STRONG TSUNAMIS IN THE MEDITERRANEAN SEA: A RE-EVALUATION

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ABSTRACT

Historical documentary sources of the Mediterranean Sea region contain much information about earthquakes and associated phenomena like tsunamis. A catalogue of historical tsunamis generated by earthquakes is compiled. One of the parameters included is the tsunami intensity calculated by several authors in the past on the basis of traditional 6-point tsunami intensity scale. The historical information is re-examined and the intensity of tsunami events is re-evaluated according to the new 12-point tsunami intensity scale introduced by Papadopoulos and Imamura. An attempt has been made to establish quantitative relations between the traditional and the new intensity scales as well as between the tsunami intensity and parameters of the earthquake size like magnitude and intensity.

KEYWORDS: Strong Tsunamis, Tsunami Intensity, Tsunami Catalog, Mediterranean Sea

INTRODUCTION

Because of the active lithospheric plate convergence, the Mediterranean Sea region is geodynamically characterized by high seismicity and significant volcanism. Furthermore, coastal and submarine landslides are quite frequent, partly in response to the steep terrain that characterizes much of the basin. Tsunamis are among the most remarkable phenomena associated with earthquakes, volcanic eruptions and landslides in the Mediterranean Basin. Until recently, however, it was a widely held belief that tsunamis either did not occur in the Mediterranean Sea or they were so rare that they did not pose a threat to coastal communities. Catastrophic tsunamis are more frequent on Pacific Ocean coasts where both local and transoceanic tsunamis have been documented. On the contrary, large tsunami recurrence in the Mediterranean Sea is of the order of several decades and the memory of tsunamis is short-lived.

For these reasons, the scientific study of tsunamis in the Mediterranean Sea was rather neglected for a long period in comparison to other parts of the world. Up until the beginning of the 20th century tsunamis were sporadically mentioned in earthquake descriptions or catalogues. By the early and mid-20th century some research was carried out after large tsunami events such as the Messina event in southern Italy (28th December 1908) and the south Aegean Sea event in Greece (9th July 1956). More systematic efforts to compile tsunami catalogues for the Mediterranean began in the 60's, when some progress was made in the fields of numerical wave modeling and tsunami hazard assessment. The beginning of 1990's marked a key turning point for tsunami science in the Mediterranean Sea region and in Europe in general. As a result of a series of well-coordinated tsunami research projects, major progress has been made in the Mediterranean region across the full spectrum of tsunami science, technology and risk mitigation. Figure 1 illustrates a map of the known tsunamigenic sources in the Mediterranean Sea region and a relative scale of their potential for tsunami generation calculated as a convolution of the frequency of occurrence and the intensity of tsunami events (Papadopoulos, 2005). The tsunami potential or hazard H of a particular zone or area has been defined as the normalized quantity:

$$H = \frac{H_a}{H_{\min}} \tag{1}$$

Here, the absolute potential H_a is an increasing function of the weighted event intensity and the event frequency:

$$H_a = \sum_{i=1}^{n} \frac{k_{ci} j_c}{t_c} \tag{2}$$

where $H_{\min} = \min(H_a)$, k_{ci} is the intensity of event i, and j_c is a weighted factor of k_c. Factor j_c has been defined to follow a power-law of base 2: 2^1 for k_c = 3, 2^2 for k_c = 4, 2^3 for k_c = 5, 2^4 for k_c = 6. Only strong events were considered, that is $k_c \geq 3$. The lower date of the time interval, t_c, over which the data set is complete is variable while the upper date was fixed to the end of 2003. The earliest year in the record was assumed to be 300 AD for k_c = 6, 1000 for k_c = 5, 1600 for k_c = 4, and 1750 for k_c = 3 (see Papadopoulos (2005) for more details).

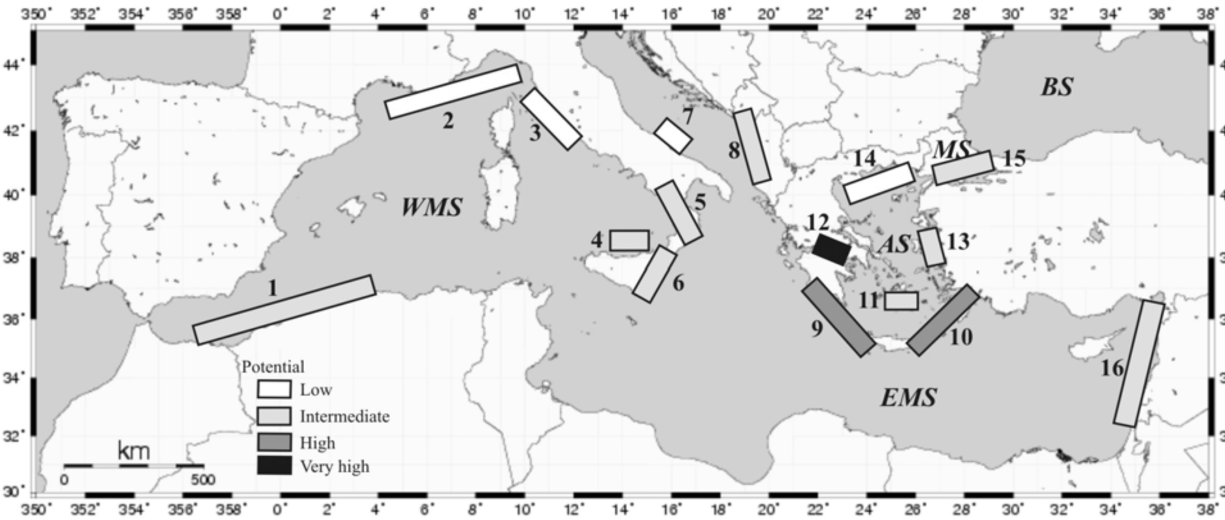

Fig. 1 The tsunamigenic zones of the Mediterranean Sea: WMS = West Mediterranean Sea, EMS = East Mediterranean Sea, AS = Aegean Sea, MS = Marmara Sea, BS = Black Sea, 1 = Alboran Sea, 2 = Liguria and Cote d' Azur, 3 = Tuscany, 4 = Calabria, 5 = Aeolian islands, 6 = Messina straits, 7 = Gargano promontory, 8 = South-East Adriatic Sea, 9 = West Hellenic arc, 10 = East Hellenic arc, 11 = Cyclades, 12 = Corinth Gulf, 13 = East Aegean Sea, 14 = North Aegean Sea, 15 = Marmara Sea, 16 = Levantine Sea (the tsunami potential of each one zone is classified in a relative scale according to the frequency of occurrence and intensity of tsunamis (after Papadopoulos, 2005))

The compilation of reliable tsunami data bases is of great importance for a wide range of tsunami-related studies: statistics and hazard assessment, wave numerical modeling, risk evaluation, operation of early warning systems, public awareness. Tsunami catalogues for the Mediterranean Sea have been compiled by several authors, like Galanopoulos (1960), Ambraseys (1962), Antonopoulos (1979), Papadopoulos and Chalkis (1984), Amiran et al. (1994), Tinti and Maramai (1996), Soloviev et al. (2000), Papadopoulos (2002), and Fokaefs and Papadopoulos (2006). However, one of the main problems which is still open is the determination of tsunami size in terms of intensity or magnitude.

In this paper, tsunami events known to have taken place in the Mediterranean Sea region are re-evaluated as for their size. In particular, the maximum intensity of 140 reliable tsunami events has been re-determined according to the new 12-point tsunami intensity scale introduced by Papadopoulos and Imamura (2001). In addition, an attempt has been made to establish quantitative relations between the traditional 6-point and the new 12-point intensity scales as well as between the tsunami intensity and tsunami height. In addition, for a small number of events relations are investigated between the tsunami intensity and tsunami magnitude as well as between the tsunami magnitude and earthquake magnitude.

INTENSITY AND MAGNITUDE OF TSUNAMIS

Tsunami size, expressed in terms of either intensity or magnitude, is a critical parameter introduced in modern tsunami databases. These parameters, however, are difficult to determine even for more recent events. Papadopoulos (2003a) showed that the traditional tsunami intensity scales are characterized by some important shortcomings. Firstly, they are 6-point scales and, therefore, are not sensitive enough. Secondly, most of them usually are dependent on physical parameters, like the wave height in the coastal zone, which means that they are rather magnitude scales than intensity scales, given that intensity should describe only the effects of the natural event.

Following the long seismological experience, Papadopoulos and Imamura (2001) proposed the establishment of a new tsunami intensity scale based on the following principles: (a) 'independency' from any physical parameter, i.e., intensity is assigned on the basis of only the impact of the tsunami wave; (b) 'sensitivity', i.e., incorporation of an adequate number of divisions (or points) in order to describe even small differences in tsunami effects; (c) 'detailed description' of each intensity division by taking into account all possible tsunami impact on the human and natural environment as well as the vulnerability of buildings and other engineered structures. The new tsunami intensity scale incorporates twelve divisions and is consistent with the 12-point seismic intensity scales established and extensively used in Europe and North America for the last 100 years. The new scale is arranged according to (a) the effects on humans, (b) the effects on the natural environment and on objects, including vessels of different sizes, and (c) damage to structures.

In the Mediterranean Sea, tsunami intensity k is traditionally estimated according to the 6-point Sieberg-Ambraseys scale (Ambraseys, 1962). On the contrary, tsunami magnitude has been calculated for only few events on the basis of the scale proposed by Murty and Loomis (1980) which is analogous to the concept of moment magnitude for earthquakes. Their tsunami magnitude, ML, is defined by

$$ML = 2\left(\log_{10} E - 19\right) \tag{3}$$

where E is the tsunami potential energy (in ergs).

THE DATA

The most updated tsunami catalogues for the region of the Mediterranean Sea are those of Papadopoulos (2002, 2003b) for Greece and surrounding regions, including the Marmara Sea, and Tinti and Maramai (1996) and Tinti et al. (2004) for the Italian region and the Côte d' Azur. The westernmost and easternmost parts of the basin, that is the Alboran Sea and the region of Cyprus and Levantine Sea, are covered by the recent catalogues of Soloviev et al. (2000) and Fokaefs and Papadopoulos (2006), respectively. In these catalogues, with the exception of Soloviev et al. (2000), an innovation is that for every tsunami event a score of reliability is assigned on a 4-point reliability scale. Thus, the reliability scores of 3 and 4 mean very probable and certain tsunami event, respectively. Reliability of the Alboran Sea tsunami waves listed by Soloviev et al. (2000) was evaluated by us.

From the above catalogues tsunamis with reliability score of 3 or 4 were extracted. Then, two subcatalogues containing 100 and 40 reliable events were compiled for the East and West Mediterranean Sea, respectively (Tables 1 and 2). However, only for eight events tsunami magnitude ML has been calculated by some authors (Table 3). After reviewing documentary sources, scientific descriptions and other studies the maximum intensity K for each one of the 140 tsunami events was determined according to the new 12-point tsunami intensity scale introduced by Papadopoulos and Imamura (2001).

Table 1: Reliable Tsunami Events Known in the East Mediterranean Sea, that is in Greece and Surrounding Regions, Marmara Sea, Cyprus, and Levantine Sea

No.	Year	Month	Day	Region	*k*	Reference	*K*	*h* (cm)
1	−426	summer		Maliakos Gulf, East Greek Mainland	5	P	8	
2	−373	winter		West Corinth Gulf, Central Greece	5	P	9	
3	66			South Crete	3	P	4	
4	142/144			Rhodes Island, South-East Aegean Sea	4	PF	7	
5	365	07	21	Crete Island	5	P	10	
6	447	01	26	Marmara Sea	4	P	8	
7	478	09	25	Marmara Sea	3	P	7	
8	544			Thrace, North-East Greek Mainland	4	P	8	
9	551	07	09	Lebanon	5	PF	8	
10	552	05		Maliakos Gulf, East Greek Mainland	4	P	8	
11	556			Cos Island, South-East Aegean Sea	4	P	8	

12	740	10	26	Marmara Sea	3	P	6	
13	749	01	18	Levantine Coast	4	PF	7	
14	1202	05	20	Syrian Coast and Cyprus	4	A	7	
15	1265	08	10	Marmara Sea	3	P	5	
16	1270	03		North Ionian Sea	3	P	5	
17	1303	08	08	Crete Island	5	P	10	
18	1343	10	18	Marmara Sea	4	PF	6	200
19	1389	03	20	Chios Island, East Aegean Sea	4	P	6	
20	1402	06		Corinth Gulf, Central Greece	4	P	8	
21	1419	05	25	Marmara Sea	3	P	5	
22	1481	05	03	Rhodes Island, South-East Aegean Sea	4	PF	7	
23	1494	07	01	Crete Island	3	P	4	
24	1509	09	10	Marmara Sea	3	P	5	600
25	1609	04		Rhodes Island, South-East Aegean Sea	5	P	8	
26	1612	11	08	Crete Island	4	P	8	
27	1630	03	09	Kythira Island, South-East Aegean Sea	3	P	5	
28	1633	11	05	Zante Island, Ionian Sea	3	P	5	
29	1650	10	11	Thera Island, South Aegean Sea	6	P	10	2000
30	1667	04	06	South Adriatic Sea	3	P	5	
31	1741	01	31	Rhodes Island, South-East Aegean Sea	5	P	8	
32	1742	02	21	West Corinth Gulf, Central Greece	3	P	5	
33	1748	05	25	West Corinth Gulf, Central Greece	4	P	9	1000
34	1759	11	25	Akko, Israel	5	PF	8	
35	1766	05	22	Marmara Sea	4	P	7	
36	1769			East Corinth Gulf, Central Greece	2	P	3	
37	1772	11	24	Foca, East Aegean Sea	3	P	5	
38	1778	06	16	Smyrna, East Aegean Sea	3	P	5	
39	1791	11	02	Zante Island, Ionian Sea	3	P	4	
40	1794	06	11	Central Corinth Gulf	3	P	5	300
41	1817	08	23	West Corinth Gulf, Central Greece	4	P	8	500
42	1833	01	19	Albania	3	P	5	
43	1851	10	12	Avlona, Albania	3	P	4	
44	1852	09	08	Smyrna, East Aegean Sea	3	P	4	
45	1853	08	18	South Evoikos Gulf, East Greek Mainland	3	P	4	
46	1856	11	13	Chios Island, East Aegean Sea	4	P	8	
47	1861	12	26	West Corinth Gulf, Central Greece	3	P	5	210
48	1866	01	02	Albania	4	P	7	
49	1866	02	02	Chios Island, East Aegean Sea	3	P	4	
50	1866	02	06	Kythira Island, South-West Aegean Sea	4	P	6	800
51	1866	03	02	Avlona, Albania	3	P	4	
52	1866	03	06	Albania	4	P	7	
53	1866	03	13	Albania	3	P	4	
54	1867	02	04	Ionian Sea	2	P	3	
55	1867	09	09	Gythion, South Greek Mainland	4	P	7	
56	1869	12	28	Avlona, Albania	3	P	4	
57	1878	04	19	Marmara Sea	3	P	5	
58	1881	04	03	Chios Island, East Aegean Sea	3	P	4	
59	1883	06	27	North Ionian Sea	3	P	4	
60	1886	08	27	South Ionian Sea	3	P	4	
61	1887	10	03	Central Corinth Gulf	2	P	3	
62	1888	90	09	Central Corinth Gulf	2	P	3	
63	1893	02	09	North Aegean Sea	3	P	4	100
64	1893	04	17	Zante Island, Ionian Sea	2	P	3	

65	1893	06	14	Avlona, Albania	3	P	4	
66	1894	04	27	North Evoikos Gulf, East Greek Mainland	2	P	3	
67	1894	07	10	Marmara Sea	3	P	6	
68	1898	06	02	Corinth Gulf, Central Greece	3	P	4	
69	1899	01	22	South Ionian Sea	3	P	4	100
70	1902	07	05	Thermaikos Gulf, North-West Aegean Sea	2	P	3	
71	1905	01	20	Magnesia, East Greek Mainland	2	P	3	
72	1911	02	18	Ochrida Lake, South Yugoslavia	2	P	3	
73	1914	11	27	Lefkada Island, Ionian Sea	3	PF	5	300
74	1914	11	27	Lefkada Island, Ionian Sea	3	PF	5	
75	1920	11	26	Saseno, Albania	3	P	5	
76	1926	08	30	Argolikos Gulf, South-West Aegean Sea	2	P	3	
77	1928	03	31	Smyrna, East Aegean Sea	2	P	3	
78	1932	09	26	Strymonikos Gulf, North Aegean Sea	3	P	4	200
79	1947	10	06	South Ionian Sea	2	P	3	
80	1948	02	09	Karpathos Island, South-East Aegean Sea	4	P	7	400
81	1948	04	22	Lefkada Island, Ionian Sea	3	P	4	100
82	1949	07	23	Chios Island, East Aegean Sea	3	P	4	200
83	1953	08	12	Kefalonia Island, Ionian Sea	2	P	3	
84	1955	04	19	Volos Gulf, East Greek Mainland	3	P	4	
85	1956	07	09	Cyclades, South Aegean Sea	5	PF	8	1500
86	1962	05	28	Lemnos Island, North-East Aegean Sea	2	P	3	
87	1963	02	07	West Corinth Gulf, Central Greece	4	P	7	500
88	1965	07	06	West Corinth Gulf, Central Greece	3	P	5	300
89	1968	02	19	Lemnos Island, North-East Aegean Sea	2	P	3	
90	1979	04	15	Montenegro	4	P	7	
91	1981	02	24	East Corinth Gulf, Central Greece	2	P	3	30
92	1983	01	17	Kefalonia Island, Ionian Sea	2	P	3	50
93	1984	02	11	West Corinth Gulf, Central Greece	3	P	4	
94	1991	01	04	Ikaria Island, East Aegean Sea	2	P	3	
95	1991	05	07	Leros Island, East Aegean Sea	3	P	4	50
96	1995	06	15	West Corinth Gulf, Central Greece	3	P	4	100
97	1996	01	01	West Corinth Gulf, Central Greece	4	P	5	200
98	1999	08	17	Marmara Sea	4	P	6	250
99	2000	04	05	Heraklion, North Crete Island	2	P	3	50
100	2002	26	03	Rhodes Island, East Aegean Sea	3	N	5	200

- Reliability is meant to assign score of at least 3 on 4-point reliability scale (for more explanation, see the text).
- Key: k = tsunami intensity in the Sieberg-Ambraseys 6-point scale; K = tsunami intensity determined in this paper according to the Papadopoulos-Imamura 12-point scale; h = maximum wave height (amplitude) in the coast.
- Key for main data sources: A = Ambraseys (1962), P = Papadopoulos (2002), PF = revised in the present paper on the basis of the historical sources listed in the tsunami catalogues referred to in the text; N = new observations collected by the first author during post-event field survey.
- Note 1: The Patras Gulf wave of 23 January 1821 (k = 4) was re-examined by Papadopoulos and Plessa (2001) who concluded that very possibly it was not a tsunami but a surge storm; therefore, this event is not included in this table.
- Note 2: The Marmara Sea events of 557, 986, and 1571 AD were re-evaluated as false events (Ambraseys, 2002) and, therefore, those are not included in this table.

Table 2: Reliable Tsunami Events Known in the West Mediterranean Sea, that is in Italy, the Côte d' Azur, and the Alboran Sea

No.	Year	Month	Day	Region	*k*	Reference	*K*	*h* (cm)
1	1169	2	4	Messina Straits	4	T	8	
2	1365	1	2	Algiers	4	S, PF	8	
3	1627	7	30	Gargano	5	PF	6	
4	1631	12	17	Campania	2	T	4	
5	1646	4	5	Tuscany	3	T	4	
6	1654	7	20	Liguria – Cote d' Azur	2	T	4	
7	1672	4	14	Central Adriatic	2	T	3	
8	1693	1	11	Eastern Sicily	5	T	7	
9	1726	9	1	Northern Sicily	2	T	3	
10	1731	3	20	Apulia	2	T	4	
11	1742	1	19	Tuscany	2	T	3	
12	1773	5	6	Tangiers	4	S, PF	7	900
13	1783	2	5	Tyrrhenian Calabria	3	T	4	
14	1783	2	6	Messina Straits	6	T	9	900
15	1784	1	7	Ionian Calabria	3	T	5	
16	1784	1	19	Messina Straits	3	T	5	
17	1805	7	26	Campania	2	T	3	
18	1818	2	20	Eastern Sicily	2	T	4	
19	1823	3	5	Northern Sicily	4	T	5	
20	1828	10	9	Liguria – Cote d' Azur	3	T	4	
21	1832	3	8	Ionian Calabria	3	T	4	
22	1836	4	25	Ionian Calabria	4	T	5	
23	1846	8	14	Tuscany	2	T	4	
24	1856	8	21	Mahon, Menorca	3	S, PF	5	
25	1875	3	17	Central Adriatic	3	T	4	
26	1887	2	23	Liguria – Cote d' Azure	3	T	4	150
27	1894	11	16	Tyrrhenian Calabria	3	T	4	
28	1905	9	8	Tyrrhenian Calabria	3	T	4	600
29	1906	4	4	Campania	2	T	3	
30	1907	10	23	Ionian Calabria	2	T, PF	3	
31	1908	12	28	Messina Straits	6	T	10	1300
32	1916	7	3	Stromboli Island	2	T	4	1000
33	1919	5	22	Stromboli Island	3	T	5	
34	1930	9	11	Stromboli Island	3	T	4	250
35	1944	8	20	Stromboli Island	4	T	6	
36	1968	4	18	Liguria – Cote d' Azur	2	T	3	
37	1979	10	16	Liguria – Cote d' Azur	3	T	4	300
38	1988	4	20	Aeolian Islands	2	T	3	
39	1990	12	13	Eastern Sicily	2	T	3	
40	2002	12	30	Stromboli Island	4	N	7	900

- Reliability is meant as in Table 1.
- Key for *k, K* and *h* is as in Table 1.
- Key for main data sources: S = Soloviev et al. (2000), T = Tinti et al. (2004), PF = revised in present paper, N = new observations collected by the first author during post-event field survey

Table 3: Mediterranean Sea Tsunamis for Which Calculation of the Murty-Loomis Magnitude *ML* Has Been Possible

Event Subregion	Date	*M*	*K*	*k*	*h* (cm)	*ML*	Authors
Gargano	30 July 1627	6.7	6	5	-	−1.4	T
Columbos	11 October 1650	-	10	6	2000	3.0	P
Eastern Sicily	11 January 1693	7.4	7	5	-	2.3	T
Tyrrhenian Calabria	5 February 1783	6.9	9	3	900	−1.8	T
Tyrrhenian Calabria	8 September 1905	7.1	4	3	600	0.4	T
Messina Straits	28 December 1908	7.2	10	6	1300	−0.4	T
Cyclades	9 July 1956	7.5	9	6	1500	3.0	P
West Corinth Gulf	7 February 1963	-	7	4	500	−11.0	P

Key: M = earthquake magnitude, K = tsunami intensity on the 12-point scale proposed by Papadopoulos and Imamura (2001), k = tsunami intensity on the 6-point Sieberg-Ambraseys scale, h = maximum wave height (amplitude) in the coast, P = Papadopoulos (2002), T = Tinti et al. (2004)

RESULTS

The tsunami intensities determined according to the new 12-point scale are shown in Tables 1 and 2. In the East Mediterranean Sea, the highest intensity of degree 10 was assigned to three large historical tsunamis that occurred in Greece and particularly in the western Hellenic arc on 365, in the eastern Hellenic arc on 1303 and in the volcanic complex of Thera (Santorini) Island, South Aegean Sea, on 1650. The first two were generated by large tectonic earthquakes while the third was associated with the submarine eruption of the volcano Columbos. Very strong tsunamis occurred in the western Corinth Gulf, central Greece, in association with two destructive earthquakes on 373 B.C. and 1748. In the West Mediterranean Sea, the highest intensity of degree 9 and 10 was assigned to two earthquake-associated tsunamis occurring in the Messina straits in 1783 and 1908, respectively.

A series of best-fit empirical relations were investigated by regression analysis between the 6-point and the 12-point intensities k and K, as well as between tsunami intensity and tsunami height, tsunami intensity and tsunami magnitude, and tsunami magnitude and earthquake magnitude. As may be observed in Figures 2-7 and in Table 4, the intensities k and K are well correlated in the entire Mediterranean basin and in the East and West Mediterranean sub-basins. The maximum tsunami wave height h seems to correlate well with tsunami intensity in a power-law mode, particularly in the East Mediterranean for intensities determined on the 12-point scale.

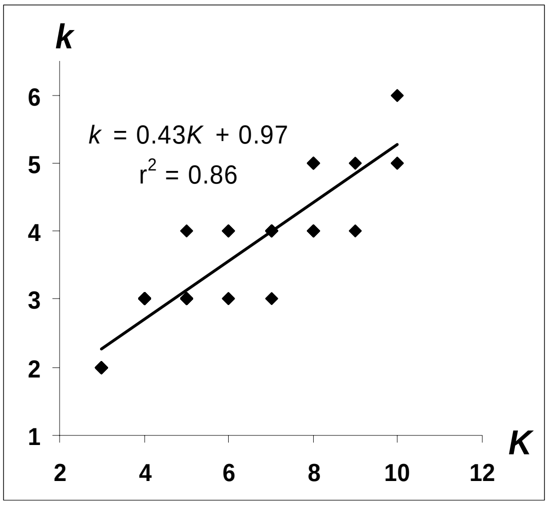

Fig. 2 Relation between tsunami intensity on 12-point scale, K, and on 6-point scale, k, in the East Mediterranean Sea

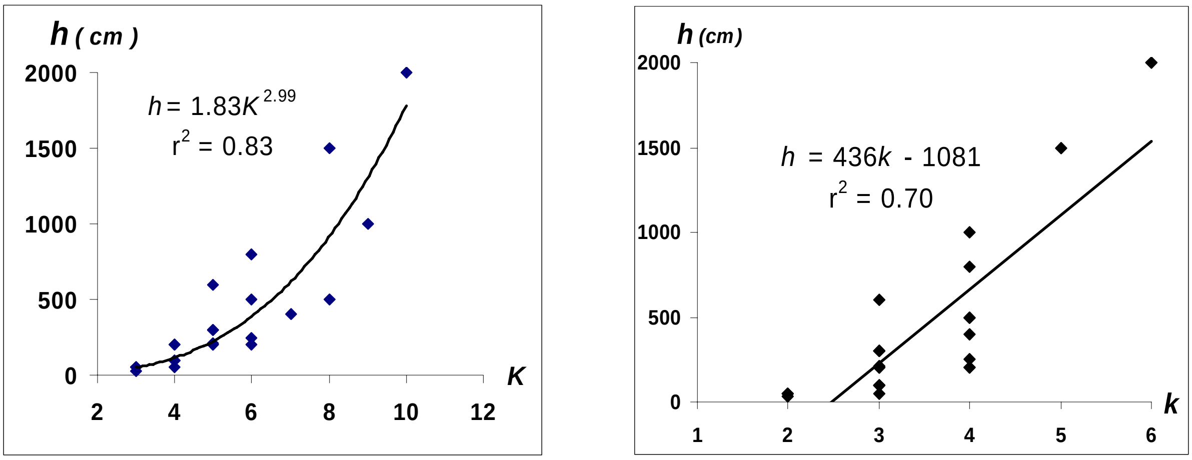

Fig. 3 Relations between wave height *h* and intensities *K* and *k* in the East Mediterranean Sea (*K* and *k* as in Figure 2)

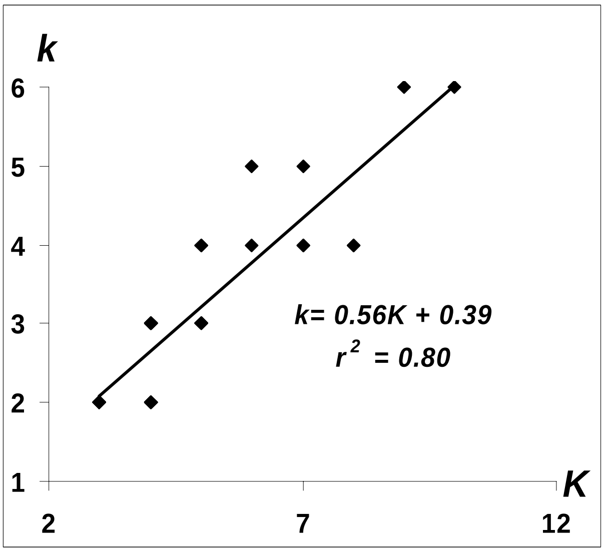

Fig. 4 Relation between intensities *K* and *k* in the West Mediterranean Sea (*K* and *k* as in Figure 2)

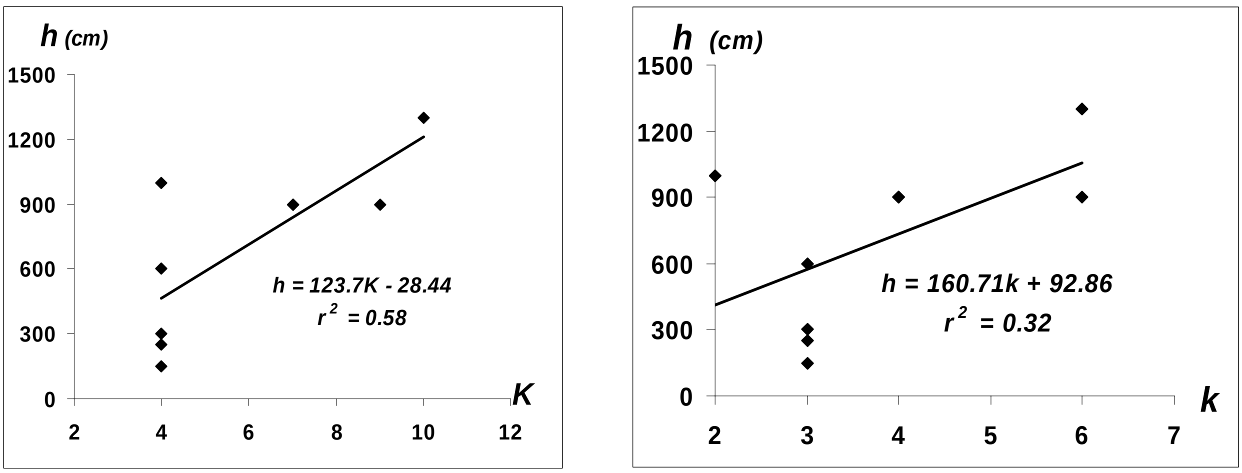

Fig. 5 Relations between wave height *h* and intensities *K* and *k* in the West Mediterranean Sea (*K* and *k* as in Figure 2)

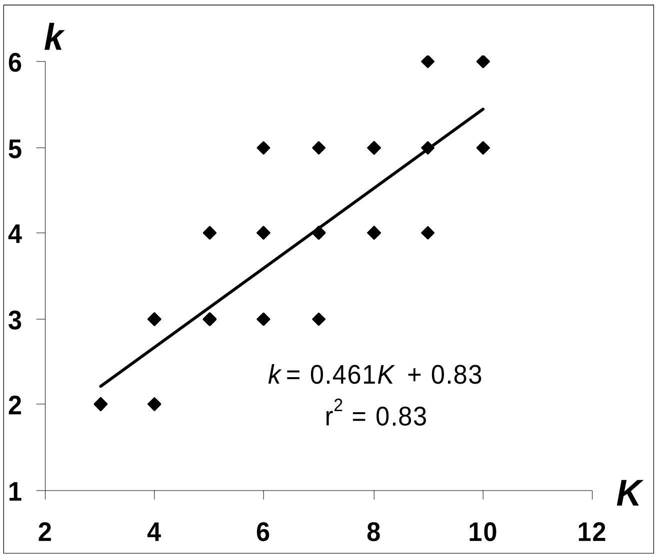

Fig. 6 Relation between intensities *K* and *k* in the entire Mediterranean Sea (*K* and *k* as in Figure 2)

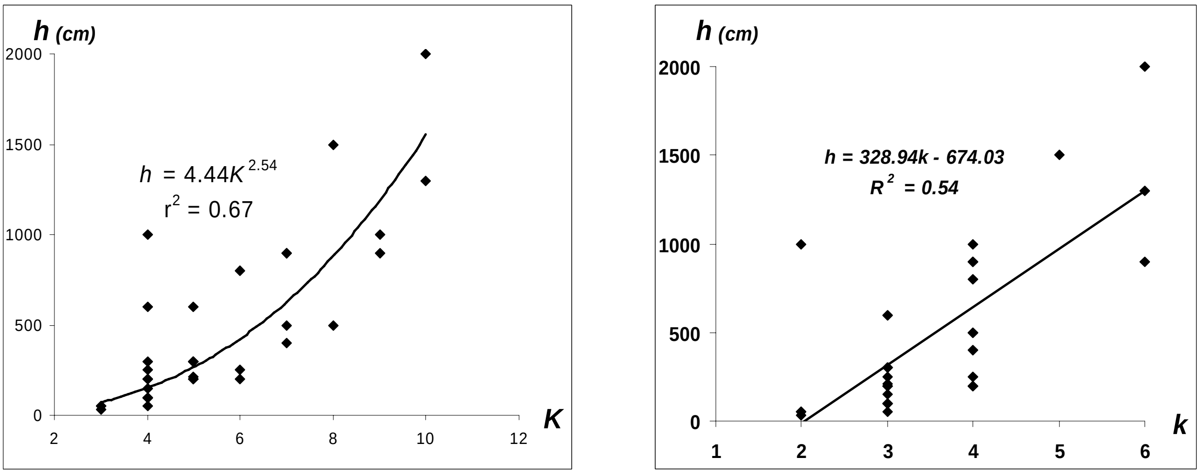

Fig. 7 Relations between wave height *h* and intensities *K* and *k* in the entire Mediterranean Sea (*K* and *k* as in Figure 2)

Table 4: Best-Fit Relations between Parameters of Tsunami Size in the Mediterranean Sea

Relation	r^2	*n*
East Mediterranean Sea:		
$k = 0.43K + 0.97$	0.86	100
$h = 1.83 \times K^{2.99}$	0.83	26
$h = 436k - 1081$	0.70	26
West Mediterranean Sea:		
$k = 0.56K + 0.39$	0.80	40
$h = 123.7K - 28.44$	0.58	9
$h = 160.71k + 92.86$	0.32	9
Entire Mediterranean Sea:		
$k = 0.46K + 0.83$	0.83	140
$h = 4.44 \times K^{2.54}$	0.67	35
$h = 328.94k - 674.03$	0.54	35
$ML = 5.96M - 42.14$	0.84	6

Key:
- *k* = tsunami intensity in 6-point scale,
- *K* = tsunami intensity in 12-point scale,
- *h* = maximum tsunami wave height in cm,
- *ML* = Murty-Loomis tsunami magnitude,
- *M* = earthquake magnitude equivalent to surface-wave magnitude,
- *r* = correlation coefficient,
- *n* = number of events

Since tsunami magnitude *ML* has been calculated for very few events, only tentative relations between *ML* and wave height, as well as between *ML* and earthquake magnitude, were determined (Table 4 and Figure 8). As one may expect, the tsunami magnitude is linearly increasing with earthquake magnitude. The maximum wave height seems to increase exponentially with *ML* but the correlation is poor. On the other hand, it was found that for the small sample of events available the tsunami magnitude and tsunami intensity are uncorrelated.

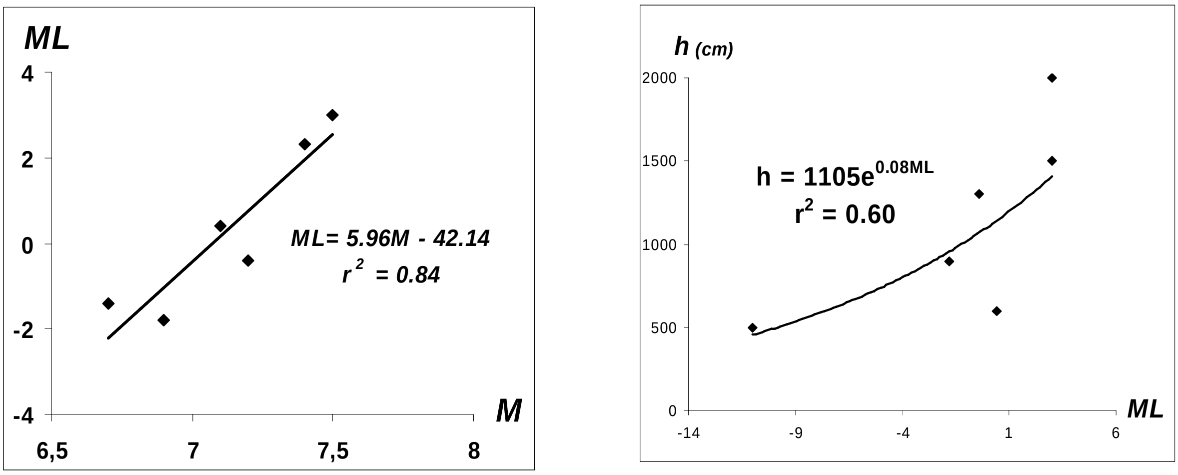

Fig. 8 Relations between Murty-Loomis tsunami magnitude *ML* and earthquake magnitude *M* (left), and between wave height *h* and *ML* (right) in the entire Mediterranean Sea

DISCUSSION AND CONCLUSIONS

The number of very strong tsunami events, that is waves with assigned intensity of at least 9, is five in the last 700 years. Therefore, it may be concluded that in the Mediterranean Sea, on an average, a very strong tsunami is expected every 140 years, provided that the historical documentation is complete for the last seven centuries. From geographical point of view, the very strong events are associated either with highly seismogenic structures like the Messina straits, South Italy, the Corinth Gulf, central Greece, and the Hellenic arc, or with the active volcanic complex of Thera, South Aegean Sea. On the contrary, not very strong tsunamis were found in the rest tsunamigenic zones of the Mediterranean Sea region (Figure 1). It should be noted, however, that these results are valid as much as the tsunami record over the last centuries could be extrapolated to longer periods of time. From this point of view, the incompleteness of the data along with the very long repeat time that may characterize the tsunami occurrence in some tsunamigenic zones, pose a serious problem in approaching reliably the repeat time of very strong tsunamis in the Mediterranean Sea. Therefore, the average recurrence of 140 years for the very strong events should be regarded as an “apparent” mean repeat time.

The relations established between parameters that describe tsunami size are of multiple values. Firstly, the intensity (k) versus intensity (K) relation makes a good basis for inverting intensity from one scale to another. On the other hand, the relations between wave height and tsunami intensity are useful for some tsunami hazard assessment. In fact, height versus intensity relation provides possibilities to assess the expected tsunami intensity from an independent estimation of the expected wave height, for example from numerical simulation experiments. In addition, the estimation of tsunami magnitude from the expected wave height or the earthquake magnitude is an important insight to energy aspects of the tsunami studies as well as for understanding properties of the tsunamigenic sources better.

APPENDIX: THE NEW 12-POINT TSUNAMI INTENSITY SCALE

The new tsunami intensity scale proposed by Papadopoulos and Imamura (2001) incorporates twelve divisions and is consistent with the several 12-point seismic intensity scales established and extensively used in Europe and North America in the last 100 years. The new scale is arranged according to the effects on humans, the effects on objects, including vessels of various sizes, and on nature, and damage to buildings:

I. NOT FELT

Not felt even under the most favourable circumstances; no effect; no damage.

II. SCARCELY FELT

Felt by few people on board in small vessels; not observed on the coast; no effect; no damage.

III. WEAK

Felt by most people on board in small vessels; observed by few people in the coast; no effect; no damage.

IV. LARGELY OBSERVED

Felt by all on board in small vessels and by few people on board in large vessels; observed by most people on the coast; few small vessels move slightly onshore; no damage.

V. STRONG

Felt by all on board in large vessels and observed by all on the coast; few people are frightened and run to higher ground; many small vessels move strongly onshore, a few of them crash into each other or overturn; traces of sand layer are left behind in grounds of favourable conditions; limited flooding of cultivated land; limited flooding of outdoors facilities (e.g., gardens) of near-shore structures.

VI. SLIGHTLY DAMAGING

Many people are frightened and run to higher ground; most small vessels move violently onshore, or crash strongly into each other, or overturn; damage and flooding in a few wooden structures; most masonry buildings withstand.

VII. DAMAGING

Most people are frightened and try to run to higher ground; many small vessels damaged; a few large vessels oscillate violently; objects of various sizes and stability overturn and drift; sand layer and accumulations of pebbles are left behind; a few aquaculture rafts washed away; many wooden structures damaged, few are demolished or washed away; damage of point 1 and flooding in a few masonry buildings.

VIII. HEAVILY DAMAGING

All people escape to higher ground, a few are washed away; most of the small vessels are damaged, many are washed away; a few large vessels move ashore or crash into each other; big objects drift away; erosion and littering on the beach; extensive flooding; slight damage in tsunami control forest, stop drifts; many aquaculture rafts washed away, a few partially damaged; most wooden structures are washed away or demolished; damage of point 2 in a few masonry buildings; most RC buildings sustain damage, damage of point 1 and flooding is observed in a few buildings.

IX. DESTRUCTIVE

Many people are washed away; most small vessels are destroyed or washed away; many large vessels move violently ashore, few are destroyed; extensive erosion and littering of the beach; local ground subsidence; partial destruction in tsunami control forest, stop drifts; most aquaculture rafts washed away, many partially damaged; damage of point 3 in many masonry buildings, a few RC buildings suffer from damage of point 2.

X. VERY DESTRUCTIVE

General panic; most people are washed away; most large vessels move violently ashore, many are destroyed or collide with buildings; small boulders from the sea bottom move inland; cars overturn and drift; oil spill, fires start; extensive ground subsidence; damage of point 4 in many masonry buildings, a few RC buildings suffer from damage of point 3; artificial embankments collapse, port water breaks damaged.

XI. DEVASTATING

Lifelines interrupted; extensive fires; water backwash drifts cars and other objects in the sea; big boulders from the sea bottom move inland; damage of point 5 in many masonry buildings; a few RC buildings suffer from damage of point 4, many suffer from damage of point 3.

XII. COMPLETELY DEVASTATING

Practically all masonry buildings demolished; most RC buildings suffer from at least damage of point 3.

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