°, magnitude 7.2, depth 10 km, and the fault parameters are: strike = 169, dip = 67, rake =18, width = 16 km, length = 60 km.

The simulation for this event gives no results, due to the location inland of the event. If the epicenter of the M 7.2 earthquake is moved offshore, same longitude, modifying the latitude to 41.3°, the results show maximum waves of 0.4 m (Table 5). The maximum wave heights and travel times for this scenario are displayed in Figure 6.

The second event of magnitude 7.6, generated on 17th of August 1999 is better documented from tsunami point of view. According to the tsunami data base of the National Oceanic and Atmospheric Administration (NOAA), this earthquake generated tsunami waves of maximum 2.52 m (Table 6). The long duration of the earthquake's ground motions (45 seconds) and the proximity of the epicenter to the Sea of Marmara and the Gulf of Izmit, show that the tsunami was generated in the Gulf of Izmit, in the eastern part of the Sea of Marmara, not in the Black Sea. The tsunami waves had a very short period, less than a minute.

The tsunami simulation results for this event are much different than the ones given by NOAA from Table 5, being underestimated. The parameters of the earthquake used for the simulation are the following: latitude 40.74°, longitude 29.86°, magnitude 7.6, depth 17 km and the fault parameters are: strike = 178, dip = 74, rake = 9, width = 19 km, length = 118.5 km. Only a table with the affected locations is displayed for this modeling simulation, the results showing maximum waves of 0.18 m in two locations from the Turkish shore-line, Izmit and Kocaeli (Table 7).

Table 7

Affected locations resulted from the simulation of the earthquake of magnitude 7.6, generated on 17th of August 1999 (source: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height	ID	
00:54 (Max: 04:02)	17 Aug 1999 04:03	Turkey	Kirklareli_Igneada_(	0.06	41.89	28.02
01:34 (Max: 01:34)	17 Aug 1999 01:35	Turkey	Sakarya_Ihsaniye	0.07	41.13	30.65
00:18 (Max: 00:32)	17 Aug 1999 00:33	Turkey	Kocaeli_Kefken	0.09	41.17	30.22
00:10 (Max: 00:20)	17 Aug 1999 00:21	Turkey	Istanbul_Sile_(m)	0.15	41.18	29.60
00:12 (Max: 01:52)	17 Aug 1999 01:53	Turkey	Golcuk	0.16	40.73	29.82
00:22 (Max: 01:48)	17 Aug 1999 01:49	Turkey	Kocaeli	0.18	40.76	29.91
00:24 (Max: 01:48)	17 Aug 1999 01:49	Turkey	Izmit	0.18	40.75	29.94

Given the low results for the maximum wave heights for this simulation scenario, and due to the close to inland location of the event, further modeling was generated. Similar to the previous case (of Mw = 7.2), the epicenter of the earthquake is moved offshore, considering the same longitude but modifying the latitude at 41.4°. Only a table with the affected locations is displayed for this simulation, the results showing maximum waves of 0.14 m in one location from the Turkish shore-line (Kirklareli Igneada), and 0.13 m in Kocaeli Kefken (Table 8). Few locations from the Bulgarian shore are listed in the table, with maximum waves of 0.08 m, but no location from the Romanian shore.

Table 8

Affected locations resulted from the simulation of the earthquake of magnitude 7.6, generated on 17th of August 1999 (offshore location) (*source*: TAT Software)

Arr. time (time of max)	Actual Time	Country	Location	Height	ID	
00:46 (Max: 03:32)	17 Aug 1999 03:33	Bulgaria	Michurin	0.06	42.18	27.85
01:06 (Max: 03:20)	17 Aug 1999 03:21	Bulgaria	Varna	0.06	43.20	27.93
01:30 (Max: 01:34)	17 Aug 1999 01:35	Turkey	Duzce_Akcakoca	0.06	41.10	31.12
00:10 (Max: 01:50)	17 Aug 1999 01:51	Turkey	Golcuk	0.07	40.73	29.82
01:24 (Max: 02:58)	17 Aug 1999 02:59	Bulgaria	Chernomorets	0.07	42.45	27.64
00:06 (Max: 00:06)	17 Aug 1999 00:07	Turkey	Korfez	0.08	40.77	29.70
00:06 (Max: 00:06)	17 Aug 1999 00:07	Turkey	Degirmendere	0.08	40.72	29.74
00:40 (Max: 02:24)	17 Aug 1999 02:25	Turkey	Karacakoy	0.08	41.43	28.46
00:46 (Max: 00:48)	17 Aug 1999 00:49	Bulgaria	Akhtopol	0.08	42.10	27.94
01:04 (Max: 01:46)	17 Aug 1999 01:47	Turkey	Sakarya_Ihsaniye	0.08	41.13	30.65
01:08 (Max: 02:28)	17 Aug 1999 02:29	Turkey	Zonguldak_Eregli	0.08	41.25	31.40
00:14 (Max: 00:52)	17 Aug 1999 00:53	Turkey	Istanbul_Sile_(m)	0.1	41.18	29.60
00:12 (Max: 01:00)	17 Aug 1999 01:01	Turkey	Kocaeli_Kefken	0.13	41.17	30.22
00:56 (Max: 03:06)	17 Aug 1999 03:07	Turkey	Kirklareli_Igneada_(	0.14	41.89	28.02

In order to make a correlation of the results from the simulations of the earthquake on 15th of October 2016, increasing its magnitude to 7.2 and 7.6, with the results of the simulations of real past events from 12th of November 1999 of magnitude 7.2 and from 17th of August 1999 of magnitude 7.6, the values are quite different, probably due to the inland or very close to inland location of the two past events from 1999. Considering only the magnitude and comparing the results of the simulations, for a magnitude of 7.2, the value of 0.42 m maximum wave height for the simulation of the earthquake from 15th of October 2016 is similar to the maximum value of 0.40 m from the simulation of the earthquake from 12th of November 1999, moving its epicenter offshore. For a magnitude of 7.6, the results are very different. The maximum wave height value of 1.59 m for the simulation using the parameters of the earthquake from 15th of October 2016 overestimating the values of the maximum height computed for the event from 17th of August 1999 of only 0.14 m (with the epicenter moved offshore), but underestimating the values of 2.52 m given by NOAA for the same event. These differences appear due to the type of earthquakes' focal mechanisms (normal and reverse fault usually generate tsunamis, strike-slip do not generate), the location itself, and also the capacity of the software to simulate events mostly offshore, rather than located very close to the shore or onshore.

5. CONCLUSIONS

This study focuses on the Istanbul seismic area, which triggered in the past high magnitude earthquakes, some of them followed by tsunami waves generation. The continental maximum

observed Magnitude is Mw = 7.6, for an earthquake generated on 17th of August1999 (USGS).

The most recent event generated in the Black Sea was observed on 15th of October 2016 of initial magnitude Mw 5.3 and final magnitude Mw 5.1, at 10 km depth, latitude 42.19°, longitude 30.68°. For this earthquake, few tsunami modeling scenarios were run, using magnitudes from 7.0 up to 7.8, with steps of 0.2. For the magnitude of 5.3 the simulations have no results, as expected, considering that previous studies have given the minimum magnitude for tsunami generation at 6.5. The modeling was accomplished using the Tsunami Analysis Tool (TAT) software.

Only two examples were displayed in this paper, for Mw = 7.2 and Mw = 7.6. The simulations show low wave heights for a magnitude of 7.2, of maximum 0.42 m in Eregli (Turkey). For a magnitude of 7.6, the maximum wave height is 1.59 m in Zonguldak Eregli (Turkey) and there are also 3 locations from Romania affected, Mangalia with 0.83 m, Techirghiol with 0.5 m and Constanta with 0.39 m.

In order to compare these simulations with real events of high magnitude, we made a correlation with two past earthquakes from the Istanbul seismic area, generated on 12th of November 1999 (Mw = 7.2) and 17th of August 1999 (Mw = 7.6).

Due to their location inland or close to inland, the tsunami simulation results for these two events display very low wave heights, of maximum 0.18 m in Izmit (Turkey) for the M 7.6, and no results for the M 7.2. If the epicenter of the 7.2 earthquake is moved offshore (same longitude, changing the latitude), the results show maximum waves of 0.4 m in Istanbul_Sile (Turkey). The National Oceanic and Atmospheric Administration (NOAA) gives for the second earthquake estimations of maximum 2.52 m tsunami waves in the Sea of Marmara. If the epicenter of the 7.6 earthquake is moved offshore (same longitude, changing the latitude), the results show maximum waves of 0.14 m in Kirklareli Igneada (Turkey).

A conclusion can be drawn regarding the TAT software, which does not give very good estimations for inland or very close to shore earthquakes. Moreover, the focal mechanism of the earthquake is an important factor in tsunami waves generation.

More studies are required in order to have a better correlation of the estimated sea level values from the simulations to the sea level measurements triggered by past events.

For a better evaluation of the tsunami waves possibility of occurrence in the Istanbul seismic area, more information regarding the parameters of high magnitude earthquakes, their location and focal mechanism, are necessary.

*Acknowledgements.*We acknowledge the support, help and collaboration of the Joint Research Centre, from the European Commission, for developing and providing the Tsunami Analysis Tool (TAT) software.

We acknowledge the support of the University of Bucharest, Faculty of Geology and Geophysics, Doctoral School of Geology.

This work was partially supported by the FP7 FP7-ENV2013 6.4-3 Assessment, Strategy and Risk Reduction for Tsunamis in Europe (ASTARTE) Project 603839/2013 and PNII, Capacity Module III ASTARTE RO Project 268/2014.

The research was supported partial by the National Authority for Scientific Research and Innovation of Romania, Nucleu Program, project No. PN 16 35 03 05.

REFERENCES

ALTINOK, Y. (1999), *Tsunamis along the coasts of the Black Sea.* Second Balkan Geophysical Congress and Exhibition, Proceedings of the Conference, pp. 46–47.

ANNUNZIATO, A. (2007), *The Tsunami Assessment Modelling System by the Joint Research Centre*. Science of Tsunami Hazards, **26**, no. 2, pp. 70–92.

DIACONESCU, M., MALIȚA, Z. (2008), *Characterization of the tsunamigenic potential of the seismic sources located around the Black Sea area.* International Seminar on Natural Hazards on the Marine Area, Proceedings of the Conference, pp. 13–14.

HANCILAR, U. (2012), *Identification of elements at risk for a credible tsunami event for Istanbul.* Natural Hazards and Earth System Sciences, **12**, pp. 107–119.

KALKAN, E., GÜLKAN, P., YILMAZ ÖZTÜRK, N., ÇELEBIR, M. (2008), *Seismic Hazard in the Istanbul Metropolitan Area: A Preliminary Re-Evaluation*. Journal of Earthquake Engineering, **12**, pp. 151–164.

MOLDOVAN, I.A., DIACONESCU, M., POPESCU, E., RADULIAN, M., TOMA-DANILA, D., CONSTANTIN, A.P., PLACINTA, A.O. (2016), *Input parameters for the probabilistic seismic hazard*

assessment in the eastern part of Romania and Black Sea area. Romanian Journal of Physics, **61**, pp. 7–8.

MOLDOVAN, I.A., DIACONESCU, M., PARTHENIU, R., CONSTANTIN, A.P., POPESCU, E., TOMA-DANILA, D. (2017), *Probabilistic seismic hazard assessment in the Black Sea area*. Romanian Journal of Physics, (accepted for publication).

PAPADOPOULOS, G.A., DIAKOGIANNI, G., FOKAEFS, A., RANGUELOV, B. (2011), *Tsunami hazard in the Black Sea and the Azov Sea: a new tsunami catalogue.* Natural Hazards and Earth System Science, **11**, pp. 945–963.

SOSSON, M., KAYMAKCI, N., STEPHENSON, R, BERGERAT, F., STAROSTENKO, V. (2010), *Sedimentary basin tectonics from the Black Sea and Caucasus to the Arabian Platform: Introduction.* Geological Society, London, Special Publications.

YALCINER, A., PELINOVSKY, E., TALIPOVA, T., KURLIN, A., KOZELKOV, A., ZAITSEV, A. (2004), *Tsunamis in the Black Sea: Comparison of the historical, instrumental and numerical data.* Journal of Geophysical Research, **109**, C12023, pp. 1–13.

United States Geological Survey (USGS) - http://earthquake.usgs.gov/earthquakes/map/

European-Mediterranean Seismological Centre (EMSC-CSEM) - http://www.emsc-csem.org/#2

http://www.geology.um.maine.edu/geodynamics/AnalogWebsite/UndergradProjects2010/PeterStrand/html/BackgroundPage.html

http://www.drgeorgepc.com/Tsunami1999Turkey.html

https://www.ngdc.noaa.gov/hazard/tsu_db.shtml

Received: April 13, 2018
Accepted for publication: February 8, 2019