Nat. Hazards Earth Syst. Sci., 12, 2507–2514, 2012
www.nat-hazards-earth-syst-sci.net/12/2507/2012/
doi:10.5194/nhess-12-2507-2012

Natural Hazards and Earth System Sciences

Preface

"New Developments in Tsunami Science: from Hazard to Risk"

I. Didenkulova[1,2], S. Monserrat[3,4], and S. Tinti[5]

[1]Laboratory of Wave Engineering, Institute of Cybernetics, Tallinn University of Technology, Estonia
[2]Nizhny Novgorod State Technical University, Russia
[3]Instituto Mediterraneo de Estudios Avanzados, IMEDEA (UIB-CSIC), Palma de Mallorca, Spain
[4]Departament de Fisica, Universitat de les Illes Balears, Palma de Mallorca, Spain
[5]Dipartimento di Fisica e Astronomia, Università di Bologna, Italy

Correspondence to: S. Tinti (stefano.tinti@unibo.it)

1 Introduction

Tsunami science has progressed very quickly in recent years after the big catastrophic event of 26 December 2004 in the Indian Ocean, which called everybody's attention to the great impact tsunamis may have on society and natural environment; subsequently, initiated discussions, activities and research on all aspects of tsunamis, but especially on the tsunami consequences and the way they can be reduced. This Special Issue (SI) on tsunamis represents a collection of papers that were presented at the tsunami symposium organized by the European Geosciences Union (EGU) during the 2010 General Assembly (2–7 May 2010, Vienna), and forms a forum offered to specialists and researchers to illustrate the latest achievements in tsunami science especially in the chain that leads from hazard to risk: more precisely in the set of topics encompassing the evaluation of the tsunami hazard, the estimation of exposure and vulnerability, the assessment of risk and the planning and the implementation of tsunami early warning system and risk mitigation policies.

The papers of this SI can be classified as (i) fundamental aspects of the tsunami theory and analysis of tsunami events with examples covering an extensive time interval from ancient times up to recent days; (ii) tsunami hazard assessment: its methods and applications; (iii) evaluation of tsunami vulnerability, tsunami damage, and tsunami risk: their methods and applications; (iv) innovative tools for tsunami early forecast and warning system as of present and of the next generation.

2 Theory of tsunamis and analysis of tsunami cases

Even though the theory of tsunami wave propagation and generation is already well developed, some new analytical findings together with analysis of real tsunami cases are always current and bring us to a new level of understanding of tsunami phenomenon.

In this SI, Didenkulova et al. (2010), following the study by Tinti et al. (2001), present analytical solution of landslide induced tsunami wave generation and propagation for two specific convex bottom profiles $h \sim x^{4/3}$ and $h \sim x^4$. The process of the resonant generation of tsunami waves by landslides is studied using the asymptotic approach of a slowly varying depth along the power bottom profile $h \sim x^{\gamma}$. The main result here is that even for the landslide moving with the resonant speed, the wave amplitudes can remain bounded and even decrease at large distances.

Furthermore, several historical tsunamis are studied in detail. Torsvik et al. (2010) study the submarine volcanic explosion in the Karymskoye lake, Kamchatka, Russia representing the circular water body with a diameter of approximately 4 km and a maximum water depth of 60 m. Volcanic explosions in the lake occurred on 2–3 January 1996 and caused tsunami run-up around the entire coastline of the lake with a maximum run-up of 29 m near the source of eruption and 2–5 m run-up away from the source. The tsunami in the lake has been simulated within the weakly dispersive Boussinesq-type model COULWAVE using the realistic pre-eruption bathymetry of the lake and a tsunami source suggested by Le Mehaute (1971). Estimated results for wave run-up are of the same order of magnitude as field measurements, except for near the source of the eruption and at a

Published by Copernicus Publications on behalf of the European Geosciences Union.

few locations where analysis show significant wave breaking. Authors also revise the empirical formula by Le Mehaute and Wang (1996) for waves at some distance from the explosive source and find that the simulated waves are generally larger than the theoretical predictions, except for eastward propagation where there is good agreement between theoretical and simulated results.

Nicolsky et al. (2010) simulate a seiche wave, a landslide-generated tsunami and a tectonic tsunami in Whittier caused by the 1964 Alaskan $M_\mathrm{w} = 9.2$ megathrust earthquake. Their results are consistent with most of the eyewitness observations and interpretations by Kachadoorian (1965). They show that the city of Whittier was inundated shortly after the beginning of the ground shaking by local waves, triggered by the land displacement and multiple submarine slope failures. The computed inundations caused by the landslide-generated tsunami closely match the observations within the downtown area and depend on the landslide configuration and volume. They found that landslide complexes at the head and along the northern shore of the Passage Canal triggered the major tsunami with devastating run-up at Whittier. The tectonic tsunami wave arrived at Whittier about an hour after the earthquake. The height of the simulated tectonic tsunami was within the tidal range in Passage Canal, which explains the reason the tectonic wave was unnoticed by local residents.

Papadopoulos et al. (2011) examine data on tsunamis occurring in the Black Sea and the Azov Sea from antiquity up to the present based on historical documents. 22 events were classified as reliable, receiving a score of 3 or 4 on a 4-grade reliability scale. Most of the events were generated in Crimea, offshore Bulgaria and offshore North Anatolia. Most of them were caused by earthquakes, such as the key event of 544/545 AD offshore Varna, but a few others were attributed either to aseismic earth slumps or to unknown causes. Although these calculations were based on a very small statistical sample of tsunami events, the repeat times found are consistent with the theoretical expectations from size-frequency relations. This observation, along with the relatively low tsunami frequency, indicates that the tsunami hazard in the Black Sea is low to moderate but not negligible. The tsunami hazard in the Azov Sea is very low because of the very low seismicity but also because of the shallow water prevailing there. In fact, only three possible tsunami events have been reported in the Azov Sea.

A complimentary approach, which can give some additional information to the tsunami data collection and extend tsunami history beyond the historical record is the analysis of paleotsunami deposits. In this way Kortekaas et al. (2011) study evidences left by historical tsunamis in the coastal sedimentary record of the Gulf of Corinth in Kirra on the north coast and Aliki on the south coast. The geological record from Kirra shows four sand layers deposited by high-energy marine flooding events. The lower sand deposit (layer 4) was radiocarbon dated to 3020–2820 BC. Assuming an average sedimentation rate of 2.6 cm per hundred years, the ages of the other three sand layers were estimated by extrapolation to the time windows 1200–1000 BC, 500–600 AD and 1400–1500 AD. There are no historical tsunamis which correlate with layers 2 and 3. However, layer 1 may represent the major 1402 AD tsunami. At Aliki, no clear stratigraphical evidence of tsunami flooding was found, but results from foraminiferal and dating analyses show that a sand layer was deposited about 180 yr ago from a marine flooding event. This layer may be associated with the historical tsunami of 23 August 1817, which caused widespread destruction in the Aegion area.

3 Tsunami hazard assessment

The first studies on tsunami hazard assessment appeared already in early 70's and were linked to the development of the computer science, so that tsunami propagation over a real bathymetry could be simulated, and to the need to improve the existing tsunami warning systems: Pacific Tsunami Warning Center (PTWC) founded in 1949, following the 1946 Aleutian earthquake and tsunami, and West Coast and Alaska Tsunami Warning Center (WCATWC) founded in 1967, following the 1964 Alaskan earthquake and tsunami. This area of research started from assessment of tsunami inundation for Hawaii (Adams, 1973) and later spread into many other areas affected by tsunamis.

Presently, there are two most popular approaches for tsunami hazard evaluation: the worst-case credible tsunami scenario approach (e.g. Tinti et al., 2005a; Okal and Synolakis, 2008) and probabilistic tsunami hazard analysis (e.g. Tinti et al., 2005b; Geist and Parsons, 2006; Annaka et al., 2007; Grezio et al., 2010). The probabilistic tsunami hazard analysis starts from the analysis of all possible potential tsunami sources that are defined by the occurrence probability in the target area, then requires simulation of corresponding tsunamis and related inundations in the area for all sources, including smaller and larger ones, and ends with application of the probability theory in order to compute tsunami inundation probabilities corresponding to different return periods. The worst-case scenario approach focuses on the largest sources, computing the associated tsunamis and inundations produced in the target area. It involves much less computations, than the probabilistic tsunami hazard analysis, and results in the worst-case inundation map rather than in a probabilistic inundation map. Both approaches are extensively used and can be applied alternatively or complimentarily. In this SI the worst-case credible tsunami scenario approach is applied to two areas in the Mediterranean, namely the Mediterranean coast of the Iberian peninsula and the Balearic Islands (Álvarez-Gómez et al., 2011) and to the city of Catania, eastern Sicily, Italy (Tonini et al., 2011), and the city of Rabat and Salé in the Atlantic coast of Morocco (Renou et al., 2011).

Álvarez-Gómez et al. (2011) characterise the potential tsunamis generated by 22 seismic tsunamigenic sources close to the Iberian Peninsula in the Mediterranean in order to identify the most hazardous sources and the areas where the impact of tsunamis is greater. They show that sources on the western edge of North Algeria are the most dangerous, due to their threat to the southeastern coast of the Iberian Peninsula and to the western Balearic Islands. In general, the Northern Algerian sources pose a greater risk to the Spanish coast than the Alboran Sea sources, which only threaten the peninsular coast. On the Iberian Peninsula, the Spanish provinces of Almeria and Murcia are the most exposed, while all the Balearic Islands can be affected by the North Algerian sources with probable severe damage, especially the islands of Ibiza and Minorca.

The next two studies were conducted in the framework of the three-year SCHEMA European project (www.schemaproject.org). Tonini et al. (2011) evaluate tsunami hazard for the city of Catania, located in eastern Sicily, which is one of the most exposed to earthquakes and tsunamis regions in Italy, focusing on such important and actively used areas, as Catania harbour and a very popular beach called La Plaia. They consider five different scenarios suggested by tectonic considerations and the largest historical events that hit the city in the past, which in the end are combined into a unique aggregated worst-case virtual scenario. La Plaia beach results to be the area most exposed to tsunami inundation, with inland penetration up to hundreds of meters. The harbour turns out to be more exposed to tsunami waves with low frequencies: in particular, it is found that the major contribution to the hazard in the harbour is due to a tsunami from a remote source, which propagates with much longer periods than tsunamis from local sources.

Renou et al. (2011) focus on the Bouregreg Valley which is the area between Rabat (administrative capital of Morocco), and Salé, characterized by large population and new infrastructure development. They consider two tsunami scenarios: based on the historical Lisbon earthquake of 1755 and on the Horseshoe earthquake of 28 February 1969. The most affected areas are located west of Rabat and near El Jadida and Casablanca. At the local scale, the maximum water levels were lower than 2 m offshore along the Rabat and Salé coasts. The values did not exceed 1 m inside the estuary and decreased below 0.5 m only 1 km upstream from the estuary in the Bouregreg River.

The results obtained in these works are useful to plan future regional and local warning systems, as well as to set the priority areas to conduct research on detailed tsunami risk. We note here, that a paper by Atillah et al. (2011), which is a companion paper to Renou et al. (2011), is also published in this SI and applies the results of the work by Renou et al. (2011) to the elaboration of inundation and building damage maps, which are discussed in the next section.

4 Tsunami vulnerability and risk assessment

Vulnerability to tsunami attacks is a science that has grown very rapidly only in recent years, and that unfortunately was neglected for a long time, remaining a low-priority issue in tsunami science. On the contrary, research on seismic vulnerability, especially vulnerability of buildings and man-made structures, was always recognized to be a fundamental factor for reducing earthquake losses in terms of human lives and economic value, and was secured by stable funding and stable interest (for a review of the development of seismic vulnerability methods and algorithms in the last 30 yr see e.g. Calvi et al., 2006).

Before 2004 studies on tsunami vulnerability were quite few and it is worth mentioning that one of the first GIS-based methods to evaluate vulnerability to tsunami waves was devised in Europe, with application to the city of Heraklion in Crete by Papathoma et al. (2003). This model, named originally PTVA (Papathoma tsunami vulnerability assessment), was later modified and adapted to different urban, environmental and social conditions. Dall'Osso et al. (2010) make use of the version 3 of the PTVA model (i.e. PTVA-3), that was devised for coastal zones of Sidney, Australia. They apply it to Stromboli and Panarea, two islands of the Aeolian archipelago, Italy, that were affected by a tsunami on 30 December 2002 generated by two landslides falling about 7 min apart from the northwestern flank of the Stromboli volcano during a strong eruptive crisis (see Tinti et al., 2006). The 2002 event caused no fatalities, because there were almost no tourists on the islands when the tsunami occurred, but it caused severe damage to a number of buildings located on the water front and on the beach. Taking the 2002 case as the tsunami scenario for the analysis, Dall'Osso et al. (2010) are able to show that the relative vulnerability index (RVI) computed through the PTVA-3 model for each building in the inundation area is consistent with the damage the building suffered as the effect of the actual 2002 tsunami. This provides a good validation of the model and shows that it can be applied to other more severe tsunami scenarios involving the same area (e.g. tsunamis due to flank collapses), but also to other areas with the same building typology in southern Italy coasts.

The PTVA model and its variants belong to the category of models based on qualitative assessment. In practice, if we restrict to building vulnerability, a number of factors (attributes) are taken into account for each building (building material, number of storeys, hydrodynamics of the groundfloor, foundation type, preservation condition, number of underground levels, etc.) and for each of them a score is assigned. In a second phase these scores are manipulated to get the RVI of the building that ranges over 5-degrees from "very low" to "very high" vulnerability (see Dall'Osso et al., 2010). A different approach is based on the concept of damage or fragility functions, which is extensively used by seismic engineers (see e.g. Karim and Yamazaki, 2003) and has been extended to tsunami vulnerability analysis. This consists in establishing physical hydrodynamic variables (inundation depth, water currents, hydrodynamic forces, etc) and to determine the level of damage on buildings of different classes, where the classification is based on building attributes. In these studies, usually the main attribute is building material (wood, brick reinforced concrete, etc). For each variable, a curve is provided establishing the probability of damage (fragility curve) or the mean damage level (damage curve) for each value of the variable. The most common example is the curve related to the inundation depth, which is the parameter that can be better established from post-tsunami field surveys and from numerical inundation models (see Koshimura et al., 2009). Valencia et al. (2011) use this approach to develop new damage functions for the Euro–Mediterranean coasts. They use a database mainly formed by observations of the effect of the 2004 Indian Ocean tsunami taken in Banda Aceh, Indonesia (Leone et al., 2006, 2010) that was expanded and reanalysed also using satellite images. In the frame of the European project SCHEMA, Valencia et al. (2011) develop damage curves taking the inundation depth as the independent variable for 5 categories of buildings from class "A" (the most vulnerable, made of wood, single storey) to class "E" (the most resistant, well designed, made of reinforced concrete with columns and infill walls), and further assume that the same building classification and the same fragility curves can be also adopted for the Euro–Mediterranean region.

Damage curves by Valencia et al. (2011) were used for tsunami damage assessment in some selected coastal areas of Europe and northern Africa in the SCHEMA project, more precisely in Rabat area, Morocco; Setúbal, Portugal; Catania, Italy; Mandelieu, France; and Varna, Bulgaria. The adopted approach was based on the credible worst-case scenario technique, consisting of identifying the sources of the largest possible tsunamis for a given test site, computing tsunami inundation maps for each source, aggregating the results to produce a unique inundation map with the maximum floodable zone, and making inventories of valuable elements that may be affected (regarding buildings) in estimating damage with the aid of the damage curves (Tinti et al., 2011). In this SI, the work made on the sites of Rabat and of Setubal is illustrated respectively in the papers by Atillah at al. (2011) and by Ribeiro et al. (2011). Atillah et al. (2011) focus on the area of the two towns of Rabat and Salé, Morocco, that practically form a unique urban complex cut by the Bouregreg river and evaluate the damage associated with an aggregated flooding scenario (see the companion paper by Renou et al., 2011 in this SI) that is mostly dominated by the 1755 tsunami source. They find that the sectors of the urban agglomerate, where heavy damage is expected, are mainly located in the ancient medina and close to the river beach where more than 55 % of the buildings are in classes "A" and "B" and offer weak resistance to tsunami attack.

Even for the town of Setúbal, Ribeiro et al. (2011) find that the aggregated scenario is dominated by the scenario of the 1755 tsunami source. This tsunami that occurred on 1 November is the largest known event recorded in the north-eastern Atlantic and severely affected Portugal, Spain and Morocco. The earthquake and tsunami generated a big catastrophe also heavily affecting Lisbon, which at those times was the capital of one of the most powerful states of the world and documentation on the event is very abundant. In addition, Setúbal was inundated and the sea found a way through the collapsed town walls to penetrate by about half a mile in the town area (Mendonça, 1758). The town is located in the Sado estuary, whose mouth is partially closed by the long and flat Tróia peninsula, which, however, was found to be ineffective to protect Setúbal from tsunami waves. By using a high-resolution simulation model that discretizes the area of interest on grids up to 10 m and 2 m cell size, Ribeiro et al. (2011) compute the extent of the inundation area in downtown Setúbal, in the industrial harbour areas and in the touristic zone of Tróia. They find that old town administrative buildings, restaurants and warehouses can be severely affected by tsunami in the downtown area, but the highest expected damage is assessed in Tróia where all light constructions (class "A") can be completely destroyed by tsunami waves.

One of the main problems connected to estimates of infrequent events (hazard, vulnerability and risk) is their reliability, which can be even stated by using the key-word uncertainty. Gardi et al. (2011) address this issue trying to single out the nature and relevance of uncertainties in all the steps of the tsunami damage assessment process. Many uncertainties are due to the identification and characterization of the potential tsunami sources and to numerical models: results of tsunami simulations (especially flooding computations) are strongly influenced by the topo-bathymetric database used in the coastal belt. Uncertainty in the damage curves have been mainly due to the poor knowledge of the hydrodynamic field in the inundated zone, since post-tsunami field surveys often cannot provide more than scattered values of inundation depth. Moreover, a detailed inventory of the vulnerable elements can be prohibitive since big tsunamis affect very large areas, and so damage assessment has to be performed on partial or incomplete datasets. Listing all possible factors of uncertainties and enucleating the most influential on the final estimates is quite important since it may suggest how to improve the assessment process, and also how to interpret and to make the wisest use of the obtained results.

Megacities can be affected by tsunamis. The most relevant example in Europe is Istanbul, in the Marmara sea, that was affected by tsunamis in the past and that is under the threat of a possible large ($M > 7.0$) earthquake occurring in the Marmara branch of the North Anatolian Fault (Erdik et al., 2004). Considering the inundation area with the 10 % exceedance probability in 50 yr, resulting from tsunami hazards analysis, Hancilar (2012) make an inventory of all elements located in the area and therefore exposed to tsunamis attack. He makes use of GIS-based inventories of building stock, lifeline systems and demographic data not only for Istanbul city but also for the surrounding coastal areas in the Bosphorus channel and in the northeastern Marmara sea, including industrial facilities (40 % of Turkey industries are located here). Restricted to building stock and population, his study quantifies the assets exposed to tsunamis in 4922 buildings with an estimated economic value of 345 million Euros and about 32 000 people, which is quite significant. This is a preliminary step to assess vulnerability and risk.

Wegscheider et al. (2011) focus on small coastal communities rather than megacities. They apply their methodology to produce risk maps for three pilot areas in southern Bali, Indonesia, where about 20 000 people live under the threat of tsunamis. The risk, that regards persons and not properties, is graded on a scale from 1 to 13 and is determined by combining in a qualitative subjective way (through a decision tree) a number of factors including hazards probability, hazards intensity, population density and population capability. Interestingly, the reaction capability of people is assessed in terms of time factors, in particular comparing the evacuation time (i.e. the time needed for a person to reach a safe place) and the time available for evacuation (the time elapsing between the reception of the warning and the arrival of the tsunami). The method is easy to understand and implement on GIS platforms and is oriented to local communities, that is, it is conceived as a practical tool to devise and implement plans of emergency evacuation and of tsunami risk reduction.

5 Tsunami early warning system and their components

Tsunami warning systems (TWS) are complicated schemes which include a combination of an initial knowledge of the source, a subsequent alert validation based on sea level measurements of the generated tsunami (either by using open ocean gauges or coastal devices) and a final numerical computation to estimate expected arrival times, wave heights and run-ups for given coastal regions. This latter numerical approach may be based on running various nested models, with different resolution in the open ocean and the coastal zone, or on the use of previously pre-computed scenario databases for some given specific regions.

When the tsunami is generated by an earthquake, tsunami alert based on seismic data only is the quickest criterion to estimate expected tsunami properties at the coast, although it may lead to underestimations or false alerts, mainly because the experimental relationship between tsunami severity and earthquake magnitude is characterized by large standard deviations (Gusiakov, 2011), and also because actual run-ups are strongly dependent on coastal details (MacInnes et al., 2009). On the other hand, tsunamis which are not induced by earthquakes can be also quite disastrous and may affect the coast in a very similar manner, and these are not included in any tsunami alert based on seismic data only. Any warning system needs to be complemented by direct sea level measurements of the tsunami once generated. A simple visual inspection of sea level records may not be enough to provide a fast and reliable tsunami warning and the problem of using automatic detection algorithms is a subject of great importance nowadays.

A real-time algorithm to detect a tsunami (seismic or not seismic) from a single sea level station is presented and tested by Bressan and Tinti (2011). The algorithm, called TEDA (tsunami early detection algorithm) implements two distinct modules: the first devised to detect the presence of tsunami waves and the other to identify high amplitude long waves.The algorithm presented is tested using a coastal station installed in the harbour of Adak, in Adak Island, Alaska, USA.

The selection of a coastal station is intentional to stress the importance of coastal gauges in the tsunami warning. Although coastal stations could be of a limited use because the response time is normally considered too short for a reliable warning system, the authors give a number of reasons justifying the use of coastal stations in operational TWS. First, when the initial incoming wave is negative, the tsunami could be identified at the coast before actual flooding occurs. Second, because any coastal detection may be of use for other locations which are more remote to the tsunami source. Third, coastal stations are cheaper, more numerous and easier to maintain than open ocean gauges. And finally, many coastal tide gauges are already integrated in monitoring networks and are equipped with the necessary real-time transmission facilities to be easily implemented without great economic efforts. The method needs to be calibrated when used for any other location since its performance strongly depends on local conditions.

Deep sea tsunami monitoring systems, as DART stations (deep-ocean assessment and reporting of tsunami) maintained by the US National Oceanic and Atmospheric Administration (NOAA) are extremely useful for the purpose of detecting a tsunami once generated in the open ocean. It is possible to integrate real time DART measurements and state-of-the-art numerical modelling to create an effective tsunami forecasting system (Titov et al., 2005). One of these schemes has been implemented by the Pacific Marine Environmental Laboratory (PMEL/NOAA) and is based on pre-computed database including a great number of model runs for simulated earthquake sources in the Pacific, Atlantic and Indian oceans (Titov, 2009). Korolev (2011) suggests a method for short-term tsunami forecasting based on a reciprocity principle (Rayleigh, 1945; Loomis, 1979), which does not require any pre-computed wave form. According to Korolev, the method is capable to provide a real-time local warning for tsunamis by only using seismological information and in-situ data from one of the DART stations. The method is tested for 2006, 2007 and 2009 earthquakes events near

Simushir Island, at the Kuril Islands, finding good correlation coefficients between the predicted and observed tsunami waveforms (from 0.50 to 0.85). The method may be used for the entire ocean provided a real-time access to sea level data from a DART station is available and works for tsunamis of different source mechanisms (seismic, landslides or other phenomena).

Once the generated tsunami has been identified, numerical computation of its propagation is an important tool to predict wave heights and run ups. However, a single numerical model, calculating the tsunami propagation from the source to the coast, does not provide enough accurate results. Some nested methods, with different wave resolution, need to be proposed instead. Due to the high resolution required near the coast to properly forecast tsunami waves dynamics (less than 100 m grid steps), these nested models are difficult to implement. In order to overcome these difficulties, Choi et al. (2011) suggest the use of a 2-D shallow-water model for open ocean computations in combination with a 1-D long wave analytical model near the coast. The main advantage of the proposed method is that it provides a quicker forecast than complicated coastal inundation models. The authors test the model for a 1993 event in Korea showing that run-up estimations are in close agreement with observations.

Allen and Greenslade (2011) suggest to modify a previously published method for generating coastal tsunami warnings from model data used by the Joint Australian Tsunami Warning Centre. This previous method, described in Allen and Greenslade (2008), was based on the precomputed tsunami scenario database T1 (Greenslade et al., 2007), while the modified method is suitable to be applied to another improved pre-computed scenario database T2, described in Greenslade et al. (2009).

In recent years tsunami-like waves induced by atmospheric processes rather than by seismic sources have been widely considered in the literature (Monserrat et al., 2006). These waves, known as meteotsunamis, are normally much less energetic than seismic tsunamis, but if some combination of resonant factors takes place, they may affect coastal areas in a very similar manner and sometimes they have even been mistaken for seismic tsunamis in several catalogues. Šepić and Vilibić (2011) show that a combined network, including atmospheric sensors and tide gauges, deployed in the Adriatic can be of use in the early detection of meteotsunamis. As meteotsunami potential danger is clearly linked to the atmospheric disturbance generating it, the monitoring network should consists of a combination of microbarograph meteorological stations and tide gauge stations. The atmospheric network should include at least three microbarographs allowing the detection of both speed and direction of propagation of the atmospheric disturbance (Monserrat and Thorpe, 1992; Šepić et al., 2009). The meteotsunami propagation has been rather complicated as compared with seismic tsunamis, since the former are continuously forced by the atmospheric perturbation as they travel as long waves in the ocean. Meteotsunamis propagate then as forced waves in opposition to seismic tsunamis which behave as free waves. Despite the relatively complex behaviour of meteotsunami propagation, the network proposed by Sepic and Vilibic (2011) seems to work reasonably for meteotsunami forecast in the Adriatic.

References

Adams, W. M.: Expected tsunami inundation for Hawaiian Islands, Mar. Technol. Soc. J., 7, 29–34, 1973.

Allen, S. C. R. and Greenslade, D. J. M.: Developing tsunami warnings from numerical model output, Nat. Hazards, 46, 35–52, 2008.

Allen, S. C. R. and Greenslade, D. J. M.: Model-based tsunami warnings derived from observed impacts, Nat. Hazards Earth Syst. Sci., 10, 2631–2642, doi:10.5194/nhess-10-2631-2010, 2010.

Álvarez-Gómez, J. A., Aniel-Quiroga, Í., González, M., and Otero, L.: Tsunami hazard at the Western Mediterranean Spanish coast from seismic sources, Nat. Hazards Earth Syst. Sci., 11, 227–240, doi:10.5194/nhess-11-227-2011, 2011.

Annaka, T., Satake, K., Sakakiyama, T., Yanagisawa, K., and Shuto, N.: Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts, Pure Appl. Geophys., 164, 577–592, 2007.

Atillah, A., El Hadani, D., Moudni, H., Lesne, O., Renou, C., Mangin, A., and Rouffi, F.: Tsunami vulnerability and damage assessment in the coastal area of Rabat and Salé, Morocco, Nat. Hazards Earth Syst. Sci., 11, 3397–3414, doi:10.5194/nhess-11-3397-2011, 2011.

Bressan, L. and Tinti, S.: Structure and performance of a real-time algorithm to detect tsunami or tsunami-like alert conditions based on sea-level records analysis, Nat. Hazards Earth Syst. Sci., 11, 1499–1521, doi:10.5194/nhess-11-1499-2011, 2011.

Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Vélez, L. F., and Crowley, H.: Development of seismic vulnerability assessment methodologies over the past 30 years, ISET J. Earthq. Technol., 43, 75–104, 2006.

Choi, B. H., Kaistrenko, V., Kim, K. O., Min, B. I., and Pelinovsky, E.: Rapid forecasting of tsunami runup heights from 2-D numerical simulations, Nat. Hazards Earth Syst. Sci., 11, 707–714, doi:10.5194/nhess-11-707-2011, 2011.

Dall'Osso, F., Maramai, A., Graziani, L., Brizuela, B., Cavalletti, A., Gonella, M., and Tinti, S.: Applying and validating the PTVA-3 Model at the Aeolian Islands, Italy: assessment of the vulnerability of buildings to tsunamis, Nat. Hazards Earth Syst. Sci., 10, 1547–1562, doi:10.5194/nhess-10-1547-2010, 2010.

Didenkulova, I., Nikolkina, I., Pelinovsky, E., and Zahibo, N.: Tsunami waves generated by submarine landslides of variable volume: analytical solutions for a basin of variable depth, Nat. Hazards Earth Syst. Sci., 10, 2407–2419, doi:10.5194/nhess-10-2407-2010, 2010.

Erdik, M., Demircioglu, M., Sesetyan, K., Durukal, E., and Siyahi,B.: Earthquake hazard in Marmara Region, Turkey, Soil Dyn. Earthq. Eng., 24, 605–631, 2004.

Gardi, A., Valencia, N., Guillande, R., and André, C.: Inventory of uncertainties associated with the process of tsunami damage assessment on buildings (SCHEMA FP6 EC co-funded project), Nat. Hazards Earth Syst. Sci., 11, 883–893, doi:10.5194/nhess-11-883-2011, 2011.

Geist, E. and Parsons, T.: Probabilistic analysis of tsunami hazards, Nat. Hazards, 37, 277–314, 2006.

Grezio, A., Marzocchi, W., Sandri, L., and Gasparini, P.: A Bayesian procedure for Probabilistic Tsunami Hazard Assessment, Nat. Hazards, 53, 159–174, 2010.

Greenslade, D. J. M., Simanjuntak, M. A., Burbidge, D., and Chittleborough, J.: A first generation real-time tsunami forecasting system for the Australian Region, Bureau of Meteorology, Melbourne, Australia, BMRC Research Report No. 126, 75 pp., 2007.

Greenslade, D. J. M., Simanjuntak, M. A., and Allen, S. C. R.: An enhanced tsunami scenario database: T2, Bureau of Meteorology, Melbourne, Australia, CAWCR Technical Report No. 014, 30 pp., 2009.

Gusiakov, V. K.: Relationship of tsunami intensity to source earthquake magnitude as retrieved from historical data, Pure Appl. Geophys., 168, 2033–2041, 2011.

Hancilar, U.: Identification of elements at risk for a credible tsunami event for Istanbul, Nat. Hazards Earth Syst. Sci., 12, 107–119, doi:10.5194/nhess-12-107-2012, 2012.

Kachadoorian, R.: Effects of the earthquake of March 27, 1964, at Whittier, Alaska, US Geol. Surv. Prof. Paper 542-B, B1–B21, 3 sheets, scale 1:4800, 1965.

Karim, K. R. and Yamazaki, F.: A simplified method of constructing fragility curves for highway bridges, Earthq. Eng. Struct. Dynam., 32, 1603–1626, 2003.

Korolev, Yu. P.: An approximate method of short-term tsunami forecast and the hindcasting of some recent events, Nat. Hazards Earth Syst. Sci., 11, 3081—3091, doi:10.5194/nhess-11-3081-2011, 2011.

Kortekaas, S., Papadopoulos, G. A., Ganas, A., Cundy, A. B., and Diakantoni, A.: Geological identification of historical tsunamis in the Gulf of Corinth, Central Greece, Nat. Hazards Earth Syst. Sci., 11, 2029–2041, doi:10.5194/nhess-11-2029-2011, 2011.

Koshimura, S., Oie, T., Yanagisawa, H., and Imamura, F.: Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia, Coast. Eng. J., 51, 243–273, 2009.

Le Mehaute, B.: Theory of explosion-generated water waves, in: Advances in Hydroscience, edited by: te Chow, V., Academic Press, New York, London, 7, 1–79, 1971.

Le Mehaute, B. and Wang, S.: Water Waves Generated by Underwater Explosion, in: Advanced Series on Ocean Engineering – Volume 10, World Scientific, 1996.

Leone, F., Denain, J. C., Vinet, F., Bachri, S.: Analyses partiale des dommages au bâti de Banda Aceh (Sumatra, Indonèsie): contribution à la connaissance du phènomène et àl' èlaboration de scènarios de risque tsunami in: Scientific internal report of TSUNARISQUE programm (2005–2006), Dèlègation Interministérielle pour l'aide Post-Tsunami (DIPT), consortium franco-indonèsien, 306 pp., 2006.

Leone, F., Lavigne, F., Paris, R., Denain, J.-C., and Vinet, F.: .: A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability, Appl. Geogr., 31, 363–375, 2010.

Loomis, H. G.: Tsunami prediction using the reciprocal property of Green's functions, Mar. Geodesy, 2, 27–39, 1979.

MacInnes, B. T., Pinegina, T. K., Bourgeois, J., Razhigaeva, N. G., Kaistrenko, V. M., and Kravchunovskaya, E. A.: Field survey and geological effects of the 15 November 2006 Kuril tsunami in the middle Kuril Islands, Pure Appl. Geophys., 166, 9–36, 2009.

Mendonça, J. M.: História Universal dos Terramotos, que tem havido no mundo de que há notícia, desde a sua criação até o século presente, Biblioteca Nacional de Lisboa, Portugal, 272 pp., 1978.

Monserrat, S. and Thorpe, A. J.: Gravity-wave observation using an array of microbarographs in the Balearic Islands, Q. J. Roy. Meteor. Soc., 118, 259–282, 1992.

Monserrat, S., Vilibić, I., and Rabinovich, A. B.: Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band, Nat. Hazards Earth Syst. Sci., 6, 1035–1051, doi:10.5194/nhess-6-1035-2006, 2006.

Nicolsky, D. J., Suleimani, E. N., and Hansen, R. A.: Numerical modeling of the 1964 Alaska tsunami in western Passage Canal and Whittier, Alaska, Nat. Hazards Earth Syst. Sci., 10, 2489–2505, doi:10.5194/nhess-10-2489-2010, 2010.

Okal, E. A. and Synolakis, C. E.: Far-field tsunami hazard from mega-thrust earthquakes in the Indian Ocean, Geophys. J. Int., 172, 995–1015, 2008.

Papadopoulos, G. A., Diakogianni, G., Fokaefs, A., and Ranguelov, B.: Tsunami hazard in the Black Sea and the Azov Sea: a new tsunami catalogue, Nat. Hazards Earth Syst. Sci., 11, 945–963, doi:10.5194/nhess-11-945-2011, 2011.

Papathoma, M., Dominey-Howes, D., Zong, Y., and Smith, D.: Assessing tsunami vulnerability, an example from Herakleio, Crete, Nat. Hazards Earth Syst. Sci., 3, 377–389, doi:10.5194/nhess-3-377-2003, 2003.

Rayleigh Lord (Strutt, J. W.): The Theory of Sound, Vol. 2, Dover, New York, 1945.

Renou, C., Lesne, O., Mangin, A., Rouffi, F., Atillah, A., El Hadani, D., and Moudni, H.: Tsunami hazard assessment in the coastal area of Rabat and Salé, Morocco, Nat. Hazards Earth Syst. Sci., 11, 2181–2191, doi:10.5194/nhess-11-2181-2011, 2011.

Ribeiro, J., Silva, A., and Leitão, P.: High resolution tsunami modelling for the evaluation of potential risk areas in Setúbal (Portugal), Nat. Hazards Earth Syst. Sci., 11, 2371–2380, doi:10.5194/nhess-11-2371-2011, 2011.

Šepić, J. and Vilibić, I.: The development and implementation of a real-time meteotsunami warning network for the Adriatic Sea, Nat. Hazards Earth Syst. Sci., 11, 83–91, doi:10.5194/nhess-11-83-2011, 2011.

Šepić, J., Denis, L., and Vilibić, I.: Real-time procedure for detection of a meteotsunami within a nearly tsunami warning system, Phys. Chem. Earth, 34, 1023–1031, 2009.

Tinti, S., Armigliato, A., Pagnoni, G., and Zaniboni, F.: Scenarios of giant tsunamis of tectonic origin in the Mediterranean, ISET J. Earthq. Techn., 42, 171–188, 2005a.

Tinti, S., Armigliato, A., Tonini, R., Maramai, A., and Graziani, L.: Assessing the Hazard related to tsunamis of tectonic origin: a hybrid statistical-deterministic method applied to southern Italy coasts, ISET, J. Earthq. Techn., 42, 189–201, 2005b.

Tinti, S., Bortolucci, E., and Chiavettieri, C.: Tsunami excitation by submarine slides in shallow-water approximation, Pure Appl. Geophys., 158, 759–797, 2001.

Tinti, S., Maramai, A., Armigliato, A., Graziani, L., Manucci, A., Pagnoni, G., and Zaniboni, F.: Observations of physical effects from tsunamis of December 30, 2002 at Stromboli volcano, southern Italy, B. Volcanol., 68, 450–461, 2006.

Tinti, S., Tonini, R., Bressan, L., Armigliato, A., Gardi, A., Guillande, R., Valencia, N., and Scheer, S.: Handbook of tsunami hazard and damage scenarios, JRC Scientific and Technical Reports, 41 pp., doi:10.2788/21259, 2011.

Titov, V. V.: Tsunami forecasting, in: The Sea, edited by: Bernard, E. N. and Robinson, A. R., Harvard University Press, Cambridge, 15, 367–396, 2009.

Titov, V. V., González, F. I., Bernard, E. N., Eble, M. C., Mofjeld, H. O., Newman, J. C., and Venturato, A. J.: Real-time tsunami forecasting: challenges and solutions, Nat. Hazards, 35, 35–41, 2005.

Tonini, R., Armigliato, A., Pagnoni, G., Zaniboni, F., and Tinti, S.: Tsunami hazard for the city of Catania, eastern Sicily, Italy, assessed by means of Worst-case Credible Tsunami Scenario Analysis (WCTSA), Nat. Hazards Earth Syst. Sci., 11, 1217–1232, doi:10.5194/nhess-11-1217-2011, 2011.

Torsvik, T., Paris, R., Didenkulova, I., Pelinovsky, E., Belousov, A., and Belousova, M.: Numerical simulation of a tsunami event during the 1996 volcanic eruption in Karymskoye lake, Kamchatka, Russia, Nat. Hazards Earth Syst. Sci., 10, 2359–2369, doi:10.5194/nhess-10-2359-2010, 2010.

Valencia, N., Gardi, A., Gauraz, A., Leone, F., and Guillande, R.: New tsunami damage functions developed in the framework of SCHEMA project: application to European-Mediterranean coasts, Nat. Hazards Earth Syst. Sci., 11, 2835–2846, doi:10.5194/nhess-11-2835-2011, 2011.

Wegscheider, S., Post, J., Zosseder, K., Mück, M., Strunz, G., Riedlinger, T., Muhari, A., and Anwar, H. Z.: Generating tsunami risk knowledge at community level as a base for planning and implementation of risk reduction strategies, Nat. Hazards Earth Syst. Sci., 11, 249–258, doi:10.5194/nhess-11-249-2011, 2011.