

## OBSERVATIONS AND MODELING OF TSUNAMIS IN THE EASTERN MEDITERRANEAN (REVIEW)

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*Люба Димова, Ренета Райкова. НАБЛЮДЕНИЕ И МОДЕЛИРАНЕ НА ЦУНАМИ В ИЗТОЧНОТО СРЕДИЗЕМНОМОРИЕ (ПРЕГЛЕД)*

Над 130 събития на вълни цунами опустошават във времето Източното Средиземноморие. Тези бедствия са обобщени в 29 области с оценка на събитията за наблюдаваните наводнения и щети. Въпреки че рискът от цунами в Средиземно море не е толкова висок, колкото в Тихия Океан, височините на наблюдаваните вълни цунами в някои зони достигат 30 m. Много от регистрираните цунами са с неизяснен източник. 26 цунамигенни зони са набелязани според техните геоложки особености, наличие на земетресения и риск от свлачища. Повечето от областите са изучени чрез моделиране на цунами, но ние обособяваме няколко от тях, в които или има несъответствие между наблюденията и моделите, или зоната не е моделирана. Преглед на техниките за моделиране на цунами показват, че повечето методи използват числени модели с уравнения за плитка вода при различни приближения, гранични условия, в сферични или декартови координати.

*Lyuba Dimova, Reneta Raykova. OBSERVATION AND MODELING OF TSUNAMI IN THE EASTERN MEDITERRANEAN (REVIEW)*

The coast of Eastern Mediterranean has been devastated by more than 130 tsunami events, which were generalized in 29 areas with evaluation of the flood damages. Despite the tsunami risk in the Mediterranean is not as high, as it is in the Pacific Ocean, the tsunami highs in some areas exceeded 30 m. Many of the observed tsunamis remain with unclear sources. Twenty-six tsunamigenic zones were defined according to the geological characteristics, risk of earthquakes and landslides. Most of the regions have been studied by tsunami modeling, however we differentiated several areas, which have big discrepancies between observed and modeled data or they are not modeled at all. A review of tsunami modeling techniques show that most of the methods use numerical modeling of shallow-water equations, with different approximations, boundary conditions, in spherical or Cartesian coordinates.

**Keywords:** tsunami, numerical methods, earthquakes, landslides, volcanoes

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## 1. INTRODUCTION

Mediterranean Sea is divided into three major regions – Western Mediterranean (WM), Central Mediterranean (CM) and Eastern Mediterranean (EM). The Eastern Mediterranean includes several seas – the Ionian Sea between Italy, Greece, and Albania, the Aegean Sea between Greece and Turkey, with the Thracian Sea in its north, the Myrtoan Sea between the Cyclades and the Peloponnese, the Sea of Crete north of Crete, the Libyan Sea south of Crete, between the island and Libya, the Sea of Marmara between the Aegean and Black Seas, the Cilician Sea between Turkey and Cyprus, the Levantine Sea between southeastern part of Cyprus and Lebanon. Black Sea is the internal sea but it is connected with the Mediterranean by the Bosphorus strait. EM is definitely the most tsunamigenic region of the Mediterranean area, with a total of 127 tsunamis occurred along the coasts of Albania, Greece, Levantine countries, Turkey and coasts of Black Sea [1].

The tsunami phenomenon is non-linear and it strongly depends from the processes in the origin and the relief of the coastal region. The most of the observed tsunami events were happened in the past and these events reach nowadays as a part of different historical resources. The information for such events is contradictory, for a number of the cases the origin is not clear. Another problem is the modeling techniques - different modeling methods often are not able to estimate the observed height of the tsunami waves. There are also several nowadays events, instrumentally registered, well observed and described. Despite of this, the source of the tsunami it not trivial to be identified.

The aims of this paper are several: to identify different coastal regions, affected by tsunamis, summarizing existing tsunami catalogues for EM and publications about single events; to identify different offshore and inland tsunamigenic zones in EM; to review the existing techniques for tsunami modeling and their effectiveness in the tsunami simulation.

## 2. OVERVIEW OF DOCUMENTED TSUNAMIS IN THE AREA OF THE EASTERN MEDITERRANEAN

The historical tsunami record in the Mediterranean region goes back to the Greek antiquity, in XIV century BC – Minoan eruption of Santorini [2, 3]. This event influenced the evolution of east Mediterranean civilization. Reviewing the number of papers we define 29 areas in EM, affected by tsunamis (Fig. 1). The tsunami intensity is given in recently defined new XII-grade scale, proposed by Papadopoulos and Imamura [4].

Region 1: Bulgarian Black Sea coast has been hit by tsunami several times. The tsunamis as natural hazard for the Bulgarian Black Sea coast have been included for the first time officially in the Map of Geological Hazards in

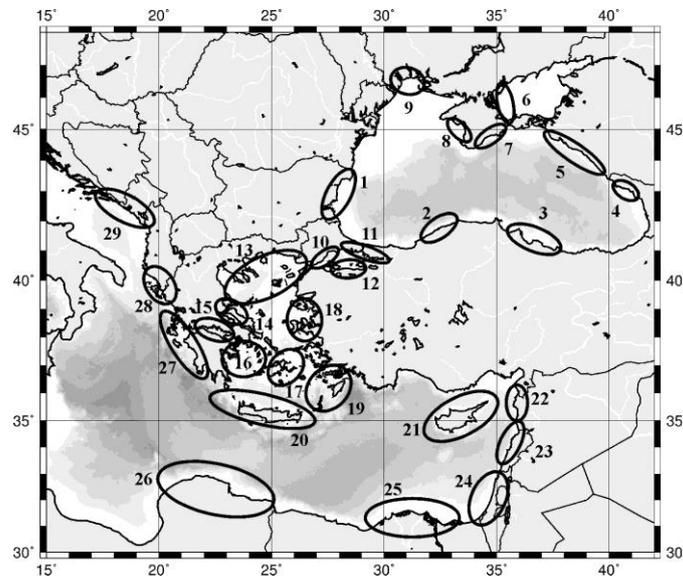
Bulgaria in 1994 [5, 6].

Five different events were reported in several papers [7–11]. Bizone, today Kavarna, was affected by earthquake that caused landslides and local tsunami around I<sup>st</sup> century BC [12] and according to other sources in III<sup>rd</sup> century BC [13]. The city of Bizone slid into the sea without any tsunami record. The sediment deposits found near Varna were radiocarbon dated at about 2000 years and probably connected to this event [14]. The information is not enough to estimate tsunami intensity [11]. One of the well documented key event in the historical earthquake and tsunami record of the Bulgarian Black Sea coast occurred in AD 544/545 [11, 12] in Odessus (modern Varna) and Dionysopolis (today Balchik) (NE Bulgarian Black Sea), Aphrodisium (Saros Bay/NE Aegean Sea) [3, 10]. Ranguelov et al. [15] proposed field evidence of local tsunami associated with earthquake ( $M > 7.6$ ) in 543 AD that caused inundation in archaeological site of Cybele Temple in Balchik, leaving there a layer of sea sand. The run-up heights exceeded 2–4 m [12] and the estimated tsunami intensity was about VIII–IX degree [10]. Another large earthquake ( $M = 7.2$ ) near the region of Shabla–Kaliakra occurred on 31 March 1901. This is one of the biggest seismic events for the last centuries [16]. The port of Balchik was inundated and the maximum height was 2.5–3 m (reported by eyewitness) [13]. The non-seismic tsunami on 7 May 2007 was observed along the Bulgarian Black Sea coast with the maximum wave amplitude of 3 m for the northern parts of the shoreline [17]. There are two main hypothesis about the source mechanism induced the tsunami: underwater landslide or an atmospheric high-frequency disturbance traveled along the shelf and generated long waves through the Proudman resonance mechanism [18, 19]. There were strong currents near the shallow regions and atmospheric disturbance that travelled with amplitude of 2–3 hPa. The period of oscillations was 4–8 minutes at the most of observed points [11]. Vilibić et al. [18] classified this event as a meteotsunami. Both hypothesis (underwater landslide and meteotsunami) were explored, but not a confirmed source was identified and both results matched relatively well the observed field data and reported video records and pictures [20]. Nevertheless the source was not identified distinctively.

Region 2: In North Turkey, the Bartın earthquake occurred on 3 September 1968 with magnitude  $M = 6.6$  [10, 11, 21,]. Different authors concluded that the event was caused by thrust faulting with an estimation of average depth of 4 km. This earthquake generated tsunami in Amasra, where the coastline was uplifted by 35–40 cm [11]. The rise of the sea in the port of Amasra was about 3 m [22]. Wedding [23] and later Altinok and Ersoy [21] indicated that the sea inundated 100 m in Amasra and after 14 minutes a second wave inundated the shore about 50–60 m.

Region 3: The tsunami occurred after the earthquake in Amasya in May 1598 [10, 11, 21]. The wave height approximately 1 m was created between the gulf of Sinop and Samsun [12]. The sea advanced for a mile inland on the coast

of Black Sea [21]. Another earthquake that generated tsunami was the Great Erzincan earthquake in 1939 [10, 11, 21]. The surface magnitude was of  $M = 8.0$  and focal depth – 20 km. Firstly the sea receded for 50 m and then advanced with 20 m in Fatsa and Giresun towns [21]. The tsunami probably was created directly from the rupture or the secondary fault or even by a submarine landslide in Black Sea, triggered by the earthquake [24]. The earthquake's epicenter was about 60 km inland, and this is one of the confirmed cases in the Black Sea of tsunami triggered by inland earthquake.



**Fig. 1.** Regions with observed tsunami in the Eastern Mediterranean (historical documents or measurements)

Region 4: The Eastern part of Black Sea, and especially Sukhumi Bay in West Georgia, was affected by catastrophic earthquake ( $M \geq 6.5$ ) in the first part of I<sup>st</sup> century AD. Russian sources reported that the city of Dioskuriada (today Sukhumi) was submerged beneath the sea [10, 11]. The run-up exceeded 2.5 m and the tsunami intensity was estimated as IV–VI [9, 10].

Region 5: This area is situated in the north-eastern part of Black Sea, the Russian coast of the sea. For less than a century in this zone have occurred several events (from north to south): Anapa (North Caucasus) on 4 October 1905, North Caucasus (10 km south from Anapa) on 12 July 1966, Cape Idokopas (Western Caucasus) on 8 April 1909, Sochi on 4 December 1970 [10, 11]. Ranguelov et al. [25] applied spectral analysis to the mareograms for the event of 12 July 1966. The source of the tsunami event from 1909 is aseismic, like underwater slides that produced wave height (3–5 m) in the open sea above the continental slope [12].

Region 6: Azov Sea is situated to the north of Black Sea. It is shallow water (14 m) sea and the seismicity of the region is very weak. However, three events of tsunami have been reported in the area [11]. The west coast of Azov Sea as well the lake Sivash were influenced by earthquake ( $M = 7.0 \pm 0.5$ ) that caused tsunami in 1650 [12, 10]. This was the first report of such event. Papadopoulos et al. [11] and Nikonov [12] made an estimation of a water level rise of 0.5–1.0 m and tsunami intensity of degree III. Recent event in August 1990 caused a sea-level rise of 0.4 m near the southern shoreline of Azov Sea.

Region 7: The Southeastern part of the Crimean Peninsula had been affected by tsunami several times [1]: 1427 in Yalta, on 5 June 1615 near Feodosiya, on 11 October 1869 near the town of Sudak and on 26 June 1927 near Yalta. The earthquake from 1927 had a magnitude of 6.0 and a focal depth of 27 km. It occurred near the submarine slope south of Yalta and caused a local tsunami on the south coast of Crimea [11, 10]. The maximum wave heights were 24 cm in Yalta according Dotsenko and Konovalov [26], while Pelinovsky [9] considered the rise of the sea level in Yalta as 16 cm. This tsunami event was registered by the mareograph network.

Region 8: Several events were reported in the west and the southwest part of Crimea [10, 11]. An earthquake ( $M = 7.7/7.5$ ) that induced tsunami waves occurred in Yevpatoriya on 12/26 October 1802 [1, 10, 11]. Probably the source of that large earthquake was the Vrancea seismic source because of its long radius and intermediate hypocentral depth. Another hypothesis for the source is that it was due to a submarine ground failure triggered by the earth shaking [11]. Other events in this region are: on 25 July 1875 and two events near Balaklava district on 11 and 16 September 1927 where the tide gauge records showed the maximum wave heights of 53 cm [10].

Region 9: Two events are related to the area of Odessa: one on 17 November 1821 and another on 23 January 1838 [10, 11, 1]. The second earthquake is considered to be an event from Vrancea seismic source with  $M = 7.3$  and tsunami intensity was evaluated to be V–VI degree [11].

More than 40 tsunamis have occurred in the area of Marmara Sea for the last 2000 years [27]. Three zones are defined here: west (region 10), north-east (region 11), and south (region 12).

Region 10: About 8 large earthquakes ( $M \geq 7.4$ ) occurred at intervals of 150–420 years in the western Marmara [28]. The latest in this zone and one of the biggest event in the Balkans was on 9 August 1912 – Şarköy-Mürefte Earthquake. It took place on the active Ganos fault zone and the length of the rupture on the surface was about 50 km [29]. The wave height was 2.7 m near Yeşilköy [30].

Region 11: About 30 events have been occurred in this zone, most of them near Istanbul and Izmit Bay [21]. Transform North Anatolian Fault crossed the zone. The Kocaeli earthquake ( $M_w = 7.4$ ) was on 17 August 1999 and caused tsunami waves with period less than 1 minute in the Izmit Bay. The most

prominent evidence of the tsunami was the sea receding during the earthquake at both sides of the bay. Field observations indicated a maximum run-up of 2.5 m [31]. In addition to tectonic displacements, the sediment slumping within the bay possibly generated tsunami waves [32].

Region 12: The south part of Marmara Sea has the lowest seismicity of whole Marmara area. Four events were reported here: in 120/128 near Kapıdağ Peninsula, Iznik and Izmit [8], in 368 in Iznik, in 543 in Kapıdağ Peninsula, Erdek and Bandırma, and in 1064 in Bandırma [21]. Probably the event from 543 is connected with the tsunamigenic event that affected Bulgarian Black Sea coast in the same year.

Region 13: An earthquake ( $M = 7.0$ ) occurred in Chalkidiki near Ierissos on 26 September 1932. This event was followed by several strong aftershocks, one of them with magnitude  $M = 6.3$ . The generated tsunami wave height was 1m [33].

Region 14: A few tsunamis were historically reported in the Maliakos Bay [3]. Papaioannou et al. [34] evaluated additional historical and archaeological reports and suggested that the 426 BC seismic event was twice moderate arguing that the large tsunami from that period may have occurred during the III<sup>rd</sup> century BC.

Region 15: More than 17 events were included in the New Tsunami Catalogue from IV<sup>th</sup> century BC to 1999 for this zone [35]. There were many reported local tsunamis in the Corinth Gulf area. Most of them were triggered by strong earthquakes or aseismic coastal and submarine landslides [35]. Some of the documented tsunamis are: in 373 BC in the area of Helike (west Corinth Gulf), in June 1402 in Central Corinth Gulf, on 25 May 1748 in Aeghion where run-ups of 10 m were observed, on 23 August 1817 in Aeghion with run-up of 5 m. A tsunami, generated by sediment slump happened on 7 February 1963 [3] and the run-up exceeded 5m.

Region 16: There were few small tsunami events in the Corinthiakos-Patras Gulf [35, 36]. The area might be affected by big tsunamis created by origins in Aegean Sea (Santorini eruptions, west Hellenic arc seismic events).

Region 17: Minoan eruption of Thera (Santorini) in 1613±13 BC created tsunami wave with height, exceeding 20 m [2]. A recent large earthquake on 9 July 1956 in Cyclades ( $M = 7.5$ ) generated tsunami. Estimations of the near-source wave height varied between 15 m and 30 m [3].

Region 18: This area had a great experience with earthquakes and tsunamis. Some of the events that triggered tsunamis in the past are: on 20 March 1389 in Chios Islands with tsunami intensity of VI degree, on 10 July 1688 in Smyrna, on 13 November 1856 in Chios Islands with tsunami intensity of VIII degree, on 7 March 1867 in Mitilim, and on 23 July 1949 in Chios Island [1, 3].

Region 19: Dodecanese Islands were affected many times by tsunamis. Several big events caused inundations and destructions in Rhodes. The first one was in III<sup>rd</sup> century BC. The earthquake on 3 May 1481 with magnitude 7.2 [3]

caused a 3 m high tsunami that flooded the Rhodes coast. Recently, on 24 March 2002, waves with heights of 3–4 m heated the town of Rhodes, most probably caused by landslide [2]. A seismic event on 9 February 1948 caused a huge wave that penetrated inland of Karpathos Island for 1 km and the sea disturbance continued for several hours [37].

Region 20: The coasts of Crete have been often destroyed by earthquakes and tsunamis. Two of the biggest tsunamigenic events happened near east and near west coasts of Crete. The event from 365 AC in west offshore of Crete was one of the key events in the history of the Eastern Mediterranean. The western segment of the Hellenic Arc was ruptured by an earthquake ( $M = 8.3$ ) and caused tsunami propagated through the whole Mediterranean [38]. The tsunami intensity was reported to be X degree [3]. There is a lot of contradictory information about the event from 1303 AC in the eastern offshore of Crete. According to many historical documents [39], there was a very large tsunamigenic earthquake that ruptured the eastern segment of the Hellenic Arc, between Crete and Rhodes islands, with observed inundation in many places in the Eastern Mediterranean – Crete, Dalaman (Turkey), Israel, Palestine, Egypt [2, 36, 40, 41]. The north coast of Crete was affected by tsunamis with intensity from V to X-XI degree, created by volcanic eruptions (1600 BC, 1650 AC), strong shallow seismic events (1958), and several offshore events near the coast [1].

Region 21: The event of May 1201±1 caused a severe tsunami on Levantine coast with intensity of VII degree [42]. Papadopoulos et al. [3] consider the possibility for inland earthquake with tsunami-generating mechanism. Shallow seismic activity is in progress in the last years in the southwest offshore of the island but without any tsunami generation.

Region 22: After a strong earthquake, a tsunami was observed on the Syrian coast on 29 December 1408 [42]. The tsunami intensity was of III–V degrees.

Region 23: A great earthquake occurred in Beirut, Sur, Sidon, Tripoli and Galilee [42]. Tsunami was reported on the Lebanese coast and the sea retreated for a mile and many ships were destroyed [8].

Region 24: There were several earthquakes in Palestine and Syria that caused tsunamis: in January 746/749 on the Levantine coast; from 30 October to 25 November 1759 tsunamis with run-up heights up to 2.5 m in Tripoli [42, 1]. A tsunami was noted as far as the Nile delta [43].

Region 25: The Mediterranean coast of Egypt, especially Alexandria was hit by a number of tsunamis in the course of the history [37, 44], two of which have flooded the city with a lot of damages: on 21 July 365 AD and on 8 August 1303 Crete tsunami events.

Region 26: Event from 365 AD, an  $M = 7.7$  earthquake in Crete, produced a unique tsunami, that propagated through whole Mediterranean, causing damages in Libya, Egypt, Calabria and reached the coast of Spain [37].

Region 27: There were several moderate to strong earthquakes, generating tsunamis in this area: on 5 November 1633 near Zante (Ionian Sea), on 18 February 1723, on 19 January 1825, and on 22 April 1948 near Leukas (Ionian Sea) [1].

Region 28: A series of local tsunamis was observed on the coast of Albania: in the area of Valona in October 1851, on 2 and on 6 January 1866 in Himara and Narta respectively [3, 45, 46], in March 1866 in Valona [45] and in Saseno Island on 18 December 1920 [1].

Region 29: There was a tsunami triggered by earthquake on 15 April 1979 in Montenegro. The thrust fault is almost parallel to the Adriatic coast [47]. The wave height was 6 m [1].

Three tsunamigenic events at least affected whole eastern Mediterranean. The observed tsunamis have various origins: earthquakes, volcano eruptions, landslides, meteorological events or combination of them. A lot of the observed tsunamis have unclear origin or the different authors gave ambiguous information for the same event. Even relatively dense population of the Mediterranean coast there are many areas that are not investigated for the tsunami impacts, they were not mentioned in any historical document, even if these areas are close to tsunamigenic zones. Moreover there are many seismic zones with very long return period that can originate big landslides and tsunamis.

### 3. OVERVIEW OF TSUNAMIGENIC ZONES IN THE AREA OF THE EASTERN MEDITERRANEAN

Different tsunamigenic zones in the Mediterranean area were identified and classified by several studies [2, 3, 48]. Each area was classified according to geographic distribution, tsunamigenic potential, generation mechanisms, tsunami intensity and the frequency of the historical events. We define 27 zones by geographic distribution (Fig. 2).

Zone 1: The area is characterized by active faults, but it is possible also aseismic landslide and turbidities origin of observed tsunami. The numerical modeling of the historical events is not in good agreement with observations [18].

Zone 2: In the area are possible landslides, triggered by the inland ruptures along North Anatolian Fault.

Zone 3: The big inland earthquakes with large ruptures along North Anatolian fault most probably caused co-seismic landslides and turbidities, responsible for the tsunamis observed in the region [11].

Zone 4: The inland and offshore earthquakes along the fault segments in the area, together with landslides are most probable origin of the observed tsunamis.

Zone 5: The observed earthquakes with  $M \sim 6.0$  together with landslide

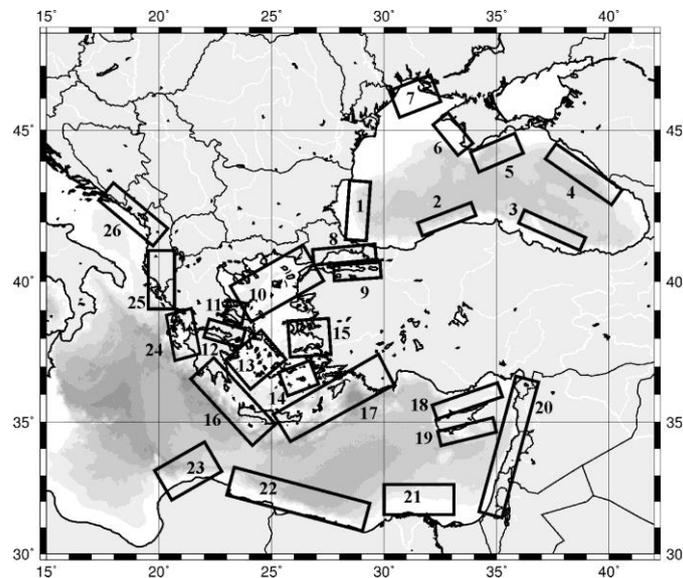
processes might cause the locally observed tsunami.

Zone 6: Similarly to zone 5, the combination between earthquakes and landslides can originate the observed and expected tsunamis.

Zone 7: The observed historical tsunamis were connected with activity of the Vrancea seismic zone, but the mechanism of the tsunami is unclear.

Zone 8: Tsunamis in this area are caused mainly by landslides, following the seismic activity along the branches of North Anatolian fault [49]. Numerical models are applied by Hébert et al. [50]. The model TWO-LAYER was used for Yenikapi, Tuzla and Armutlu Peninsula to obtain run-up estimates [32].

Zone 9: Similarly to zone 8, the observed tsunamis are connected with landslides, caused by the seismic activity along the faults in the region [32, 49].



**Fig. 2.** Tsunamigenic zones in the Eastern Mediterranean

Zone 10: The area is dominated by strike-slip faulting but there the tsunami activity in the region is almost absent [51].

Zone 11: Earthquakes, triggering landslides, caused very high local tsunamis in this zone. In the western part of the zone, extensive submergence of a coastal strip, caused by moderate earthquake ( $M = 6.6$ ), was most probably the origin of the observed tsunami [35].

Zone 12: The area is characterized by relatively frequent, locally high tsunamis. The most of the observed tsunamis were generated by co-seismic or aseismic landslides. Well documented aseismic landslide occurrence in 1963 permitted to model the process. Numerical simulations tested two landslide models: rigid-body model [52] and an initial external dynamic action to the layered sediment structure [37]. Both models reproduced well-enough the

observed run-up data.

Zone 13: There are not records of big tsunamis in the area, but this zone is very close to the west Hellenic Arc, Santorini area and some significant active fault systems.

Zone 14: Seismic and volcanic activities in the area often were accompanied by landslides inducing tsunamis [53]. Two of the largest tsunamis in Mediterranean were caused by Santorini and Columbo eruptions, although the mechanism of tsunami generation is still uncertain: circular caldera collapse or by massive pyroclastic flow.

Zone 15: Most probable mechanism for the observed tsunamis is related to seismic origins.

Zone 16: The earthquake rupture of west Hellenic Arc generated the biggest tsunami event in the whole Mediterranean. The impact on many coastal zones is modeled by different authors [54] but some more areas most probably were affected too, for example Argolic gulf or Libyan coast. There are some contradictory hypotheses about the earthquake mechanism.

Zone 17: Similarly to zone 16, a co-seismic tectonic displacement in relation with the rupture along the east Hellenic Arc caused big tsunami, with strong impact on the coasts of Aegean Islands, southwest Turkey, Cyprus, Asia Minor coast and Egypt. But tsunami mechanism is unidentified. There are several historical seismic tsunamis in the easternmost side of the Hellenic Arc, around the Rhodes Island, with unclear generation mechanisms [55].

Zone 18: The north coast of Cyprus is bounded by the trench zone that can originate landslides and relevant tsunamis [42].

Zone 19: Similarly to zone 18, the southeastern coast of Cyprus is surrounded by fault systems. The submarine landslides are not excluded as the reason for the tsunami generation.

Zone 20: The number of the observed locally strong tsunamis by the inland earthquakes along the strike-slip Levantine rift remains unexplained. The most plausible explanation is the co-seismic submarine landslides [56]. Probably some faults, connected with the Dead Sea Transform Fault, in the south part of the region caused landslides generating the observed tsunamis [57, 58].

Zone 21: This area was affected by big tsunamis caused by west and east Hellenic Arc and Cyprian Arc ruptures. UBO-TSUF code [59] was used for tsunami simulations for interaction with the irregular coast of Alexandria [60].

Zone 22: The small disturbances from the Hellenic Arc earthquakes can originate the submarine landslides with locally significant tsunamis.

Zone 23: Similarly to zone 22, this area can be affected by tsunami, caused by submarine landslides.

Zone 24: The dominant strike-slip faulting of the fault system in this area is not related to significant tsunami events in the region [51]. Massive avalanches from Mt. Etna can be responsible for some of the tsunamis observed in the region [61].

Zone 25: Tsunami hazards scenarios were made for this area. Analytical solutions were combined with bathymetric data and well known data for several events for evaluation of maximum amplitude reached by a hypothetical tsunami event [62]. The typical focal mechanisms are thrust and strike-slip.

Zone 26: The seismicity of the coastal region here is determined by the subduction of the Adriatic plate under the Dinarides [62]. The typical fault mechanisms are thrust or strike-slip. Analytical simulations for the tsunami models were used and synthetic mareograms were made for realistic oceanic models [63].

The expected effects of a tsunamigenic event strongly depend of the cause of the tsunami: tectonic, landslide or volcanic origin. The repeatability of tsunamis is also determined by their origins. The distribution of high run-ups and the extent of the inundated coast are very different in the case of the occurrence of a localized landslide, a gigantic collapse, or a displacement of the sea bottom [64]. Moreover, for most of the historical tsunamis in the Mediterranean area, the definition of the actual source is still a matter of debate [3].

#### 4. OVERVIEW OF TSUNAMI MODELING METHODS

Modeling of tsunami contributed to understanding the nature of such complex process that might have significant impact on the coastal areas in the Mediterranean. Numerical models are powerful tool for tsunami research since they can be used to reconstruct modern and historical events. The simulations can help to produce forecasts of tsunami impact and inundation in systems of early warning. Although there is no case of devastating tsunami in Europe in the past 100 years, the potential hazard in EM is high. There are several projects that estimated the tsunami hazard for a number of densely-populated cities (for example ASTARTE: Assessment, STRategy And Risk Reduction for Tsunamis in Europe). The evaluation of the tsunami hazard depends strongly of the capability of tsunami modeling method: its flexibilities, the simplifications assumed, required computing resources, successful modeling of observed events.

There are a number of methods for tsunami modeling. Most of them are based on the numerical modeling of shallow-water equations, but there are also analytical methods with possibility to model the tsunami generation from inland, near coastal earthquakes.

One of the most successful numerical codes for tsunami propagation and inundation modeling is UBO-TSUFD, developed by the Tsunami Research Team of the University of Bologna, Italy. The code resolves the non-linear shallow water (NSW) theory which is an estimation of the equations of Navier-Stokes. UBO-TSUFD is developed in a Cartesian frame and by mean of an explicit leapfrog (LF) finite-difference method on a staggered grid. The method considered moving boundaries to calculate the ocean inundation and withdrawal at the coast. The NSW equations hold under the assumptions of pressure

hydrostaticity and of fluid incompressibility, so the vertical component of fluid particles acceleration is negligible compared to the gravity acceleration and the horizontal components of the velocities are constant along the water column [59]. The problem is reduced from three to two dimensions in space and one dimension in time. The Coriolis force is neglected that is applicable for seas as Mediterranean. The bottom friction is taken into account. The NSW equations in Cartesian frame are:

$$u_t + uu_x + vv_y + g\eta_x + f_x = 0, \quad (1)$$

$$v_t + uv_x + vv_y + g\eta_y + f_y = 0, \quad (2)$$

$$\eta_t + (u(h+\eta))_x + (v(h+\eta))_y = 0, \quad (3)$$

where  $u$  and  $v$  are the depth-averaged velocity components, respectively, for the horizontal coordinates  $x$  and  $y$ ,  $g$  is the gravity acceleration,  $\eta$  is the water surface elevation measured from the still sea surface,  $h$  is the undisturbed water depth,  $f_x$  and  $f_y$  are the  $x$  and  $y$  components of the bottom friction (Fig. 3). The discharge fluxes  $M$  and  $N$  are related to the velocities  $u$  and  $v$  by the formulas:

$$M = u(h+\eta) = uD, \quad (4)$$

$$N = v(h+\eta) = vD, \quad (5)$$

where  $D = h + \eta$  is the total water column. Eqs. (1)-(3) can be improved as

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{D} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{D} \right) + gD \frac{\partial \eta}{\partial x} + f_x = 0, \quad (6)$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{MN}{D} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{D} \right) + gD \frac{\partial \eta}{\partial y} + f_y = 0, \quad (7)$$

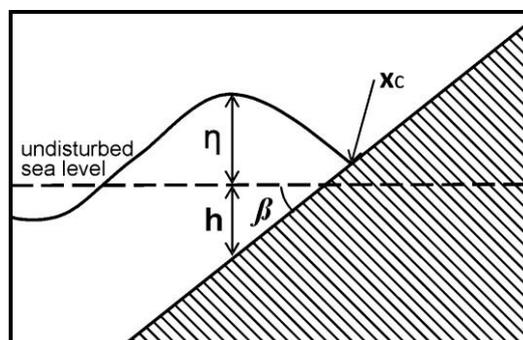
$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0. \quad (8)$$

The bottom friction components  $f_x$  and  $f_y$  are normally submitted by the fluxes  $M$ ,  $N$  and Manning's roughness coefficient  $n$ :

$$f_x = \frac{gn^2}{D^{7/3}} M \sqrt{(M^2 + N^2)}, \quad (9)$$

$$f_y = \frac{gn^2}{D^{7/3}} N \sqrt{(M^2 + N^2)}. \quad (10)$$

Elevation  $\eta$  is calculated in the centre of every cell of the grid, while fluxes  $M$  and  $N$  are shifted by a half spatial step along their respective directions. The boundary conditions are applied for the fluxes in the nodes that are placed (right and upper sides of the boundary mesh) thus the geometric asymmetry of the computational grid is obtained.



**Fig. 3.** Schematic representation of tsunami

The code UBO-TSUFED was validated for different cases and reproduced quite well the theoretical and experimental data [65–67].

MOST (The Method Of Splitting Tsunami) is numerical technique that was created as part of the Early Detection and Forecast of Tsunami (EDFT) project [68]. This method modeled tsunami generation, its propagation and its run-up onto the shoreline. The generation of tsunami is based on the elastic deformation theory. The MOST propagation model uses a numerical dispersion scheme and the NSW wave equations in spherical coordinates, with Coriolis terms [69]. The MOST inundation calculations are sufficiently accurate where adequate bathymetric and topographic data are available. The run-up distribution is useful to develop hazard mitigation tools and guidance products such as inundation maps.

COMCOT (Cornell Multi-grid Coupled Tsunami Model) technique is another numerical model that allows both simulation and visualization of the whole process, from tsunami generation and propagation to run-up/run-down in coastal regions [70]. COMCOT adopts the leap-frog time-differencing scheme to solve NSW equations in spherical coordinates and Cartesian coordinates on staggered grids [71]. The evaluation of free surface elevation and volume flux are staggered in both time and space. The moving boundary scheme is applied to model the run-up and run-down.

An advanced method for modeling of tsunami generation, propagation and coastal inundation is 2-DH model [72]. This method is applied to simulate representative earthquake-induced tsunami scenarios in the Eastern Mediterranean. The non-linear wave transformation in the swash zone was calculated by non-linear breaking wave model based on the higher-order Boussinesq equations for breaking and non-breaking waves [73]. The numerical solution is based on the accurate higher-order numerical scheme of Wei and Kirby [74], who proposed a fourth order predictor-corrector scheme for time stepping, discretizing the first-order spatial derivatives to fourth-order accuracy. The shoreline in the model can be considered either as a solid boundary (fully or partially reflecting) or as a boundary allowing sea mass inland penetration and

inundation [72].

Analytical modeling is another useful tool to solve the problem with the tsunami generation. The first approach is based on the modal theory that gives a solution corresponding to the exact boundary conditions [75]. It can be extended to models with slightly varying thickness of the water layer and it is valid only for sources located under the ocean. The equations of motion are solved for a multi-layered model structure, according to Haskell [76], so the set of equations is converted into a matrix problem. The modal method allows to compute synthetic signals for both laterally homogeneous (1D) and laterally heterogeneous (2D) structures [62].

The Green's function technique approach is used for sources placed near the coastline and even inland (proposed by Kajiura [77] and developed by Yanovskaya et al. [78]). The solution for the Green's function in the liquid layer is performed by an integral form with the approximation adopted asymptotic representation of the integral solution by Hankel's functions, which allows the computation only for the far-field case [62].

A technique, developed by Annunziato [79] is used in Joint Research Center for global modeling and early warning announcements. It tests in real time all the events occurring in the world, calculates the expected tsunami wave height and identifies the locations where the wave height reaches dangerous level.

Numerical modeling represents relatively well the process of tsunami generation, propagation and inundation. The main problems are connected with realistic modeling of the rupture processes of big seismic events, the irregularity of landslides and inland conditions – forests, buildings and other particularities that modified ground relief. In some cases should be considered several near contemporaneous sources as earthquake and landslide or volcano eruption and landslide in order to obtain the observed inundation amplitudes. The problem of combined action of earthquake rupturing, together with the underwater sediments sliding (turbidities) is still not solved satisfactory. The high resolution bathymetry is another problem influencing the solution, especially in case of the existence of strong refractors. The high sensitive refraction models are usually inadequate due to the existing low bathymetry resolution maps.

## 5. CONCLUSIONS

Tsunami is complex, non-linear phenomenon and only prevention of it is to understand well their impact on the populated coasts. The observed tsunami events in eastern Mediterranean are summarized in 29 zones. The most destructive events are observed around the island of Crete – the earthquakes caused tsunamis affecting whole Mediterranean. Many of the moderate seismic events ( $M < 7.0$ ) in combination with landslides originated significant local inundations. There are several documented cases when the coast inundation is

caused by meteorological processes. A number of observed tsunamis are with unknown origin.

We define 26 tsunamigenic areas in eastern Mediterranean that are identified with existing active or long-time non active faults, volcanic zones and landslide areas. The most of these areas are studied more or less successfully by different tsunami-modeling techniques. We identify several zones, potentially tsunamigenic that are still not modeled or modeled by general initial parameters.

There are a number of tsunami modeling techniques, most of them numerical and based on shallow-water theory. One of the most used methods in the Mediterranean is UBO-TSUFDF – well balanced between computing resources needed and some simplifications that is able to model tsunami by earthquakes or landslides. Analytical methods for tsunami modeling are able to model tsunami using Green's function of inland earthquakes.

Tsunamis in Eastern Mediterranean are not that big and destructive as transoceanic tsunamis and they are not so frequently as in the area of Pacific Ocean, but the tsunami risk for some areas is rather high and should be studied in details.

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