ISET Journal of Earthquake Technology, Paper No. 465, Vol. 42, No. 4, December 2005, pp. 189-201

ASSESSING THE HAZARD RELATED TO TSUNAMIS OF TECTONIC ORIGIN: A HYBRID STATISTICAL-DETERMINISTIC METHOD APPLIED TO SOUTHERN ITALY COASTS

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ABSTRACT

Italy is one of the countries of the Mediterranean Sea most affected by tsunamis. Catalogues of Italian tsunamis show that Italian coasts were attacked by large tsunamis in the past that had catastrophic effects, causing thousands of victims and severe damage. Though the cases of tsunamis associated with volcanic activity and submarine slides cannot be neglected, most tsunamis were the results of coastal and submarine earthquakes. Therefore, assessing the occurrence probability of tsunamigenic earthquakes is an important contribution to the global evaluation of tsunami hazard. Improving a methodology used for a preliminary evaluation of tsunami hazard in Italy more than one decade ago, this paper applies probabilistic seismic hazard techniques focussing on Calabria and Sicily, that are among the most active seismic and tsunamigenic regions in Italy. The estimated tsunami activity, expressed in terms of the number of expected events in a 10,000-year period with run-up heights exceeding a given threshold value, is compared with the information deducible from the most recent Italian tsunami catalogue.

KEYWORDS: Coastal Tsunami Amplification, Eastern Sicily, Hybrid Method, Southern Calabria, Tsunami Hazard

INTRODUCTION

One of the main goals of tsunami hazard research is the estimate of the number and size of future events expected to occur along the coasts of a specific geographic area. Typically, the goal is achieved by applying statistical methods to catalogues containing the historical record of past tsunamis in the studied region. In the particular case of Italy, which is one of the countries most exposed to the tsunami threat in the Mediterranean, the most recent tsunami catalogue (Tinti et al., 2004; to be hereafter referred to as ITC2004) contains 67 events, several of which were disastrous, spanning the time interval from 79 A.D. to December 30, 2002. The largest number of tsunamis (49 out of 67) was generated by offshore or coastal earthquakes, the remaining being imputable mainly to volcanic activity (flank instabilities and pyroclastic flows). The total number of events in ITC2004 is indeed too small to be used in reliable statistical analyses, but the observations that about 73% of the Italian tsunamis were induced by earthquakes, and that Italian earthquake catalogues are much richer in events than ITC2004, suggest that the problem of tsunami hazard assessment along the Italian coasts can be formulated in terms of probability estimation of tsunamigenic earthquakes occurrence. The approach we describe in this study represents an evolution of the one developed in two previous papers by Tinti (1991, 1993). It can be called a hybrid method because it involves two separate and parallel tasks, which are carried out through statistical and deterministic tools. In the purely statistical part, we determine the earthquake occurrence rate in a given geographical area starting from a selected earthquake catalogue; the final result of this part is represented by distribution maps of the estimated parameters *a* and *b* of the truncated Gutenberg-Richter magnitude-frequency law. The second part is based on deterministic models and empirical relationships, allowing one to compute, for any given earthquake magnitude, the initial disturbance of the sea level, the corresponding maximum tsunami wave height along any coastal portion of the region under study, and finally to retrieve the minimum magnitude required to produce coastal wave heights larger than a given threshold. Combining the results obtained in the two separate procedures, we can compute the number of tsunamis expected to produce wave heights exceeding a given threshold in a given time interval. The information on the number of events can be easily translated into exceedance probability estimates if we adopt a suitable probability distribution function (e.g., Poissonian).

In the following sections we will briefly describe the most recent Italian tsunami catalogue (ITC2004), the two chosen earthquake catalogues and the basic steps of the aforementioned hybrid procedure. Then, we discuss the results of the application of the methodology to the southern Italian regions of Calabria and Sicily, which are the most exposed regions, both to seismic and tsunami hazards in Italy. The analysis is carried out starting from two different earthquake catalogues and by using different empirical amplification relationships between the initial sea disturbance induced by an earthquake and the final maximum coastal water height. The results are finally compared with the information deducible from ITC2004.

THE ITALIAN TSUNAMI CATALOGUE (ITC2004)

Compiling tsunami catalogues is the first and basic step to assessing the level of tsunami hazard to which a given geographic area is exposed. As regards Italy, Tinti and Maramai (1996) undertook a careful revision of previous compilations, introducing also new catalogue standards that were elaborated in the course of the European Union projects, GITEC (Genesis and Impact of Tsunamis on the European Coasts) and GITEC-TWO (Genesis and Impact of Tsunamis on the European Coasts – Tsunami Warning and Observations) (see, in particular, UB, 1999). Based on the same philosophy, Tinti et al. (2004) carried out a further revision of the Tinti and Maramai (1996) compilation. The resulting catalogue, which is here denoted as ITC2004 and is freely available through internet, contains 67 events, starting from the tsunami generated by the large Plinian eruption of Vesuvius in 79 A.D., up to the two tsunamis generated by two landslides on the western flank of the Stromboli volcano on December 30, 2002.

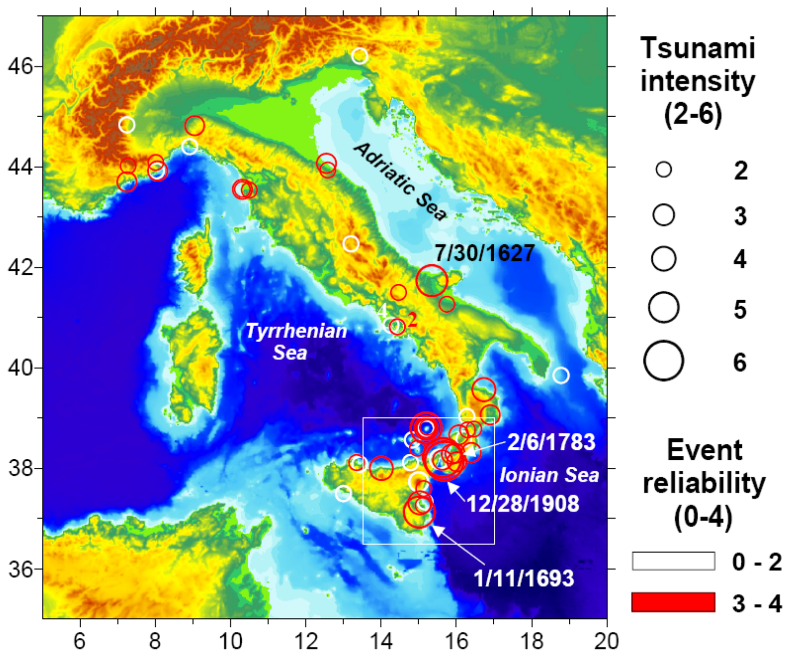

Fig. 1 Geographical distribution of the 67 tsunami events contained in ITC2004 (the position for each tsunami is the position of its source (earthquake, landslide, volcanic eruption); each tsunami is assigned an intensity and a reliability index; date and position of the four largest tsunamis in ITC2004 are especially identified)

Figure 1 shows the geographic distribution of the 67 events contained in ITC2004, as well as the tsunami intensity (on the Sieberg-Ambraseys scale; Ambraseys, 1962) and the event reliability. Note that an intensity equal to 1 corresponds to a very light tsunami, i.e. to a tsunami that is only visible on tide gauge records. Since no tide-gauge network specifically conceived for tsunami detection has been installed till now in Italy, no events with this intensity are contained in the catalogue. This is also the reason why the intensity scale reported in Figure 1 starts from degree 2. The highest-intensity tsunamis contained in ITC2004 were all generated by earthquakes: in chronological order, they are the 30 July 1627 event affecting the coasts of the Gargano promontory in the southern Adriatic Sea, the 11 January 1693 tsunami affecting the entire eastern Sicily coast, and the 6 February 1783 and 28 December 1908 tsunamis generated in the Messina Straits. Another very important parameter is the reliability index, defined in a 5-degree scale in Tinti et al. (2004). Degree 0 on this scale is equivalent to a “very improbable tsunami”, while degree 4 corresponds to a “definite tsunami”.

Most tsunamis are caused by earthquakes (49 events). Some tsunamis (12) are due to the volcanic activity of Vesuvius, of Etna, and of the Aeolian Islands volcanoes (Stromboli, Vulcano). The remaining events are due to sliding phenomena associated with earthquakes or to gravitational instabilities, or have unknown causes. Concerning the geographic distribution, one can easily observe that tsunamis mostly affect the region highlighted by a white rectangle in Figure 1, embracing the southern coasts of Calabria, the Messina Straits, the Aeolian archipelago, the entire eastern Sicily, and large portions of the northern and southern coasts of Sicily. This is the area we will focus our attention on in this paper. The ITC2004 events that took place here are listed in Table 1. If one takes into account only the tsunamis that occurred in approximately the last 350 years, that is the time interval in which ITC2004 can be reasonably considered complete (see Tinti et al., 2004, for a discussion on the catalogue completeness), one deduces that as many as 12 earthquakes generated tsunamis with observed coastal heights about or larger than 1 m. On a more standard 10,000-year basis, this corresponds to about 340 tsunamigenic earthquakes. This information will be precious in the last section of this study, where we will compare this value with the rate of tsunamigenic earthquakes estimated through our hybrid statistical-deterministic approach, as described in the following sections.

Table 1: Tsunamis within the Region of Study (see Figure 1)

Year	Month	Day	Sub-region	Reliability Index	Tsunami Intensity	CPTI04[1] Magnitude	Tsunami Cause
1169	2	4	Eastern Sicily	4	**4**	6.60	E
1329	6	28	Eastern Sicily	2	3	-	V
1613	8	25	Northern Sicily	1	2	5.57	E
1638	3	27	Tyrrhenian Calabria	2	2	7.00	E
1649	1		Messina Straits	1	**3**	5.03	E
1693	1	9	Eastern Sicily	2	2	-	E
1693	1	11	Eastern Sicily	4	**5**	7.41	E
1726	9	1	Northern Sicily	4	2	5.61	E
1783	2	5	Tyrrhenian Calabria	4	**3**	6.91	E
1783	2	6	Messina Straits	4	6	5.94	M
1783	2	7	Tyrrhenian Calabria	1	2	6.59	E
1783	3	1	Tyrrhenian Calabria	3	2	5.92	E
1783	3	28	Tyrrhenian Calabria	3	2	6.94	E
1784	1	7	Ionian Calabria	4	**3**	4.1*	E
1784	1	19	Messina Straits	4	**3**	4.1*	E
1818	2	20	Eastern Sicily	4	2	6.00	E
1823	3	5	Northern Sicily	4	**4**	5.87	E
1832	3	8	Ionian Calabria	4	**3**	6.48	E
1836	4	25	Ionian Calabria	4	**4**	6.16	E
1894	11	16	Tyrrhenian Calabria	4	**3**	6.05	E
1905	9	8	Tyrrhenian Calabria	4	**3**	7.06	E

1907	10	23	Ionian Calabria	4	**3**	5.93	E
1908	12	28	Messina Straits	4	**6**	7.24	E
1916	7	3	Aeolian Islands	4	2	5.07	E
1919	5	22	Aeolian Islands	4	3	-	V
1926	8	17	Aeolian Islands	2	2	5.32	E
1930	9	11	Aeolian Islands	4	3	-	V
1940	1	15	Northern Sicily	2	2	5.34	E
1944	8	20	Aeolian Islands	4	4	-	V
1954	2		Aeolian Islands	1	2	-	V
1988	4	20	Aeolian Islands	4	2	-	V
1990	12	13	Eastern Sicily	4	2	5.68	E
2002	12	30	Aeolian Islands	4	5	-	V

E: Earthquake
V: Volcanic Activity
M: Earthquake-Induced Mass Failure
Earthquake events with intensity ≥ 3 (approximately corresponding to tsunami run-up heights ≥ 1 m) are in bold.
For earthquake-induced tsunamis (E), the 7th column gives the magnitudes of the parent shocks as reported in CPTI04[1] (with the exception of cases marked with an asterisk, which are taken from the catalogue C1).

THE EARTHQUAKE CATALOGUES

The number of tsunamis (67) contained in ITC2004 is too small to be used in any reliable statistical analysis. Conversely, earthquake catalogues are much richer in entries. Hence, it sounds reasonable to convert the problem of the tsunami hazard assessment along the Italian coasts into the probability estimation of tsunamigenic earthquakes occurrence.

In this study, we use two different compilations. The first that will be denoted hereafter as C1, is an internal file managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV, 1991) in Rome. It is probably the largest compilation of Italian earthquakes, spanning a time period of over 2,000 years. This however suffers from the fact that no systematic critical revision of the events is routinely carried out, and therefore several events might have been characterized by incorrect parameters or, more rarely, might represent false entries.

The second catalogue, referred to as C2 henceforth, has been built by the authors of this paper by using the very recent "Parametric Catalogue of Italian Earthquakes" (CPTI04[1]) to integrate and correct C1. The criteria adopted to build up C2 can be summarised in the following points: 1) all the earthquakes with hypocentral depth larger than 30 km have been excluded, because the tsunamigenic potential of deeper earthquakes can be considered negligible; 2) all the events that occurred before 1000 A.D. are taken from CPTI04[1]; 3) the events with CPTI04[1] magnitude larger than 4.9 are taken from CPTI04[1]; and 4) all the other events are taken from C1.

There is one further important correction regarding the 11 January 1693 tsunamigenic earthquake that affected south-eastern Sicily. A very interesting debate is still going on regarding the correct position of the generic fault of this earthquake. Based on macroseismic data analysis and inversion, both C1 and CPTI04[1] put the epicentre of this earthquake inland, and favour source mechanisms involving large strike-slip components. The position and the focal mechanism are in contrast with the historical accounts on the effects of the tsunami that followed the earthquake, which were disastrous in a large portion of the eastern Sicily coast and were felt in large coastal portions facing the western Ionian Sea. To match the historical evidences on the tsunami, normal faulting along offshore structures parallel to eastern Sicily must be invoked (see, for example, Tinti et al., 2001). Several offshore faults have been mapped during different seismic surveys (e.g., Argnani and Bonazzi, 2002), while no direct evidence exists for inland faulting. For these reasons, we chose to move the epicentre of the 11 January 1693 earthquake offshore, namely at 15.39°E, 37.27°N.

[1] Catalogo Parametrico Dei Terremoti Italiani, 2004 version (in Italian); available at http://emidius.mi.ingv.it/CPTI/

The resulting databases are displayed in Figure 2. A number of clusters are evident along the Tyrrhenian coast of Calabria, in the Aeolian Islands, in the Messina Straits, and in the areas of Mount Etna and Gulf of Catania. The magnitude distributions of the two catalogues are illustrated in Figure 3. The largest differences in the histograms are found in the range of the major earthquakes, and may be better appreciated in the bottom graph: observe that C1 tends to underestimate the magnitudes.

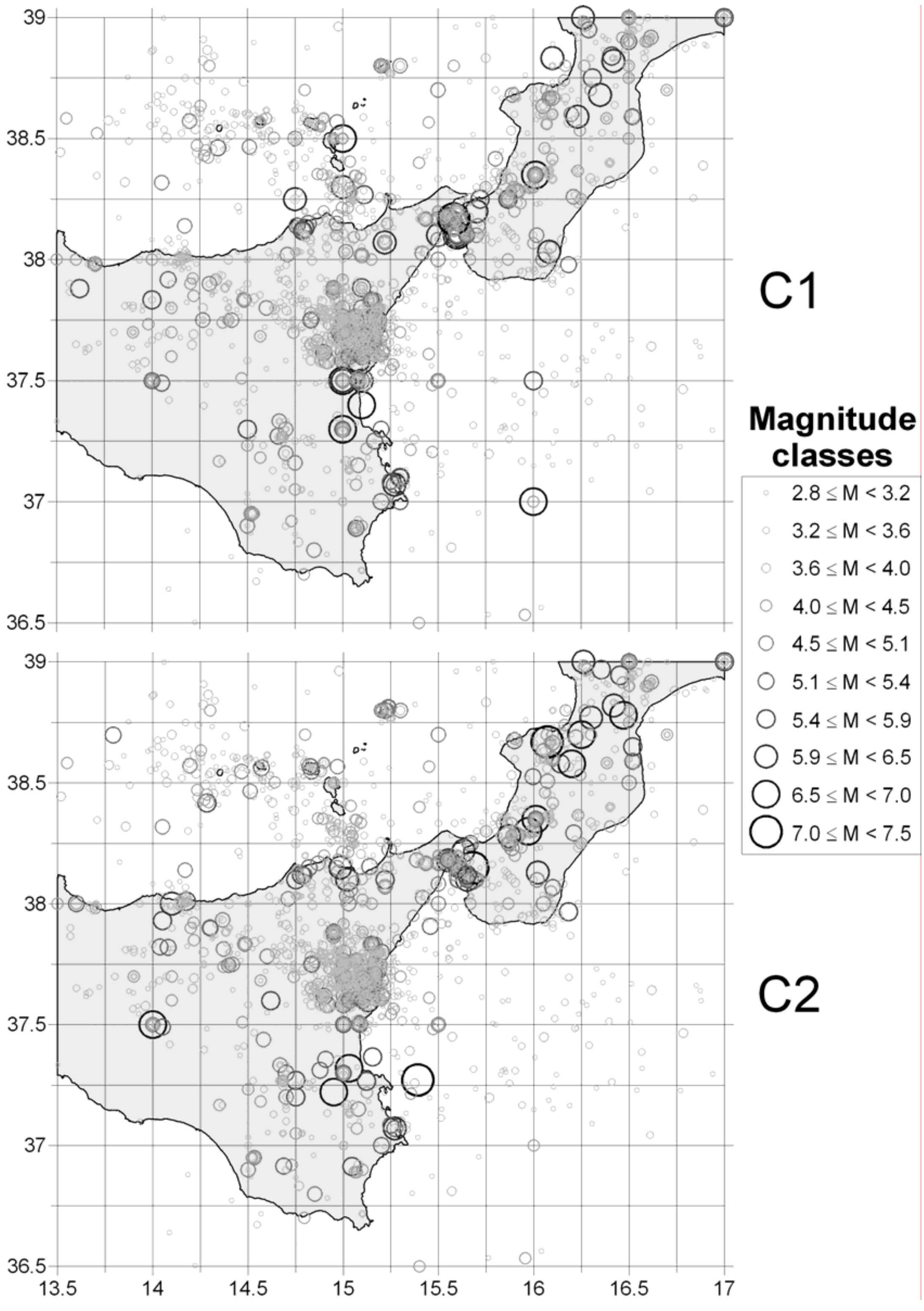

Fig. 2 Distribution of the earthquakes contained in the catalogues C1 and C2 (events belonging to different magnitude classes are plotted with different sizes; the magnitude classes are the same as used in the statistical analysis, with the exception that in the analysis the last two classes are combined together)

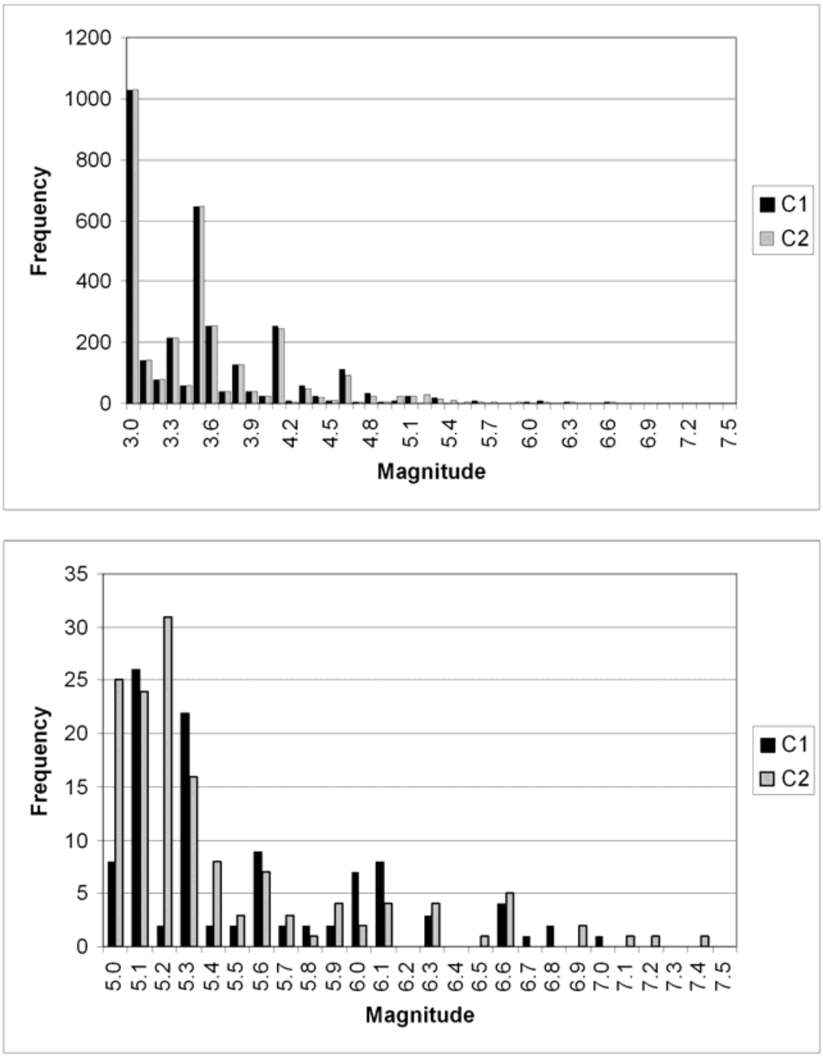

Fig. 3 Magnitude distributions of the two catalogues C1 and C2

STATISTICAL ANALYSIS OF EARTHQUAKE CATALOGUES

The statistical procedure applied in this paper to make evaluations of seismic potential on the two catalogues C1 and C2 is basically the one introduced and developed by Tinti (1991, 1993). The geographic area under consideration is partitioned into a given number of cells, and the final goal of the statistical analysis is the estimation of seismicity rates within each cell. The area shown in Figure 2 is subdivided into 140 cells, 0.25°×0.25° each. Given a catalogue, the procedure involves steps that are applied to the whole region as well as steps applicable at the cell level. The details of the method can be found in Tinti (1991, 1993). Here the procedure is schematically summarised as follows:

- The first step is regarding the completeness of the given catalogue and is applied at a regional level. It is performed through a technique introduced by Tinti and Mulargia (1985). This technique works on Magnitude Class Subcatalogues (MCS). The magnitude classes used in this paper are the same as those used to plot Figure 2 (see legend and caption there). The completeness analysis is carried out for each MCS on the basis of the non-parametric Kolmogorov-Smirnov test. The result is the subdivision of the MCS in time sub-sequences having homogeneous Regional Apparent Rate (RAR) of earthquake occurrences. For each MCS, the RAR is a piecewise function of time from which it is possible to deduce the MCS completeness period and hence the Regional "True" Activity Rate (RTAR). These results are used to assign different weights to different portions of the catalogue.
- The bridge between the global and the cell-based scales is represented by the introduction of the so-called "Experimental Space Distribution Function" (ESDF) for each MCS. The basic idea is that each

earthquake can be assigned an "influence area", which is centred at the earthquake epicentre, depends on the earthquake magnitude, and is weighted according to the weighting scheme resulting from the first step. The ESDFs are then derived by overlapping the earthquake areas and through proper normalisation over the entire region. An example of ESDF (normalised to 100) is shown in Figure 4 for the MCS with $M \geq 6.5$. Note that the plots relative to C1 and C2 are sensibly different, the difference being mainly due to the way C2 was built.

- By combining RTAR and ESDF, we can compute the Cell Activity Rate (CAR) for each MCS. The next stage consists in computing the set of cumulative CAR versus magnitude. This set is fit against a truncated Gutenberg-Richter law, resulting in the computation of the parameters *a* and *b* for each cell. This represents the final step of the seismicity analysis.

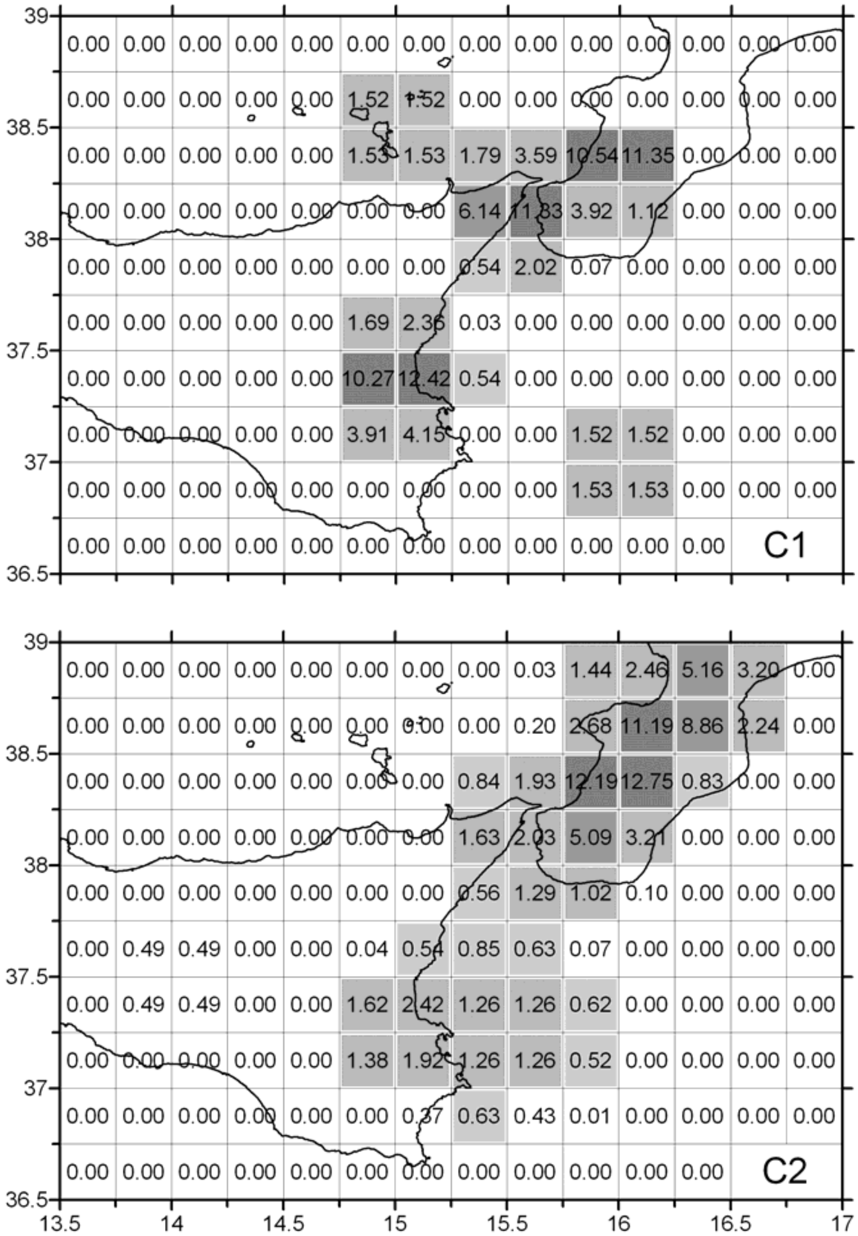

Fig. 4 Experimental Space Distribution Functions (ESDFs, normalised to 100) for the magnitude class $M \geq 6.5$

TSUNAMI POTENTIAL ASSESSMENT

The second part of our hybrid procedure is mainly based on deterministic models and empirical relationships. The first problem consists in determining the initial disturbance of the sea for any value of earthquake magnitude. We take into consideration the magnitude interval [4, 9], and scan it at steps of 0.1. For each given magnitude, we need to retrieve the relative earthquake fault parameters. Assuming that the fault has a simple rectangular shape, we compute the fault rupture area and the subsurface length via the empirical relationships by Wells and Coppersmith (1994) (Figures 5(a), 5(b)). Following Galadini et al. (2000), we put the constraint that the seismogenic layer in the region under consideration is not deeper than 16 km. Hence, the width of the fault is forced to saturate at a given value, which in general depends on the angle of dip: for vertical faults (dip $\delta = 90°$), the maximum width is exactly 16 km (Figure 5(c)). Further, to retrieve the value of the uniform slip on the fault plane, we first make use of the formula by Hanks and Kanamori (1979) relating moment magnitude and scalar seismic moment M_0, and then we use the classical definition of M_0 to obtain the average fault slip (Figure 5(d)). We further restrict our analysis to vertical faults with pure dip-slip mechanism since this is expected to be the configuration with the highest tsunami generation efficiency. For each cell and any given magnitude, by making use of the analytical formulas by Okada (1992) valid for a rectangular fault that is embedded in a perfectly elastic, isotropic, homogeneous half-space delimited by a flat free surface, we compute the maximum vertical offset (maximum uplift-maximum downlift) of the sea floor. It is a commonly adopted practice to identify the maximum vertical offset with the maximum initial tsunami height (Figure 5(e)). Note that the maximum vertical offset is found to be relatively insensitive to the dip angle in the interval 60°-90° (Figure 5(f)). Finally, the strike is varied from North-South to East-West and the resulting maximum offset is selected.

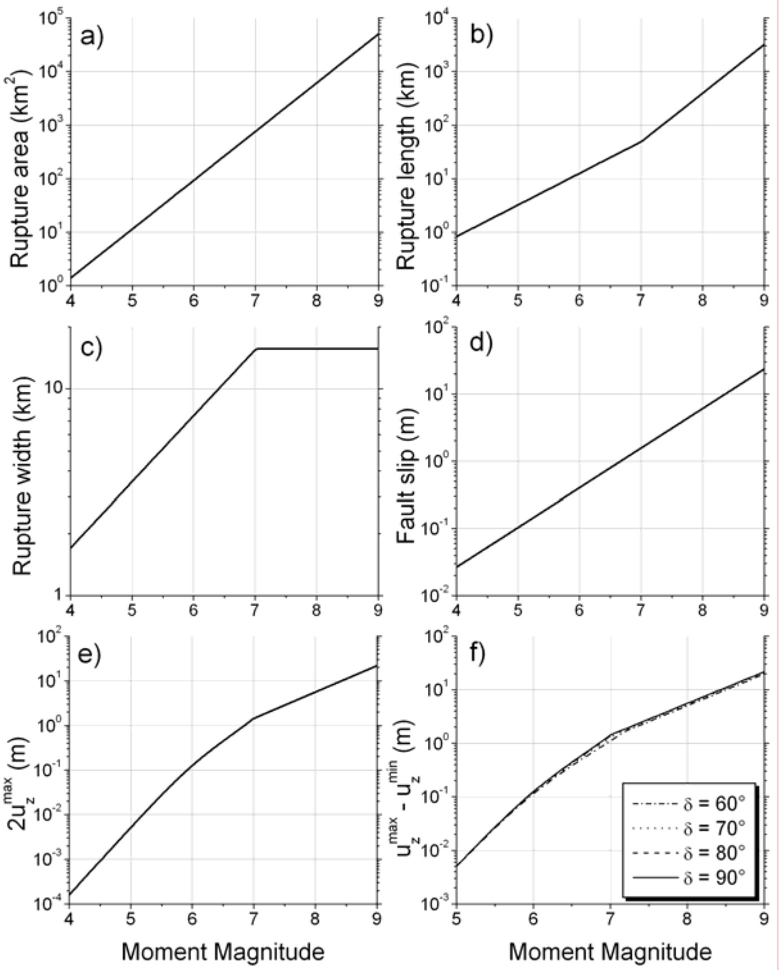

Fig. 5 (a) Area, (b) length, and (c) width of the faults as functions of the earthquake moment magnitude, computed through Wells and Coppersmith (1994) empirical relationships, (d) Uniform slip on the fault computed through Hanks and Kanamori (1979) formula and through the definition of scalar seismic moment, (e) Maximum vertical offset as a function of earthquake magnitude for vertical dip-slip faults, (f) Dependence of the maximum vertical offset on the dip angle of dip-slip faults

The second step consists in passing from the tsunami initial condition to the corresponding expected maximum tsunami wave height along any coastal portion of the region under study. Since the number of examined configurations is too high to allow for a full tsunami numerical simulation for each case, we adopt simple amplification formulas relating the tsunami initial condition to the tsunami height at the coast. In particular, we used two different simplified amplification formulas for offshore sources. The first by Synolakis (1987) relates the tsunami coastal height R to the tsunami height H and the water depth d at the source, as well as to the coastal sea-bottom slope β, assumed to be constant, as follows:

$$R = 2.831(\cot\beta)^{1/2} H^{5/4} d^{-1/4} \tag{1}$$

This may be also written as:

$$R = 2.831 L^{1/2} H^{5/4} d^{-3/4} \tag{2}$$

where L is the horizontal length of the slope. The second, W&A, by Ward and Asphaug (2003) is based on Green's amplification law and considers tsunami coastal height as a function only of the water depth at the source:

$$R = H^{4/5} d^{1/5} \tag{3}$$

As regards the amplification of tsunamis induced by coastal and inland sources, a constant amplification factor equal to 2 was used, in agreement with the results by Tinti and Tonini (2005) who showed that for most of the tsunamis generated in the near-shore zone the run-up height is expected to be less than twice the initial tsunami height.

The last part of this second step consists in performing an inverse procedure allowing to retrieve, for each cell and for each adopted amplification law, the minimum magnitude required to produce tsunami heights larger than a given threshold at the coastline.

RESULTS AND CONCLUSIONS

The cell *a* and *b*-values of the truncated cumulative Gutenberg-Richter law as obtained through the statistical analysis, together with the magnitude values resulting from the deterministic procedure, allow us to compute the number of tsunamigenic earthquakes that are expected to occur in a given period and produce tsunami heights larger than a given value along any coastal segment in the region under consideration. This can be performed locally (i.e., cell per cell) and, hence, for the entire region.

Figures 6 and 7 illustrate the results for the catalogues C1 and C2, respectively. They show contour plots of the number of tsunamigenic earthquakes expected to occur in 10,000 years and capable of producing coastal tsunami heights larger than 1 m.

In both Figures 6 and 7, the upper and lower panels contain the results relative to the application of Synolakis (1987) and Ward and Asphaug (2003) amplification formulas for the offshore sources, respectively. A general observation is that W&A law is able to produce more pronounced amplifications than Synolakis formula. Concerning Figure 6, relative to the C1 database, there are two clear peaks of tsunamigenic earthquakes in correspondence with the Messina Straits and with the area of Mount Etna-Gulf of Catania. The contour levels exhibit a predominant west-east trend crossing northern Sicily, the Messina Straits and western Calabria, while their orientation is mainly along the north-south axis in eastern Sicily. The overall picture is partly different in Figure 7, where the catalogue C2 is taken into account. Here the contour levels clearly follow the orientation of the Calabrian Arc, with the highest concentrations of tsunamigenic earthquakes found along the Tyrrhenian coasts of Calabria and in the Straits of Messina, as well as in south-eastern Sicily, in the area going from Catania to Siracusa. This area was most heavily affected by the 11 January 1693 tsunami.

There is a very important point regarding the comparison between the predicted total number of events in the whole region N_{TOT}, indicated at the right-bottom of each plot in Figures 6 and 7, and the number of earthquake-generated tsunamis contained in ITC2004. At the end of the section describing the Italian tsunami catalogue we mentioned that ITC2004 seems to predict the occurrence of about 340 earthquakes every 10,000 years, which are able to generate tsunami waves with coastal heights exceeding 1 m. It can be easily verified that all the predicted values underestimate the ITC2004 prediction. The underestimation is particularly dramatic for the catalogue C1 combined with the Synolakis amplification law (by roughly ten times), while the catalogue C2 with W&A amplification formula predicts a total number of tsunamigenic events (112) that is three times smaller than the ITC2004 rate.

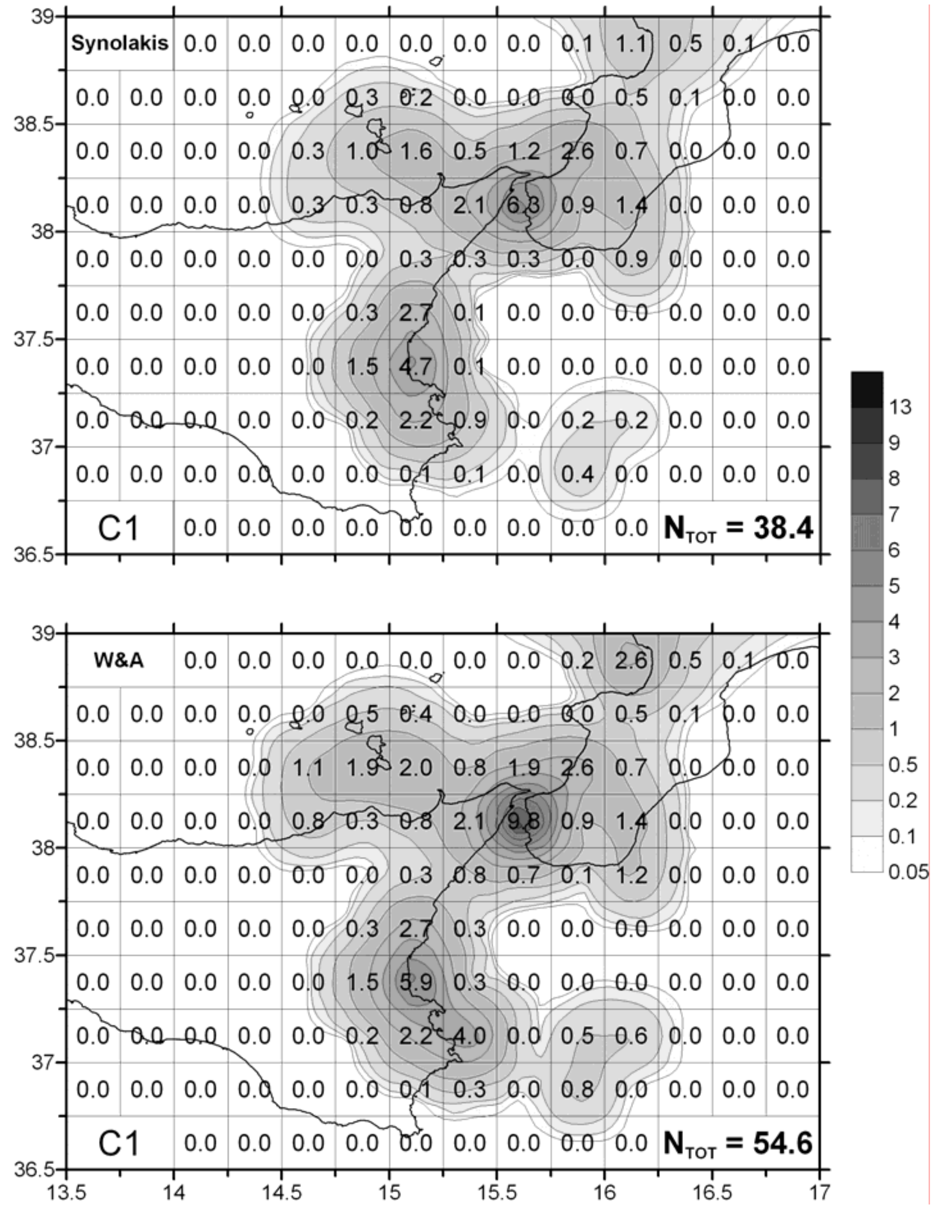

Fig. 6 Contour plots, and cell-by-cell and cumulative number of tsunamigenic earthquakes expected to generate tsunami waves with coastal heights larger than 1 m along any coastal segment in 10,000 years (the results refer to the catalogue C1; N_{TOT} is the total number of expected events in the entire region)

The information on the number of tsunamigenic earthquakes can be translated into probability estimations if an assumption is made on the statistical distribution governing the earthquake occurrences. If a Poissonian process is adopted, we obtain the results displayed in Figure 8. The two plots represent respectively the dependence of the number of events expected in 10,000 years (upper plot) and of the probability of exceedance in 100 years (lower plot) on the coastal tsunami height.

In conclusion, one of the major goals of our future research will consist in understanding the reason for the underestimation of the number of tsunamigenic earthquakes predicted by our hybrid procedure with respect to the information contained in ITC2004. Full numerical simulations of tsunami propagation, at least for some selected earthquakes and areas, could possibly improve the overall results. A strong hint comes however from the observation that some earthquakes that produced tsunamis with intensity 3 had magnitude less than 6 according to Table 1 (see the 7^{th} column). This magnitude is too small to generate tsunami of that size, if one believes in the empirical relationships given in Figure 5. This would point either to the inadequacy of those empirical laws, at least for the region under study, or to the incorrectness of the magnitude determination. This latter option is probably true and shows that a debate should be opened on the reliability of the magnitude estimation for historical earthquakes, in particular for the tsunamigenic earthquakes whose epicentres are found typically very close to the coast or completely offshore. For these cases, the inversion of macroseismic data could provide biased estimates of the earthquake magnitude and/or incorrect epicentral positions, hence affecting the estimation of the tsunamigenic potential of the sources.

ACKNOWLEDGMENTS

This research was funded by the Italian Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) and by the Istituto Nazionale di Geofisica e di Vulcanologia (INGV), Rome, Italy.

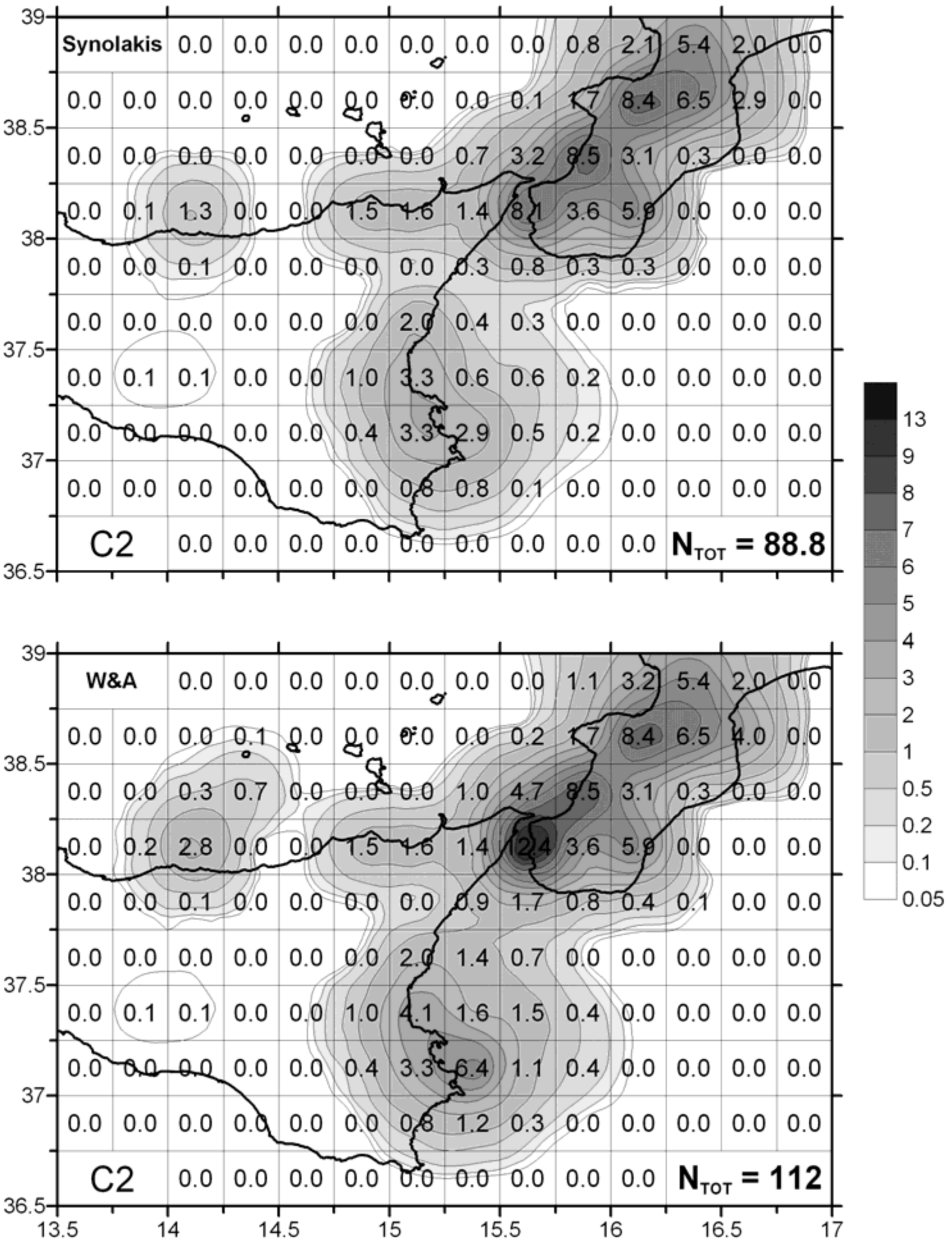

Fig. 7 Catalogue C2 contour plots, and cell-by-cell and cumulative number of tsunamigenic earthquakes expected to generate tsunami waves with coastal heights larger than 1 m along any coastal segment in 10,000 years (N_{TOT} is the total number of expected events in the entire region)

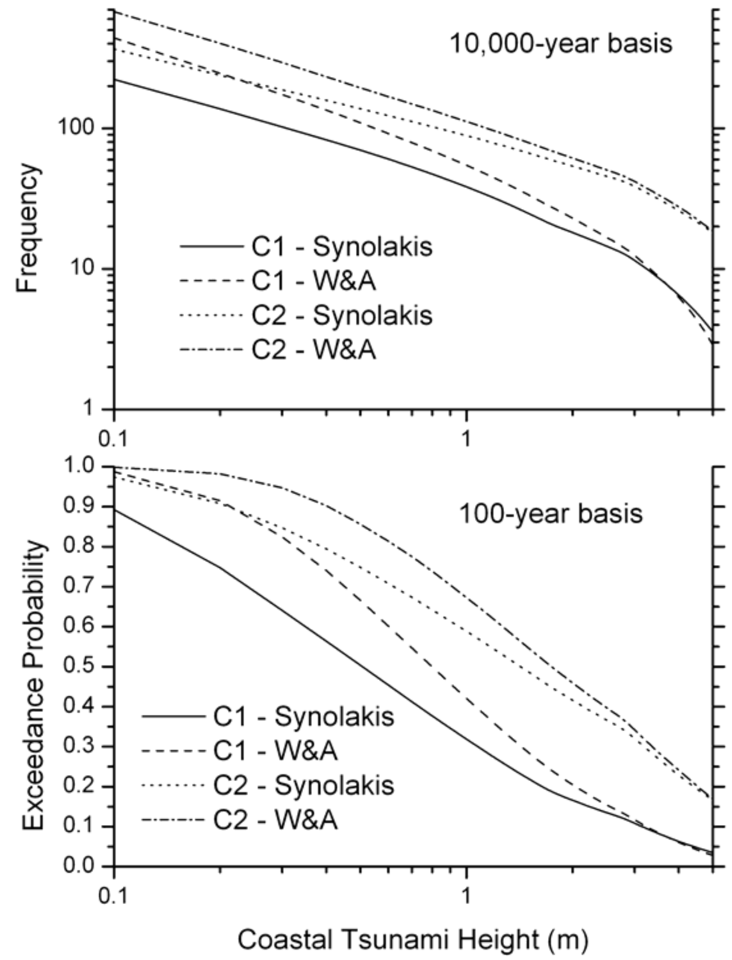

Fig. 8 Dependence of the number of events expected in 10,000 years (upper plot) and of the probability of exceedance in 100 years (lower plot) on the coastal tsunami height (the probability estimation is based on the assumption that the occurrence of the tsunamigenic earthquakes is a Poissonian process)

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