Paper nhess-2015-71 by Omira et al.

Large submarine earthquakes occurred worldwide, 1-year period (June 2013 to June 2014), - Contribution to the understanding of tsunamigenic potential

Answers to reviewers comments

Reviewer #2

Comment #1

Abstract: seems to me too long; there is no mention of the discussion about TWC (Tsunami Warning Centers); the statement "We also find that the tsunami generation is mainly dependent of the earthquake focal mechanism and other parameters such as the earthquake hypocenter depth and the magnitude." is a trivial notion. Please be more specific in formulating the finding of this work.

Answer to comment #1

The text of the paper's abstract is reworked in which the "discussion about TWC" is mentioned. Also more specifications of the finding of the present work are clearly stated.

In the revised version of the paper the abstract is as follow:

"This paper is a contribution to a better understanding of tsunamigenic potential from large submarine earthquakes. Here, we analyse the tsunamigenic potential of large earthquakes occurred worldwide with magnitudes around Mw7.0 and greater, during a period of 1 year, from June 2013 to June 2014. The analysis involves earthquake model evaluation, tsunami numerical modeling, and sensors´ records analysis in order to confirm the generation or not of a tsunami following the occurrence of an earthquake. We also investigate and discuss the sensitivity of tsunami generation to the earthquake parameters recognized to control the tsunami occurrence, including the earthquake magnitude, focal mechanism and fault rupture depth. We further discuss the performance of tsunami warning systems in detecting the tsunami and disseminating the alerts. A total of 23 events, with magnitudes ranging from Mw6.7 to Mw8.1 have been analyzed. This study shows that about 39% of the analyzed earthquakes caused tsunamis that were recorded by different sensors with wave amplitudes varying from few centimetres to about 2 m. Tsunami numerical modeling shows good agreement between simulated waveforms and recorded ones. We find that most generated tsunamis were caused by shallow earthquakes (depth <30km) and thrust faults that took place on/or near the subduction zones. The results of this study can help on the compilation of tsunami catalogs."

Comment #2

Section 1 "Introduction" – It is said that "Analysis of available sensors' records reveals that 39% of the considered earthquakes caused tsunami." – Were there any tsunami records (of earthquakes or other sources) at the given time frame that were not included in this analysis? That would give the reader a better perspective of the scope of this work.

Answer to comment #2

To our knowledge, during the given time frame, the significant tsunami event that was clearly recorded by various tide gauge stations along the coast of Oman and Pakistan, occurred following the 24 September 2013 inland Pakistan earthquake. This tsunami is supposed to be caused by a submarine landslide that follows the earthquake occurrence (Heidarzadeh and Satake, 2014).

The following sentence is inserted in the Introduction section in order to highlight that tsunami events of non-seismic origin were not included in our study:

"Analysis of available sensors records reveals that 39% of the considered earthquakes caused tsunami. Tsunami caused by non-seismic events, such as the 24 September tsunami, possibly associated to submarine landslide (Heidarzadeh and Satake, 2014), that occurred following the Mw7.7 inland Pakistan earthquake and recorded by TD stations along the Omani coast, are disregarded in our study."

Comment #3

Section 2 "earthquake events...." - is mostly a technical description of the events discussed in this work and their plate tectonic environment. In my opinion it exhausts the reader. Instead, this section can be shortened and concentrate on the most important issues that are relevant to tsunami generation. The informative data can be summarized in a table and further descriptions can be presented in the form of a supplementary material.

Answer to comment #3

The Section 2 is shortened accordingly, excluding information that are not necessary for our study (i.e for tsunami generation purpose), and additional references are added for further details on the tectonic of the regions where the analysed events have occurred.

Comment #4

Section 3.2 "Tsunami numerical modelling...." - refers only to the tsunamigenic earthquakes, yet several of the non-tsunamigenic events, mainly the shallow ones, seem capable of producing tsunamis as well, but these are not discussed at all. What is the role of the shallow events that did not produce a tsunami in the overall analysis, especially in the tsunami warning process?

Answer to comment #4

We completely agree with the referee comment regarding the importance of discussing the role of non-tsunamigenic shallow earthquakes in the tsunami warning process. We insert a paragraph in the discussion section (sect 4.2) in which we discuss this issue in the light of the work published by Tinti et al. (2012) on the applicability of the NEAM decision matrix. The paragraph is as fllow:

"It is important to mention here that among the studied events some of them are non-tsunamigenic even though they seem able to cause tsunamis due to their shallow

rupture. Such events can lead to the dissemination of false alerts especially when the TWS is based upon a pre-defined decision matrix. The events occurred in the Mediterranean Sea (Mw6.8 Hellenic and Mw6.9 Aegean events) clearly illustrate the limitation of the use of decision matrix that is usually based only upon earthquake parameters (magnitude, depth, and location) to estimate the severity of the tsunami. This is in accordance with the study by Tinti et al. (2012) that investigated the limitation of the decision matrix for the NE Atlantic, Mediterranean and connected Seas (NEAM) region showing the importance of considering additional earthquake characteristics such as the focal mechanism."

Comment #5

Section 4.2 "Tsunamigenic potential and sensitivity to earthquake parameters"- Submarine earthquakes are also capable of generating submarine landslides that in turn may generate tsunamis as well. Were there any of the recorded tsunamis studied here of such origin?

Is there any role of the water depth at the epicentral area in tsunami generation?

At the end of this section it is said that "This is due to the fact that the thrust/reverse ruptures are the favorite earthquake mechanisms for tsunami generation as they are able to cause a vertical displacement of the ocean bottom." – I think this is too simplistic statement. In general, the dip of submarine thrusts tends to be smaller than that of the normal fault (see the fault plane solutions), and hence their vertical offset is smaller (for the same given magnitude), in contrary with the above statement. How would you explain the 'strike slip' tsunamis? In respect with this problem it would be interesting to compare the tsunami heights also with the vertical displacements of the events discussed in this work.

Answer to comment #5

1. No, none of the tsunamis studied here have been induced by submarine landslides.

2. The role of water depth appears to be important on affecting the tsunami generation when the duration of the earthquake rupture is longer (when it is not considered instantaneous) (Saito and Furumura, 2009). Also, for short source duration, the source size, compared to the water depth, may have effect on tsunami generation, in particular when the source size is smaller than approximately 10 times the sea depth (Saito and Furumura, 2009).
   In tsunami generation modelling, it is widely considered that sea-surface perturbation is equal to the sea-bottom deformation assuming that the sea-water is an incompressible fluid and that the earthquake rupture is instantaneous. In such a case, the sea-bottom deformation is usually modelled using the half space elastic theory of Okada (1985) and then this deformation is transferred as it is to the sea-surface presenting the tsunami generation. In this case the water depth is assumed to have no effect on tsunami generation.

3. The sentence "This is due to the fact that the thrust/reverse ruptures are the favorite earthquake mechanisms for tsunami generation as they are able to

cause a vertical displacement of the ocean bottom." is corrected according to the referee comment and became: *" This is due to the fact that the dip-slip faults, including normal and reverse ruptures, are the favorite earthquake mechanisms for tsunami generation more than the strike-slip ones as they induce more substantial vertical displacement of the ocean bottom. Although, the strike-slip earthquakes may also trigger tsunamis, in particular when they present a dip-slip component."*

The two cases of strike-slip focal mechanisms that generated tsunamis among the analysed events in this study were in fact not pure strike-slip faults. The first one is a left strike-slip with a small dip-slip/thrust component (rake equal to 3° and dip 44°); and the second one also has a dip-slip/reverse component (rake equal to 152° and dip 63°).

Comment #6

Section 4.3 " Tsunami warning"- Alerts were also issued to the Hellenic and Aegean events by National Observatory of Athens (Greece) and Kandilli Observatory and Earthquake Research Institute (Turkey). They were Candidate Tsunami Watch Providers at that time.

Analyzing the performance of the TWC should be extended and discuss also the events that did not generate tsunamis. Were there any false warnings or missed alarms? Would also be of help to present all this data in a table in relation with all the events.

Answer to comment #6

Section 4.3 is re-organized accordingly: 1) Alerts issued to the Hellenic and Aegean events by NOA and KOERI are mentioned in the text (sect 4.3); 2) Discussion of the possible false warnings or missed alarms after the events that did not cause tsunamis is introduced accordingly in the section 4.3; 3) A table with data on tsunami warning messages for all the studied events is created and inserted in the revised version of the manuscript.

Comment #7

Section 5 "Conclusions": Earthquake depth is an important factor – that is well known, but what about the shallow events that did not generate tsunamis?

"TWCs around the world have performed well" – further analysis and discussion (such as mentioned above) should be added in order to support this statement.

"In summary the present study can help on the compilation of global tsunami catalog as well as the characterization of tsunami decision matrixes for the various oceanic regions." Please explain more specifically how this could/should be done.

Answer to comment #7

Conclusions Section (Sect. 5) is re-worked according to the reviewer comments and the answers to all the referee questions are introduced in the revised version of the paper. The conclusion section became:

"This study is a contribution to a better understanding of the tsunami potential from large submarine earthquakes occurring worldwide. The study considered the preliminary parameters evaluated for the earthquake events and the tsunami recorded data and used source evaluation models together with tsunami modeling to investigate the tsunami potential. The analysis of 23 submarine earthquake events occurred worldwide with magnitudes ranging from Mw6.7 up to Mw8.1 leads to the following conclusions:

1. Significant number of events (39%) was tsunamigenic.

2. The earthquake depth and focal mechanism are important factors that control the tsunamigenic potential of seismic events.

3. For some events, in spite of the shallow depths and the relatively large earthquake magnitudes, no tsunami was generated.

4. Most tsunami events were caused by shallow earthquakes (depth <30km) and thrust faults that took place on/or near the subduction zones.

5. *Numerical modeling of tsunami is an important tool for wave amplitudes and tsunami travel time estimates and then relevant for any TWS, in spite of some limitations on source evaluation and bathymetric data.*

6. TWCs around the world have performed relatively well for the most analyzed cases as they provide first warning within 10 min for more than 78% of the tsunami events. However for some events "false alerts" were disseminated, in particular in the Mediterranean Sea (Mw 6.8 Hellenic and the Mw6.9 Aegean events) where the tsunami warning is mainly based on the use of a pre-defined decision matrix.

In summary the present study can help on the compilation of global tsunami catalog as well as the characterization of tsunami decision matrixes for the various oceanic regions. The analyzed events for which the tsunami generation is confirmed can be considered when compiling the tsunami catalog. Tsunami decision matrixes that are based only on limited earthquake parameters (magnitude, depth, and location) should be improved and revised in order to increase the number of the considered earthquake parameters taking into account the focal mechanism, for instance."

Comment #8

Technical corrections: The manuscript needs further editing in order to shorten the text and make it compact, clear mistakes and improve the language. Here are several examples only (in addition to the comments mentioned by reviewer #1):

P. 1862, line 20: Should be 'on' instead of "....is mainly dependent of the ..."?

P. 1863, Line 23: "Interpolate" (appears twice) – should be interplate and/or intraplate?

P. 1864, line 18: Should be "... sensors' records..." instead of "... sensors'records...".

P. 1864, line 6: ".... (tides gauges (TD) ...", Should be an even number of parenthesis ....;

P. 1864, line 9: Please add the web address of USGS earthquake database.

P. 1869, lines 15-16: Hellenic arc is in the Eastern side of the Mediterranean....

Answer to comment #8

All the technical corrections were considered.

References:

Heidarzadeh and Satake, 2014

Heidarzadeh, M., and Satake, K.: Possible sources of the tsunami observed in the northwestern Indian Ocean following the 2013 September 24 Mw 7.7 Pakistan inland earthquake. Geophysical Journal International, 199(2), 752-766, 2014.

Okada (1985)

Okada, Y.: Surface deformation due to shear and tensile faults in a half-space, Bull. Seismol. Soc. Am., 75(4), 1135–1154, 1985.

Tinti et al. 2012

Tinti, S., Graziani, L., Brizuela, B., Maramai, A., and Gallazzi, S.: Applicability of the Decision Matrix of North Eastern Atlantic, Mediterranean and connected seas Tsunami Warning System to the Italian tsunamis, Nat. Hazards Earth Syst. Sci., 12, 843-857, doi:10.5194/nhess-12-843-2012, 2012.

Saito and Furumura, 2009

Saito, T., and Furumura, T. : Three-dimensional tsunami generation simulation due to sea-bottom deformation and its interpretation based on the linear theory, Geophysical Journal International, 178(2), 877-888, 2009.