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Discussions

Assessment of tsunami hazard for the American Pacific coast from southern Mexico to northern Peru

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Abstract

Central America has been struck by at least 49 tsunamis between 1539 and 1996. As many as 37 of these events occurred at the Pacific Coast, and 31 were generated by earthquakes. Some of the events have been destructive, but despite this, tsunamis are an underrated hazard in Central America: people are not aware that they are at risk and even recent tsunami events have been forgotten. Recent studies, following the destructive tsunami occurred in Nicaragua in 1992, have revealed that Central America is a moderately tsunamigenic zone that is mainly affected by tsunamis triggered by earthquakes, especially at the Pacific coast where the Middle American Trench runs parallel to the coast. In this study, a statistical first and then a deterministic analysis for the Pacific coast of Central America has been carried out. The statistical approach aims to estimate the Gutenberg-Richter coefficients of the main seismic tsunamigenic regions of the area in order to assess the annual rate of occurrence of tsunamigenic earthquakes and their corresponding return period. A deterministic approach is then used to compute the tsunami run-up distribution along the coast corresponding to a given annual rate of occurrence of tsunamigenic earthquakes.

1 Introduction

Central America is located at the southernmost isthmian portion of the North American continent, its main land lays on the North American Plate and on the Caribbean Plate whereas its Pacific coast runs parallel to the Middle American Trench, where the Cocos Plate subducts beneath the Caribbean Plate and the Nazca Plate subducts beneath the South American Plate. The region covers an area of approximately 524 000 km^2 and its population is about 40.5 million people.

Earthquakes, landslides, mudslides and hurricanes are among the most known natural hazards. Tsunamis, on the other hand, are not considered a major hazard in Central America, people are not aware that they could be at risk and even recent tsunami

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events that occurred in the area have been forgotten. Despite this, recent studies have established that tsunamis generated along the Central American coasts can be moderate at regional scale (Fernandez et al., 2004) but can also be significantly destructive at local scale (Alvarez-Gomez et al., 2012). The latter fact is indeed confirmed by the 2012 tsunami occurred in El Salvador. According to the preliminary report by the Salvadoran authorities, on the 26 August 2012, an $M = 6.7$ earthquake occurred offshore the coast of Usulutan (southern El Salvador) triggering a local tsunami that propagated perpendicularly from its source, the waves penetrated 300m inland and had a run-up of 2.3 m at Isla de Mendez. Due to the fact that the affected area was not densely populated, the tsunami did not cause any victims, and damage was observed only on poorly built huts used by fishermen. The tsunami effects on the ground were observed and described by fishermen that were working in the zone when the flooding occurred (MARN, http://www.marn.gob.sv/phocadownload/Presentacion_Tsunami_%20ES.pdf).

The most recent destructive event was the 2 September 1992 offshore the Nicaraguan coast. The run-up values measured at that time varied between 2 and 7 m, leaving about 170 fatalities and 13 000 homeless. This event has led to several studies including the compilation of a tsunami catalogue for the region and some empirical, statistical and deterministic tsunami assessments, and has also increased the tsunami awareness of the authorities (Satake et al., 1993). The studies performed after 1992 revealed that the Pacific coast of Central America is prone to be hit by tsunami waves triggered mainly by earthquakes; nevertheless, local tsunami warning systems have not been implemented in the region. The need of setting tsunami early warning systems to save lives in case of tsunami has been reaffirmed in recent years by disastrous and major tsunamis, i.e. the 2004 Indian Ocean tsunami, the 29 September 2009 Samoan tsunami and the 27 February 2010 Chilean tsunami, not to mention the catastrophic 11 March 2011 tsunami in Japan.

In this paper, an assessment of the tsunami hazard along the Pacific coast of Central America is performed through a hybrid probabilistic-deterministic analysis, following a method that was first introduced for the Italian coasts by Tinti (see Tinti, 1991a,

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b; see also El Alami and Tinti, 1991). The statistical approach aims to estimate the Gutenberg-Richter (GR) coefficients of the main seismic tsunamigenic regions of the area in order to evaluate the annual rate of occurrence of tsunamigenic earthquakes and their corresponding return period. A deterministic analysis is used to compute the tsunami run-up distribution along the coast corresponding to a given annual rate of occurrence of a tsunamigenic earthquake.

In order to establish the framework of this analysis, the paper contains a brief summary of the geotectonics and seismicity of the area of study, a detailed description of the Central American Tsunami Catalogue, and also the tsunamigenic potential of the surrounding coastal areas, belonging to Mexico, Colombia and Ecuador. In the second stage, the paper focuses on the seismic catalogues available for the area of study, and the data chosen to perform the statistical analysis. The aim of the statistical approach is to estimate, through the GR law, the number of events exceeding a threshold magnitude value for the zones under analysis. This estimation will be then used in the deterministic analysis to estimate the run-up values expected along the Pacific Central American coast.

2 Geotectonics and seismicity of the studied area

Geologically speaking, Central America can be divided in northern and southern Central America. Guatemala, Honduras, El Salvador and northern Nicaragua can be included in the northern portion, whereas southern Nicaragua, Costa Rica and Panama are considered the southern portion. Northern Central America has a continental style crust and it contains Palaeozoic or older rocks and sediments from the upper Palaeozoic, the Mesozoic and the Tertiary. A Cretaceous type crust composes the southern portion, and it has on top thick marine and tertiary volcanic sediments. This portion is, at the moment, a transition zone from pure oceanic to continental crust (Bommer and Rodriguez, 2002).

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The Pacific coast of Central America runs parallel to the Middle America Trench, which is the zone where the Cocos plate subducts beneath the Caribbean plate. It has been established that the incoming plate along the Middle America trench was formed at similar ages although its morphology changes dramatically along the strike. The region is characterised by a smooth slope at the Nicaraguan coast, a very steep slope in Guatemala and a transition zone along the Salvadoran coast. The smooth slope is built of en-echelon terraces, whereas the steep slope contains several canyons and gullies. The transition zone can be described as rough terrain variable in width (Ranero et al., 2004). Figure 1 shows approximate locations of tectonic plate boundaries in Central America proposed by Bird (2003).

There are basically three seismogenic sources in northern Central America. First the Cocos-Caribbean subduction zone, that produces the largest earthquakes in the region, and the Cocos-North American convergence zone. Second the North America-Caribbean interaction zone, and third the upper crust seismicity along the quaternary volcanoes. Southern Central America's seismicity is due to the interaction of four main tectonic plates and several microplates at their boundaries (Bommer and Rodriguez, 2002).

The subduction zone of Central America can be classified as an intermediate stage between the *Mariana* and the *Chilean* style subduction zones. It has a steep dip that shallows from southern Nicaragua to northern Guatemala and the overriding zone (the Caribbean Plate) is slightly extensional (Dewey et al., 2004).

Recent research has established the plate kinematics schemes of Central America through the use of GPS observations. The North American plate moves to the south-west at rates of about 21 $\mathrm{mm\,yr^{-1}}$, whereas the Caribbean plate moves at about 9 $\mathrm{mm\,yr^{-1}}$ to the south-east and the Cocos plates moves northeastward at approximately 70 $\mathrm{mm\,yr^{-1}}$. The Cocos-Caribbean and North American junctions are not an ideal stable triple junction, the Cocos Plate seems to be mechanically stronger than the North American and Caribbean plates and as a consequence the roll-back of Cocos plate's slab is continuous along the Middle American Trench, which also means

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that the forearc motion must be also continuous along the junction (Phipps Morgan et al., 2008).

At the Caribbean coast, Northern Central America's geomorphology is characterised by sierras formed of several sub-parallel ranges, composed of metamorphosed deposits, separated by faults and grabens. At the Pacific coast, volcanic ranges and plateaus are located in Nicaragua, El Salvador and parts of Honduras and southwest Guatemala (Bommer and Rodriguez, 2002).

2.1 Tsunamis in Central America

The 1992 Nicaraguan tsunami highlighted the need of studying these phenomena in the Central American area. Several studies have been conducted with the aim of establishing the tsunamicity in the region. The 1992 event was very destructive along the Pacific Nicaraguan coast, but caused no damage in the rest of the Central American countries. This might have contributed to the little awareness of the rest of the Central American population regarding to tsunami hazard.

Several studies established that Central America is a moderate tsunamigenic region (Fernandez et al., 2000; Alvarez-Gomez et al., 2012) where destructive tsunamis have been reported and that all countries are likely to be hit by tsunami waves in the future. The studies have also shown that the Caribbean coast is less tsunamigenic than the Pacific coast. At the Pacific coast, preliminary tsunami hazard estimation were performed in 2000 by the Centro de Investigaciones Geofísicas (CIGEFI) de la Universidad de Costa Rica, the Red Sismológica Nacional (RSN: ICE-UCR), the Instituto de Sismología, Vulcanología, Hidrogeología y Meteorología de Guatemala and the Institute of Solid Earth of the University of Bergen, Norway. It has been found that Nicaragua, El Salvador, and Honduras are the most prone coasts to be hit by tsunamis. Numerical simulations were also carried out in 2004 by the Central American Seismological Centre (CASC), the Centro de Investigación Cientifica y Educación Superior de Ensenada (CICESE) and the Escuela Centroamericana de Geología de la Universidad de Costa Rica in order to study historical tsunamis.

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Alvarez-Gomez et al. (2012) established the contribution of the outer-rise normal earthquakes to the tsunamigenic potential of the Pacific coast of Central America revealing that the seismicity generated by the outer-rise faults might have been related to tsunamigenic earthquakes. Numerical simulations by the same authors found out that the outer-rise seismicity could trigger tsunamis whose run-up values might vary from 2 to 5 m, propagating locally and affecting several hundreds of kilometres along the coastal areas.

The Central America tsunami catalogue compiled by Molina (1997) contains 50 events that occurred between 1539 and 1996 in a geographical window from 6° to 18° N and 93° to 77° W. Information for each event includes date, earthquake source parameters, tsunami parameters and tectonic region of the source. Maps of the region struck by the tsunami and the triggering earthquake epicentres are commonly shown, and in some cases, figures regarding macroseismicity are also included. Thirty-six events are well documented, whereas, according to the author, 9 events have a low reliability and might have not occurred.

Earthquakes triggered almost all of those tsunamis except two that were supposed to be seiches in the Nicaraguan lake and a tsunami caused by volcanic lahars at northern Nicaraguan coast.

The catalogue was divided in three main time periods that correspond to the XVI–XVIII, the XIX and the XX centuries. Only 4 tsunamis were reported in the first period, whereas 11 and 35 events were reported in the XIX and XX centuries. The tsunamis compiled in the catalogue have magnitudes varying between 0 and 2.5 according to the Imamura-Iida scale and the damage reported describe destruction of small ships, coastal infrastructure and sometimes destruction of small villages.

As many as 38 of the tsunamis reported in the catalogue occurred in the Pacific coast whereas 12 were reported in the Caribbean coast (Molina, 1997). Six of the tsunamis registered at the Pacific were associated to an unknown cause, the rest were associated to earthquakes that occurred at the Cocos-Caribbean subduction zone, Panama fracture zone, North American-South American plates boundary or due to

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shallow faults. All of the tsunamis observed at the Caribbean coast were associated to earthquakes (Fernandez, 2000). Tsunamis associated with submarine landslides, terrestrial landslides or volcanic eruptions have not been reported in the area. Submarine eruptions are not a possible tsunamigenic source in the region, because there are no active submarine volcanoes in the area. However, it is possible that one of the inland volcanoes located in Nicaragua (i.e. the Cosigüina Volcano) triggered tsunamis (M. Fernández, personal communication, 2006).

In order to have a better picture of the tsunamigenic activity of the studied area, events that have occurred along the Pacific coasts of Mexico, Colombia and Ecuador were added to the Central American tsunami Catalogue. The information for those events was taken from the NOAA/NGDC (National Oceanic Atmospheric Administration/National Geophysical Data Center) tsunami event runup database (http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=167&d=166).

According to Singh et al. (2008), there have been several moderate tsunamigenic earthquakes along the Pacific Coast of Mexico in the last century. They have mainly triggered local tsunamis of limited extent, but there is also evidence of the occurrence of a much larger event along the coast of Oaxaca on the 28 March 1787. The description of such event by Suárez and Albini (2009) suggests a sea withdrawal of over 4km followed by a flood of about 6 km near the Alotengo Lagoon. The waves also transported inland some fish and shellfish at Pochutla (nowadays Puerto Angel) and also at the coastal area south of the city of Tehuantepec. Farreras and Sanchez (1991) believe that historic accounts of the last three centuries prove that locally generated tsunamis pose a significant threat to the southwestern coast of Mexico and Central America.

Moving southwards off Central America, the interaction zone between the North Andes and the Nazca Plates is very active, specially the coastal area belonging to Colombia and northern Ecuador. During the last century four major earthquakes occurred in this zone in 1906, 1942, 1958 and 1979, and they all triggered destructive tsunamis (Restrepo and Otero, 2007). The 12 December 1979, an $M_w = 7.9$ earthquake occurred at the Ecuador-Colombian boundary, generated a tsunami that caused light damage

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in Ecuador but was very destructive along the Colombian coast (Espinoza, 1992). The death toll between the earthquake and the tsunami was 452 victims. The waves hit the coastal area from Tumaco to Guapi. The Island of San Juan, located 60 km north from Tumaco, was the most severely affected area and was completely destroyed by the tsunami. The Island of Guano was completely vanished after the flooding, whereas at north-western Tumaco local floodings were reported (Restrepo and Otero, 2007). In Fig. 2 the events reported in the Central American tsunami catalogue and those from the NOAA/NGDC Tsunami Event and Runup Database are shown.

Given that the number of events contained in the Central American tsunami catalogue is not large enough to perform a reliable statistical analysis and also considering that tsunamis in Central America are mainly triggered by earthquakes, it has been decided that earthquake catalogues are going to be used to perform the statistical analysis.

3 Statistical analysis of a suitable earthquake catalogue

There are several earthquake catalogues that contain events registered in Central America (see Table 1). Some of these catalogues cover small areas of Central America, while some others contain only recent events or only events with high magnitude. Epicenters of the earthquake catalogues that were available for our study have been plotted in Fig. 3.

A brief description of some of the catalogues contained in Table 1 are presented in the following. The catalogue compiled by Leeds (Leeds, 1974) contains 399 events that occurred between 1520 and 1973 with magnitude varying from 3.7 to 7.7. The catalogue covers Nicaragua only. The Ambraseys–Adams catalogue contains about 1800 events that occurred in Central America from 1898 to 1995, the magnitude values (M_s) varying from 3 to 7.9 (Ambraseys and Adams, 2000). The catalogue compiled by Singh et al. (1984) contains 31 shallow events with magnitudes between 7 and 8.4. The "National Oceanic and Atmospheric Administration" (NOAA-USA) cata-

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logue contains about 1400 events that occurred from 1471 to 2008. The magnitude range goes from 1.6 to 9.5 and covers the whole American continent. The catalogue compiled by the "Centro Regional de Sismologia para America del Sur" (CERESIS, http://www.ceresis.org/portal/catal_hipo.php) contains more than 1000 events that occurred in South America. The Mexico noticeable earthquake catalogue contains 181 events, whose magnitude varies between 6.4 and 8.2. Last, but not least, the Mexico SSN (SSN, Servicio Sismologico Nacional, http://www.ssn.unam.mx/) catalogue contains about 9400 events from 1998 to 2008, with magnitude range from 2.3 to 7.6.

The earthquake catalogue selected to carry out the analysis is the Ambraseys and Adams (2000) catalogue (hereafter called the AMB-AD catalogue), given that it is a specific study of the seismicity of Central America, it has a large number of events with specified magnitude values and covers the whole Central American area.

In order to increase the number of events contained in the AMB-AD catalogue, and also to cover a larger temporal and spatial window, the NOAA catalogue events were added. The NOAA events falling within the area of study were selected and if one event was found to be contained in both catalogues, generally the NOAA event was deleted. Events with depth greater than 100 km were removed, given that they are unlikely to cause tsunamis. Following this procedure, a catalogue Ambraseys-Adams-NOAA (from now on AMB-AD-NOAA catalogue) was produced (see Fig. 4) containing 1931 events that took place from 1530 to 2012 with the purpose to use it in this research.

3.1 MOTIVATION for the study

A statistical analysis of the AMB-AD-NOAA catalogue was performed aiming to estimate the annual rate of occurrence of earthquakes with magnitude higher than a given value M, that is the so-called cumulative rate. The AMB-AD-NOAA catalogue was divided into six zones, considering their geographical location and the probable tectonic unit related to the earthquake. The first zone covers the Pacific coast of southern Mexico, the second zone extends along the Pacific coast from southern Mexico to Panama, the third zone covers the Atlantic coast from southern Mexico to Panama, the forth

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zone goes from southern Panama to the Pacific coast of Ecuador, the fifth zone covers the Atlantic coast of Venezuela and the lesser Antilles and the sixth zone covers Cuba and the Antilles (see Fig. 5). Events within zones 1, 2 and 4 are related to the subduction zone of the Middle American Trench, whereas events within zone 3, 5 and 6 are related to the deformed belt of North Panama or the deformed belt of the southern Caribbean.

Zone 2 has the largest number of events. Zones 3, 5 and 6 have a small number of earthquakes and belong to the Atlantic region, and therefore they are not taken into account in this study.

A completeness analysis based on a method introduced by Albarello et al. (2001) was applied to the AMB-AD-NOAA earthquake catalogue in the zones 1, 2 and 4. The method consists of the following steps. First, one establishes magnitude classes depending on the magnitude distribution of the historical events, and in each class counts all those events whose magnitude is within the bound limits of the class. Magnitude frequencies are given in Fig. 6.

Second, per each magnitude class one divides the time axis in intervals of 50 or 20 yr, depending on the catalogue time length of each zone; and plots the number of events occurring in each time interval in complementary cumulative graphs. Finally those time intervals that fit a trend defined by a straight line going to zero at the present time are considered as complete. The completeness periods for each zone are shown in Figs. 7, 8 and 9 for some of the magnitude classes.

Having performed the completeness analysis, the GR coefficients were computed for each zone. The traditional cumulative GR magnitude-frequency law has the following expression

$$\mathrm{Log}N = a - bM \tag{1}$$

where N is the expected number of events with magnitude larger then M, a and b are coefficients that are constant for a seismic homogeneous zone. The parameter a is associated with the seismic activity of a particular region, whereas b is the power-law exponent of scaling.

The above GR equation has been modified in order to account for the maximum possible magnitude that may occur within each zone and that is assumed to be larger than the maximum observed magnitude. The modified or truncated cumulative GR equation has the expression:

$$\mathrm{Log}\,N = a + \mathrm{Log}\left(\frac{e^{-\beta M} - e^{-\beta M_{\max}}}{e^{-\beta M_{\min}} - e^{-\beta M_{\max}}}\right) \quad \text{with} \quad \beta = \frac{b}{\mathrm{Log}\,e} \tag{2}$$

Here $M_{\min}$ is the lower bound of the magnitude interval where the GR coefficients are estimated and $M_{\max}$ is the maximum magnitude value expected for the zone studied.

The values of a and b obtained for zones 1, 2 and 4 and the magnitude range used for the estimation are shown in Table 2.

From the cumulative GR law, one can deduce the corresponding non-cumulative law and hence compute the annual rate of occurrence of an earthquake for any given magnitude range, even below the estimation interval of the law, though extreme back extrapolation can lead to unreliable estimates. In this work we have used the cumulative distributions. The annual rate of occurrence is simply N, where N is the number of events, resulting from the application of the cumulative GR law and the corresponding return period is $1/N$.

4 Tsunami hazard assessment

The main idea we used to assess tsunami hazard was to consider the tsunamigenic power of each occurring earthquake. The occurrence rate of the earthquakes in each zone was established by means of the statistical analysis described in the previous sections. The tsunamigenic potential of each earthquake was instead estimated by

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means of a simplified deterministic procedure. From the magnitude of an earthquake one first derives the fault parameters, then the vertical sea floor displacement, then the initial condition of the generated tsunami, and then the amplification of the tsunami at the coast through hydrodynamical methods if the bathymetry is known. This sequence of actions is the one that is usually adopted when one studies the generation and propagation of individual tsunamis by means of tsunami simulation models. Indeed, given a well-defined earthquake source (fault geometry, co-seismic slip distribution, etc.), and given a properly detailed bathymetry, one applies a tsunami model to compute the propagation of a tsunami, including amplification and run-up at certain coastal targets (see for example how to build and handle tsunami scenarios in Tinti et al., 2011; see also Tinti and Armigliato, 2003; Tinti et al., 2005; Tonini et al., 2011). The full application of such a scheme requires a very large computational load if one likes to treat sources differing in magnitude, fault geometry, slip distribution and location, just to mention a few variables, since it implies handling a very larger number of individual scenarios.

In this paper we drastically simplify the approach by considering a number of assumptions. We assume that the GR laws assessed for each zone can be applied to earthquakes occurring along the offshore trench, with strike aligned with the trench and fault mechanism compatible with the subduction occurring in the trench. This assumption is somewhat too strong since historical epicentres are spread over an area larger than the trench and they are not all of the thrust type, and so they are not equally favourable to tsunami generation. In practice, the seismic activity rates deduced from considering only the earthquake catalogue cannot be simply used to make inferences on the frequency of tsunami events since not all earthquakes generate tsunamis. The best way to assess the fraction of tsunamigenic vs. non-tsunamigenic earthquakes is to compare the tsunami and the earthquake catalogues. We have made this evaluation per magnitude classes. Since tsunami events are not so numerous we have assessed the magnitude class fraction over for the whole region covered by the catalogue (i.e. the region of the zone 1+ zone 2 + zone 4) rather than on a zone basis. Knowing this fraction, we have made use of it as a reduction factor, that is we have estimated the activity

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rate of tsunamigenic earthquakes by multiplying the number of earthquakes resulting from the truncated GR law deduced in the previous section by this factor. At this stage of the analysis we can state that the previous assumption that all the earthquakes of the same zone occur in the trench region has been mitigated into the more reasonable assumption that all tsunamigenic earthquakes occur in the trench region. In order to consider distinct local analyses within each zone we divide the trench in a number of segments and we adapt (i.e. reduce) the zone activity rate to each segment by means of a proper normalization procedure in such a way that the total number of tsunamigenic earthquakes expected in the zone is not altered.

To each sector we associate a bathymetry profile or transect from the trench to the coast running in a direction preferentially normal to the trench. We assume that the earthquake epicentre is located offshore in the trench region and that the largest sea floor displacement induced by the earthquake does occur along the profile. Further, we assume that the vertical coseismic sea floor displacement is equal to the vertical displacement of the sea surface. Hence we are able to compute the initial sea surface wave profile along the bathymetric transect and we compute how the initial wave amplitude is amplified while approaching the coast following the bathymetric profile. In doing this we assume a 1-D tsunami propagation towards the coast, that is however accommodated to a 2-D propagation by the application of a suitable reducing factor accounting for wave geometrical spreading. This strategy allows us to build a one-to-one association between each trench sector and a coastal segment, by means of the link formed by the bathymetric profile. Furthermore, we are allowed to build an association between each magnitude and the corresponding maximum wave height or a run-up height at the coast for each trench sector. Therefore the statistics on earthquake magnitude based on the adapted GR law can be transferred to the tsunami run-up height at the coast.

In the following we show the application of this approach and we discuss further the inherent approximations and implications.

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We start with the partition of the zones in segments following the trench. We have divided the part of the Central American trench falling in the three zones under study in as many as 130 segments and we have correspondingly taken 130 bathymetric profiles. The profiles are shown in Fig. 10. They tend to be equally distributed along the trench line. The length of the transects changes remarkably from one region to the other since it depends upon the variable distance of the trench from the coast.

The bathymetric profiles along the transects, though quite different from each other, nonetheless can be approximated by two ramps. The first starts from a depth chosen depending on the region and on the particular local bathymetry characteristics (varying between 3000 m and 1000 m), and ends at a depth of 20 m. The details on the profile length and slope do not matter for this first ramp in our analysis as will become clear later on. The second ramp starts at the depth of 20 m and ends at the coast. For this second ramp we are interested in computing the slope, since it will enter the amplification formula for the run-up computation. This oversimplified bathymetry will be used to compute the amplification of the tsunami approaching the coast.

A second step consists in the deterministic assessment of the tsunamigenic potential along each transect. For a given magnitude, the geometrical parameters of the fault, i.e. length (L) and rupture area (A) are computed using the Blaser et al. (2010) empirical relations holding for thrust faults, and the fault width is computed accordingly as A/L. Indeed, several other empirical relations exist relating earthquake magnitude to fault parameters (e.g. Wells and Coppersmith, 1994; Strasser et al., 2010; Leonard, 2010): the reason why we chose here the Blaser et al. (2010) formulas is that they focus especially on subduction zone earthquakes. Future studies may investigate on the dependence of the final results on the choice of the regressions. In addition, by inverting the Hanks and Kanamori (Hanks and Kanamori, 1979) formula:

$$M = \frac{2}{3}\mathrm{Log}M_0 - 10.7 \tag{3}$$

one can derive the seismic moment M_0 (in dyne-cm) from the earthquake moment magnitude M, and then estimate the average slip u on the fault through the relationship

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$M_0 = A\mu u$, where A is the fault area and μ is the rigidity of the crust, assumed in this case being equal to 5×10^{10} Pa. To maximize the effect of the earthquake on the vertical deformation of the sea floor, we have assumed that all earthquakes are shallow events with the upper edge of the fault placed at the depth of 20 km, that remains fixed for every magnitude. In addition, the assumption of low-angle faults is made (dip varying between 15° and 30°) which is quite typical of many trench faults located in the shallow portion of the slab. To approximately reproduce the different geometrical characteristics of the subducting slab in the zones we chose, we assigned dip angles of 20°, 16° and 29° to zone 1, zone 2 and zone 4, respectively. Finally, through the Okada (1992) model one can compute the maximum positive vertical displacement of the sea floor $u_{z\max}$. If one supposes that this is equal to the vertical displacement of the sea surface, this value can be further taken as the positive amplitude of the tsunami wave in the source region.

Hence, for each transect and depending on the magnitude, the initial tsunami positive amplitude is reduced by a factor equalling the square root of the ratio between the fault length corresponding to that magnitude and the total profile length. The physical basis for this reduction is to be found in the work by Comer (1980) and represents the spreading that the tsunami experiences during its propagation from the source.

We are then ready to compute the amplification experienced by the tsunami wave from the source region up to the coast. The tsunami amplitude obtained from the previous step is first amplified along the first ramp by means of the classical Green's formula:

$$\frac{\eta_2}{\eta_1} = \left(\frac{H_1}{H_2}\right)^{1/4} \tag{4}$$

where η_1 and η_2 are the wave heights at depths H_1 e H_2, with $H_1 > H_2$. In our case, H_1 varies between 3000 m and 1000 m, depending on the zone and specific profile, while H_2 is 20 m. Furthermore, η_1 is the wave height obtained after correcting the initial tsunami positive amplitude by the spreading factor, as described above. Note that no information of the bathymetry profile between H_1 and H_2 is needed at this stage.

Finally, the run-up at the coast was estimated using a modified version of the amplification formula by Carrier and Greenspan (1958), that can be written as follows:

$$\frac{\eta_3}{\eta_2} = 2\pi\sqrt{\frac{2H_2}{\lambda\alpha}} \quad (5)$$

where η_3 is the final amplification (or run-up), η_2 is the wave height computed previously at the depth $H_2 = 20\,\text{m}$, λ is the wavelength and α is the (average) slope of the second ramp.

5 Results and discussion

At the end of the analysis, by combining the results obtained for the rate of tsunamigenic earthquakes on a trench segment and the generation and amplification of the tsunami along the corresponding profile to the coast, we can calculate the occurrence probability of run-up exceeding a given value for the corresponding coastal segment as well as other related quantities, including the runup distribution along the coast corresponding to a given return period, which is very important for engineering and civil protection reasons. This is plotted in Figs. 11 and 12. The first provides a comparative view of the maximum expected runup for different recurrence times in a geographical perspective, while Fig. 12 shows a simplified 2-D representation of the expected run-up height distribution along the coast from central Mexico to northern Peru, embracing all the Pacific coast of Central America.

There are a number of considerations that can be made commenting these graphs.

First, it seems clear that the expected run up heights along the coast are quite unequally distributed and that in some segments the values are much larger than in others. Though there is a local variability (run-up may change from one segment to the next) that is probably linked to the method of analysis and should be investigated deeper, nonetheless one can identify some trends and behaviour over larger scales (that is involving several adjacent coastal segments).

Second, the computed values of runup are not extremely large: The largest runup does not exceed 7.5 m in 500 yr, and is about 3.5 m in 50 yr, which are values significantly smaller than the one observed worldwide. For example, the tsunami run-up database managed by NOAA, USA, (http://www.ngdc.noaa.gov/hazard/tsu.shtml) counts as many as 68 tsunami events that occurred since 1900 that were able to produce run-up higher than 10m in the coasts of the world oceans and as many as 11 events that took place since 2000. Therefore, it seems that run-up values higher than 7.5 m are more frequent elsewhere than in the coasts of the region under analysis in this paper.

Third, the countries where run-ups are expected to be higher are El Salvador, Honduras, Nicaragua and Costa Rica in central America, and also in the central Pacific Colombia, while they are assessed to be modest (usually less than 3 m in 500 yr) especially in Mexico, in Panama and in southern Colombia.

Fourth, the expected runup heights are an increasing function of the return time, which is a trivial observations. It is worth observing however that the difference between the 50 yr runup and the 100 yr runup is in certain places larger than the difference between the 500 yr run-up and the 100 yr runup, which is due to the essentially to the fact that the those run-up are caused by earthquakes with magnitude close to the upper limit of the truncated frequency-magnitude GR law. Practically a magnitude saturation implies a saturation of the tsunami height offshore and a saturation of the runup at the coast.

The analysis we performed and present here accounts only for runups associated with local tsunamigenic earthquakes that occur in front of the coast under study. Inundations caused by remote sources, located for example far away on the other side of the Pacific, or by sources that are found in the trench but remarkably shifted to the north or to the south are not considered here. And equally not considered are sources

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different from earthquakes. In principle this may appear a severe limitation, and I deed it has to be removed in further more accurate studies, but for a preliminary assessment, though crude, it can be accepted since from historical records it emerges that all largest recorded run-ups in the coasts of the countries studied here are due to local earthquakes, with sources less distant than 150 km from the affected coast. This is not always true, however. If we consider for instance central and southern Peru, that is a country just to the south of the region analysed here, we can find run-up values larger than 5 m caused by Chilean earthquakes, that is earthquakes with sources that are more than 1000 km away (http://www.ngdc.noaa.gov/hazard/tsu.shtml).

A further limitation of the present analysis is that it does not take into account the occurrence of the tsunami earthquakes, that is of those earthquakes that are able to cause tsunamis much larger than expected solely on the basis of their magnitude. They were first identified by Kanamori (1972) and studied later by several researchers (see Okal and Newman, 2001 for a review) and poses a serious puzzle both for tsunami hazard assessment and tsunami early warning systems. Though the cause of tsunami earthquakes is not certain yet, it seems that they are characterised by slow rupture processes that can be revealed among other means by a deficiency in generation of *T* waves compared to reference earthquakes of the same moment magnitude (see Okal et al., 2003).

These earthquakes are quite rare and very few so far have been recognised to belong to this category. It is worth stressing that two of them have occurred in our region, i.e. the 1932 Manzanillo, Mexico tsunami and the 1992 Nicaragua tsunami. The first of the two that was described as a tsunami earthquake was the 1992 tsunami that occurred on 2 September in Nicaragua following a $M = 7.7$ earthquake and caused run-up usually between 3–7 m, but with extremes exceeding 10 m (Satake, 1995; Piatanesi et al., 1996; NOAA runup database). The second was interpreted as a tsunami earthquake only recently and can be seen as one of the latest additions to the category (Okal and Borrero, 2009). The 22 June 1932 earthquake was a $M = 7.0$ aftershock of the big Jalisco $M = 8.2$ 3 June earthquake that caused more than 400 fatalities in Mex-

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ico close to the border with Guatemala. In spite of the relatively moderate magnitude the aftershock triggered a tsunami larger than the main shock. The 3 June tsunami hit the Bahia San Pedrito in Manzanillo with reported run-up at most about 3 m, while the 22 June tsunami hit and destroyed the little coastal city of Cuyutlán killing more than 100 people with waves reported to be about 10 m high (Farreras and Sanchez, 1991).

Another remark is that our analysis cannot take into account very local amplification effects of tsunami waves. In this paper a coastal zone as long as 6000 km has been divided in 130 coastal segments that are separated by 45 km on average and the resulting resolution is not enough to capture the high variability of the coastal topo-bathymetric and geomorphological features that, as is well known, influence the tsunami flooding and runup.

6 Conclusions

In this paper we have applied a hybrid method to assess the tsunami hazard on the coast of a long zone of Pacifica America running from Central Mexico to northern Peru. The "hybrid" denotation refers to the fact that we have used probabilistic methods to assess the rate of occurrence of earthquakes, whereas we have made use of deterministic simple formulas to evaluate the tsunami amplification at the coast, given that an earthquake of a given magnitude has occurred in a given place, following an idea introduced by Tinti (1991) for tsunami hazard computations in Italy.

Our analysis has to be considered preliminary or "expedite", since computations could be simple and quick by exploiting a number of assumptions, regarding the frequency magnitude law (a truncated GR was assumed), the empirical regression law connecting the fault parameters and the magnitude, the 1-D propagation of tsunami along transects or profiles, made less stringent by the application of a spreading factor, the oversimplification of the bathymetry along the profiles.

From a physical point of view, the most relevant limitation is that we restrict the analysis only to local earthquake sources, occurring along the trench, and also dis-

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card tsunami earthquake mechanisms, though there are at least two examples of such earthquakes in the seismic history of the region.

Our analysis allows us to compute the probability distribution of the runup along the coast and therefore to give answer to questions such as: what is the return time of a given runup value? Or what is the maximum runup expected in a given return period? In the paper we provide in Figs. 11 and 12 an example of the of the second type of computations.

The results of our analysis is that the region we have studied is affected by moderate tsunami hazard compared to other regions in the Pacific and the Indian ocean where much hogher runup are expected on the basis of the historical reports, and that Central America from El Salvador to Nicaragua and also the central zone of the Pacific Colombia are the ones with the highest expected runups.

The runup obtained with our method are to be considered average or reference values in the coastal segment for which they are computed, since they were derived by taking into account general simplified bathymetric trends offshore. Higher values could be expected in correspondence with special local features like at the end of narrow bays, pocket beaches, on the lee side of small islands, etc.

A complementary approach to study tsunami hazards is based on worst-case scenarios where the largest possible "credible" tsunamis that may affect the target area are studied through numerical simulations and, when available, historical cases data (see e.g. Tinti and Armigliato, 2003 and Tonini et al., 2011 for application in the Mediterranean sea). The authors believe that this approach could be useful to overcome some of the limitations of the method used in this work since it could allow to extend the analysis to non-earthquake sources and to account for a finer resolution on the coast. This will be the next step of the research.

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References

Albarello, D., Camassi, R., and Rebez, A.: Detection of space and time heterogeneity in the completeness of a seismic catalogue by a statistical approach: an application to the Italian area, Bull. Seismol. Soc. Am., 91, 1694–1703, 2001,

Alvarez-Gomez, J. A., Gutierrez-Gutierrez, O. Q., Aniel-Quiroga, I., and Gonzalez, M.: Tsunamigenic potential of outer-rise normal faults at the Middle America trench in Central America, Tectonophysics, 574–575, 133–143, 2012.

Ambraseys, N. N. and Adams, R.: The seismicity of Central America, Imperial College Press, 2000.

Bird, P.: An updated digital model of plate boundaries, Geochem. Geophys. Geosyst., 4, 1027, doi:10.1029/2001GC000252, 2003.

Blaser, L., Krüger, F., Ohrnberger, M., and Scherbaum, F.: Scaling relations of earthquake source parameter estimates with special focus on subduction environment, Bull. Seism. Soc. Am., 100, 2914–2926, doi:10.1785/0120100111, 2010.

Bommer, J. J. and Rodrıguez, C. E.: Earthquake-induced landslides in Central America, Eng. Geol., 63, 189–220, 2002,

Bryant, E.: Tsunami the underrated hazard, Cambridge University Press, 2001.

Carrier, G. F. and Greenspan, H. P.: Water waves of finite amplitude on a sloping beach, J. Fluid Mech., 4, 97–109, 1958.

CERESIS: available at: http://www.ceresis.org/portal/catal_hipo.php, last access: 2010.

Comer, R. P.: Tsunami height and earthquake magnitude: theoretical basis of an empirical relation, Geophys. Res. Lett., 7, 445–448, 1980.

Dewey, J. W., White, R., and Hernández, D. A.: Seismicity and Tectonics of El Salvador, Natural Hazards in El Salvador: Geol. Soc. Am. Special Paper, 375, 363–378, 2004.

El Alami, S. O. and Tinti, S.: A preliminary evaluation of the tsunami hazards in the Moroccan coasts, Sci. Tsunami Hazards, 9, 31–38, 1991.

Espinoza, J.: Terremotos Tsunamigenicos en el Ecuador, Acta Oceanografica del Pacifico, INOCAR, Ecuador 7, 1992.

Farreras, S. F. and Sanchez, A. J.: The Tsunami Threat on the Mexican West Coast: A Historical Analysis and Recommendations for Hazard Mitigation, Nat. Hazards, 4, 301–316, 1991.

Fernández, M., Ortiz-Figueroa, M., and Mora, R.: Tsunami Hazards in El Salvador, Natural Hazards in El Salvador, Geological Soc. Am. Special Paper, 375, 435–444, 2004.

Fernández, M., Molina, E., Havskov, J., and Atakan, K.: Tsunamis and Tsunami Hazards in El Salvador, Natural Hazards in El Salvador, Geol. Soc. America Special Paper, 375, 435–444, 2000.

Fisher, R.: Middle America Trench: Topography and Structure, Scripps Institution of Oceanography, University of California, La Jolla, California, 1961,

GEBCO website: available at: http://www.gebco.net, last access: May 2013.

González, F.: Tsunami!, Scientific American, 280, 56–65, 1999.

Hanks, T. C. and Kanamori, H.: A moment-magnitude scale, J. Geophys. Res., 84, 2348–2350, 1979.

Kanamori H.: Mechanism of tsunami earthquakes, Phys. Earth Planet. Inter., 6, 346–359, 1972.

Leeds, J.: Catalogue of Nicaraguan Earthquakes, Bull. Seismol. Soc. Am., 64, 1135–1158, 1974.

Leonard, M.: Earthquake fault scaling: self-consistent relating of rupture length, width, average displacement, and moment release, Bull. Seism. Soc. Am., 100, 1971–1988, doi:10.1785/0120090189, 2010.

Molina, E.: Tsunami Catalogue for Central America 1539–1996, Reduction of Natural Disasters in Central America, Technical Report, No. II 1–04, Institute of Solid Earth Physics, University of Bergen, 1997.

MARN, Ministerio del Medio Ambiente y Recursos Naturales de El Salvador http://www.marn.gob.sv/phocadownload/Presentacion_Tsunami_%20ES.pdf latest access: on 1 November 2011.

NOAA, National Oceanographic and Atmosferic Data, available at: http://www.ngdc.noaa.gov/hazard/, last access: May 2013.

NOAA-NGDC- National Oceanic and Atmospheric Administration- National Geophysical Data Center Tsunami Event and Runup Database: http://www.ngdc.noaa.gov/nndc/, last access: June 2013.

Noticeable earthquakes Mexico: available at: http://usuarios.geofisica.unam.mx/vladimir/sismos/100a%F1os.html, last access: May 2013.

Okada, Y.: Internal deformation due to shear and tensile faults in a half-space, Bull. Seism. Soc. Am., 82, 1018–1040, 1992.

Okal, E. A. and Newman A. V.Tsunami earthquakes: The quest for a regional signal, Phys. Earth. Planet. Inter., 124, 45–70, 2001.

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Assessment of tsunami hazard for the American Pacific coast

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Okal, E. A., Alasset, P. J., Hyvernaud, O., and Schindelé F.: The deficient T waves of tsunami earthquakes, Geophys. J. Int., 152, 416–432, 2003.
Okal, E. A. and Borrero J. C.: The 'tsunami earthquake' of 1932 June 22 in Manzanillo, Mexico: seismological study and tsunami simulations, Geophys. J. Int., 187, 1443–1459, 2008.
Phipps Morgan, J., Ranero, C. R., and Vannucchi, P.: Intra-arc extension in Central America: Links between plate motions, tectonics, volcanism, and geochemistry, Earth Planet. Sci. Lett., 272, 365–371, 2008.
Piatanesi, A., Tinti, S., and Gavagni, I.: The slip distribution of the 1992 Nicaragua earthquake from tsunami data, Geophys. Res. Lett., 23, 37–40, 1996.
Ranero, C. R., Weinrebe, W., Grevemeyer, I., Morgan, J. P., Vannucchi, P., and Von Huene, R.: Tectonic Structure of the Middle America Pacific Margin and Incoming Cocos Plate from Costa Rica to Guatemala, Geophys. Res. Abstr., 6, 05185, European Geosci. Union, 2004.
Restrepo, J. C. and Otero, L. J.: Modelacion Numerica de Eventos Tsunamigenicos en la Cuenca Pacifica Colombiana- Bahia de Buenaventura, Rev. Acad. Colomb. Cienc.: XXXI, Num. 120-Sept, 363–377, 2007,
Satake, K.: Linear and nonlinear computations of the 1992 Nicaragua earthquake tsunami, Pure Appl. Geophys., 20, 863–866, 1995.
Satake, K., Bourgeois, J., Abe, Ku., Abe, Ka., Tsuji, Y., Imamura, F., Iio, Y., Katao, H., Noguera, E., and Estrada, F.: Tsunami field survey of the 1992 Nicaragua earthquake, Eos Transactions, Am. Geophys. Union, 74–13, 145–160, 1993.
Singh, K., Rodriguez, M., and Espindola, J. M.: A Catalog of Shallow Earthquakes of Mexico from 1900 to 1981, Bull. Seism. Soc. Am., 74, 267–279, 1984.
Singh, S. K., Pérez-Campos, X., Iglesias, A., and Pacheco, J. F.: An exploratory study for rapid estimation of critical source parameters of great subduction-zone earthquakes in Mexico, Geofísica Int., 47, 355–369, 2008.
Strasser, F. O., Arango, M. C., and Bommer, J. J.: Scaling of the source dimensions of interface and intraslab subduction-zone earthquakes with moment magnitude, Seism. Res. Lett., 81, 941–950, doi:101785/gssrl.81.6.941., 2010,
Suárez, G. and Albini, P.: Evidence for Great Tsunamigenic Earthquakes (M 8.6) along the Mexican Subduction Zone, Bull. Seism. Soc. Am., 99, 892–896, doi:10.1785/0120080201, 2009.
SSN, Servicio Sismologico Nacional: http://www.ssn.unam.mx/ last access: May 2013.
Synolakis, C. E.: The run-up of solitary waves, J. Fluid Mech., 185, 523–545, 1987.

NHESSD
1, 2983–3021, 2013

Assessment of tsunami hazard for the American Pacific coast

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Tinti, S.: Assessment of tsunami hazard in the Italian Seas, Nat. Hazards, 4, 267–283, 1991a.
Tinti, S.: Tsunami potential in Southern Italy, Sci. Tsunami Hazards, 9, 5–14, 1991b.
Tinti, S. and Armigliato, A.: The use of scenarios to evaluate tsunami impact in South Italy, Mar. Geol., 199, 221–243, 2003.
Tinti, S., Armigliato, A., Pagnoni, G., and Zaniboni, F.: Scenarios of giant tsunamis of tectonic origin in the Mediterranean, ISET J. Earthq. Technol., 42, 171–188, 2005.
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, 1–41, doi:10.2788/21259, 2011.
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.
UNESCO: Tsunami Glossary: A Glossary of Terms and Acronyms used in the Tsunami Literature, Intergovernmental Oceanographic Commission, Technical Series 37, UNESCO, 1991.
Wells, D. L. and Coppersmith, K. J.: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seism. Soc. Am., 84, 974–1002, 1994,

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Table 1. Seismic Catalogues of Central America.

Number	Authors	Area covered	Time covered	Earthquake type
1	Leeds	Nicaragua	1520–1973	all
2	Ambraseys-Adams	Central America	1898–1995	all
3	Peraldo and Montero	Not available	1500–1899	
4	Rojas	Not available	1502–1992	
5	Singh, Rodriguez and Espinoza	Southern Mexico, Pacific	1900–1981	shallow
6	NOAA	Mexico, Central and South America	1471–2008	all
7	CERESIS	South America	1530–1991	all
8	Mexico noticeable earthquakes	Mexico	1900–1999	$m > 6.5$
9	Mexico SSN	Mexico	1998–2008	all

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Table 2. GR Coefficients and magnitude boundary values.

	a	b	M_{min}	M_{max}
Zone 1	0.001	1.914	7.3	8.5
Zone 2	0.737	0.678	6.0	8.7
Zone 4	−0.543	1.282	7.4	8.7

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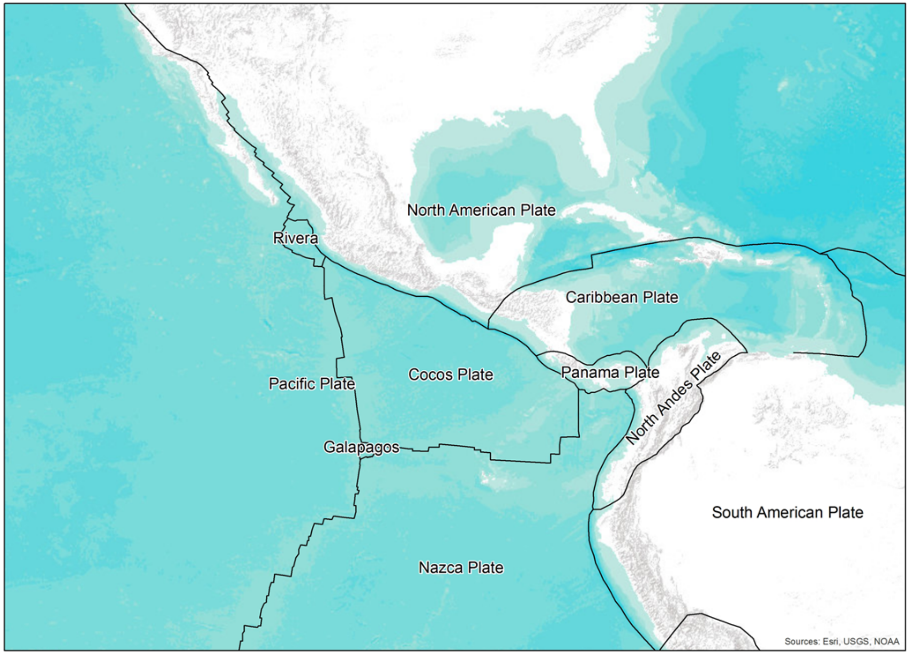

Fig. 1. Tectonic plates (after Bird, 2003).

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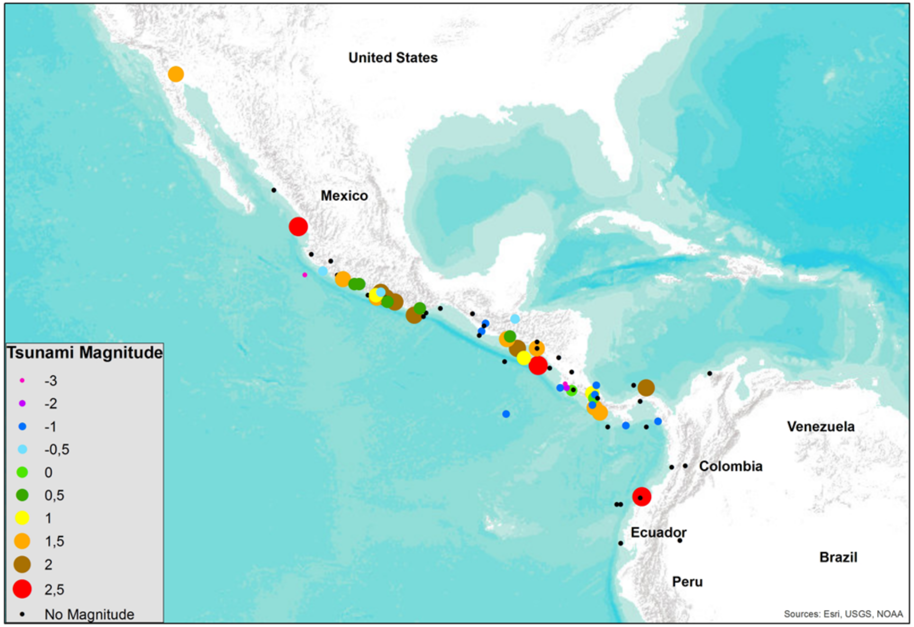

Fig. 2. Tsunamis in Central America based on (Molina, 1997) and NOAA-NGDC- Tsunami Event and Runup Database (http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=167&d=166).

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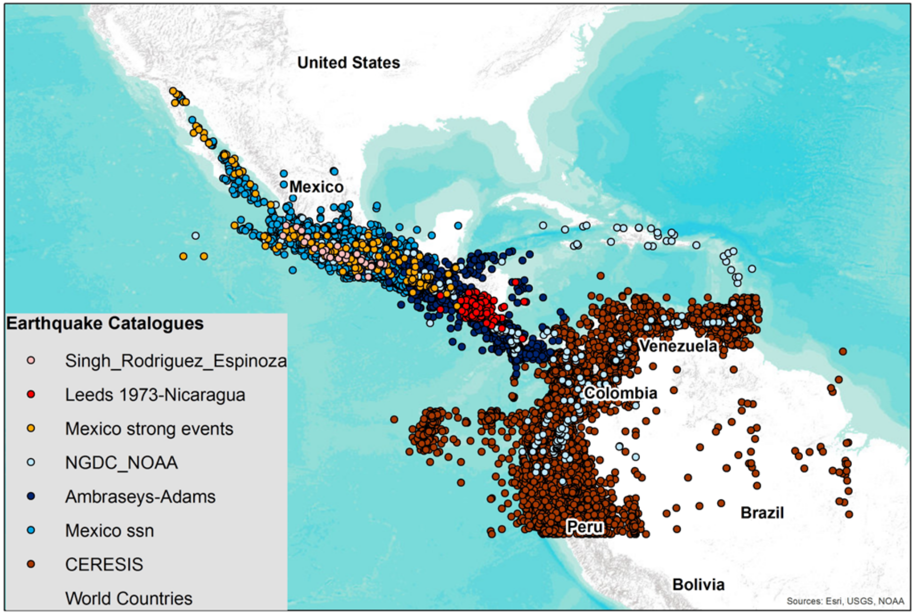

Fig. 3. Seismic Catalogues of Central America.

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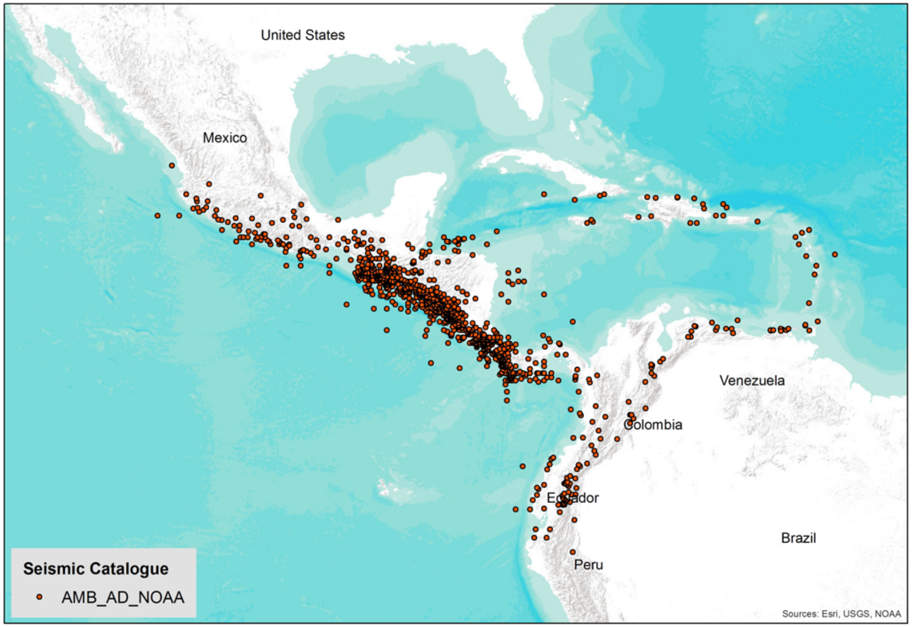

Fig. 4. AMB-AD-NOAA joined Catalogue.

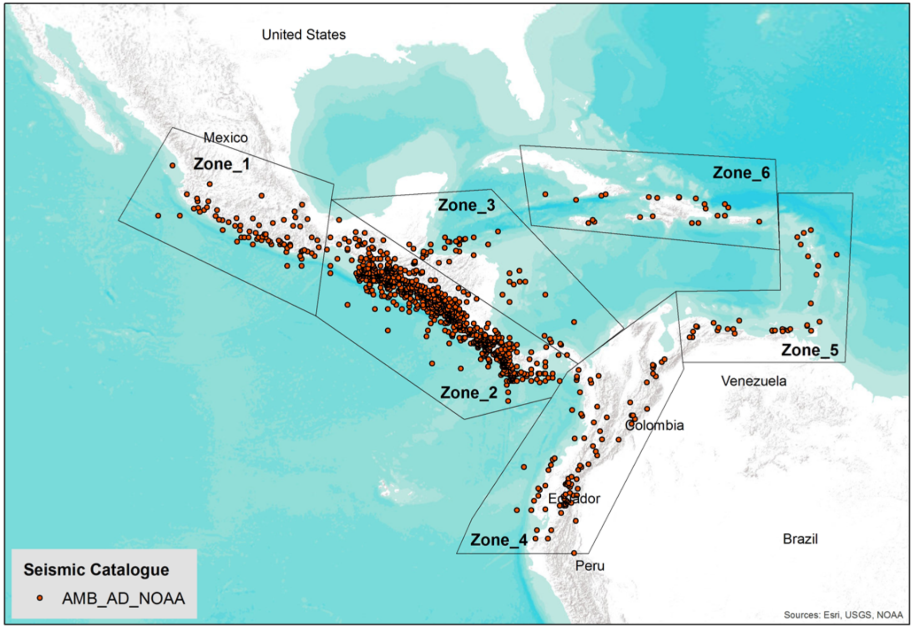

Fig. 5. Seismic zones in Central America.

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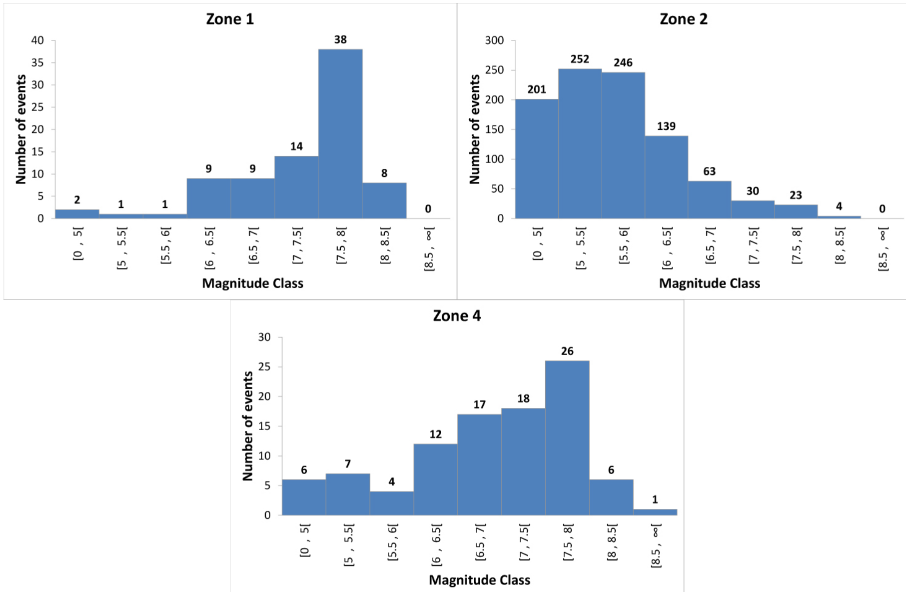

Fig. 6. Magnitude Frequencies in Zones 1, 2 and 4.

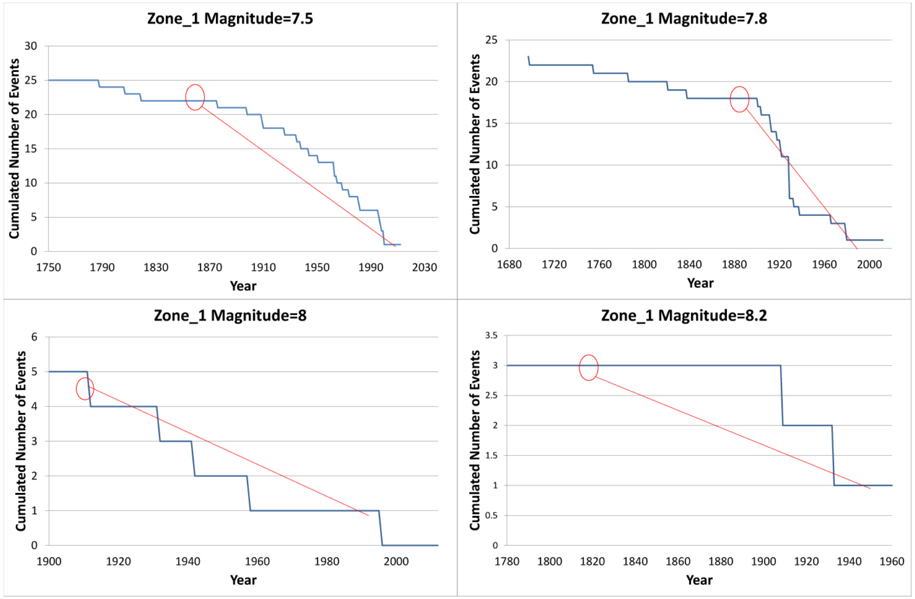

Fig. 7. Completeness analysis, Zone 1.

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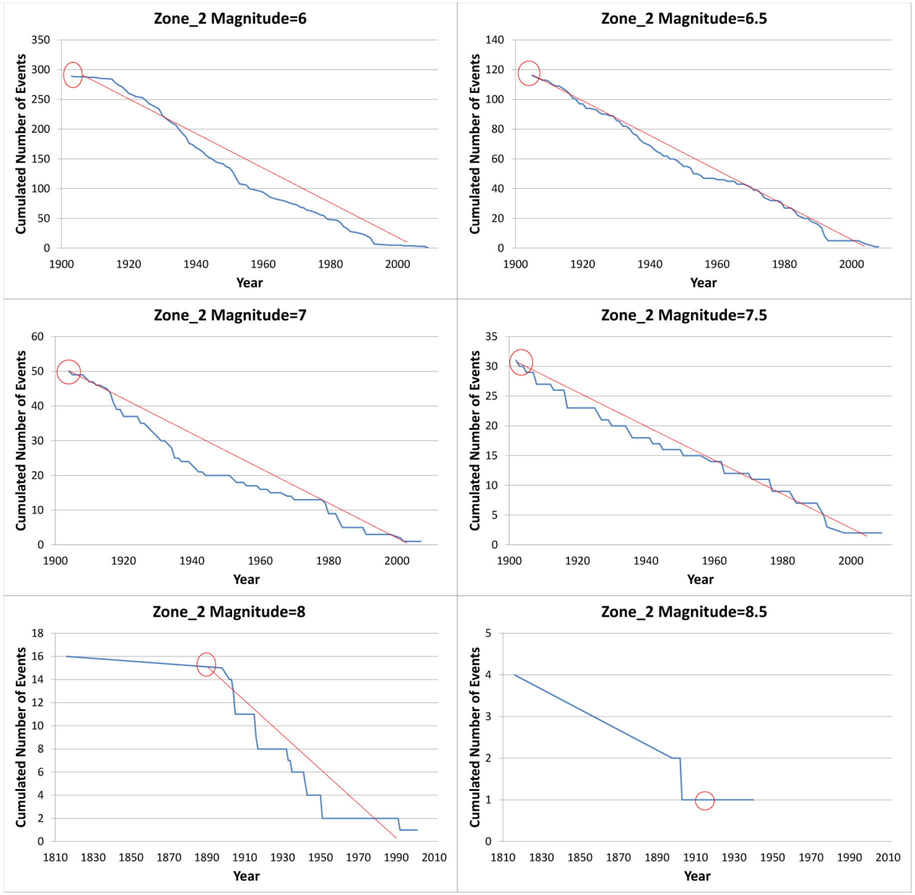

Fig. 8. Completeness analysis, Zone 2.

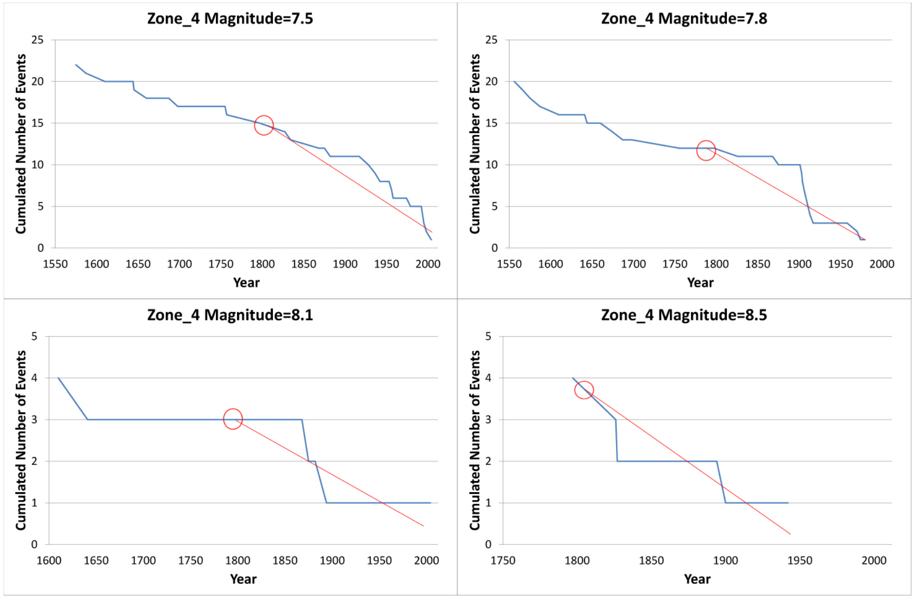

Fig. 9. Completeness analysis, Zone 4.

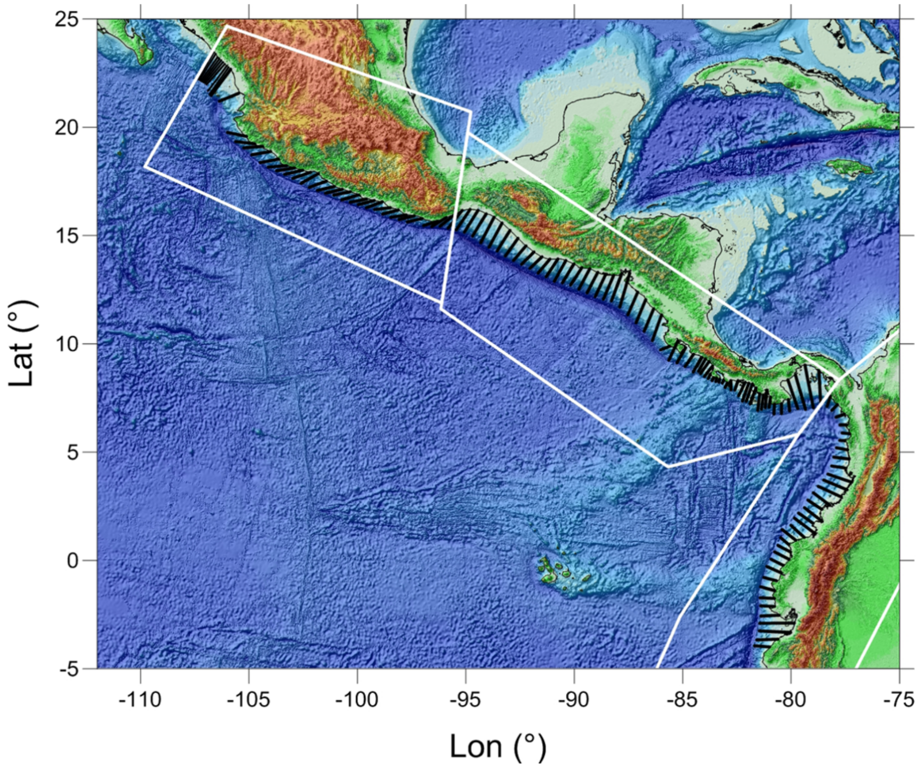

Fig. 10. Transects along the Central American coast.

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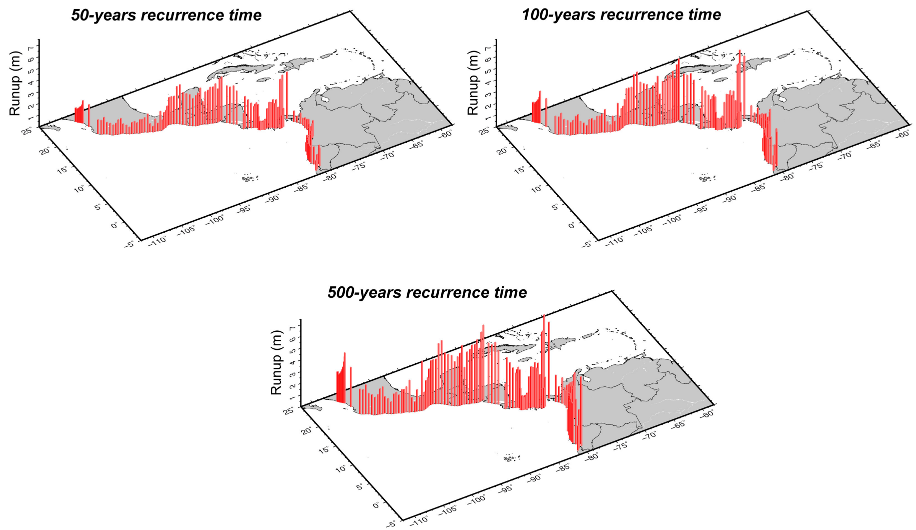

Fig. 11. Maximum expected runup height distribution for different return periods.

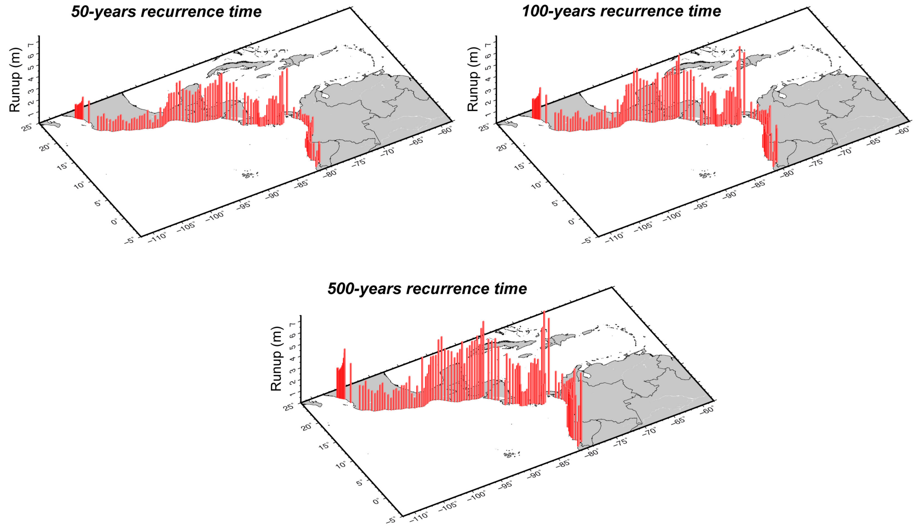

Fig. 12. Maximum expected runup distribution vs. distance along the coast.

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