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Evaluating Tsunami Hazard in the Northwestern Indian Ocean

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Abstract—We evaluate here the tsunami hazard in the northwestern Indian Ocean. The maximum regional earthquake calculated from seismic hazard analysis, was used as the characteristic earthquake for our tsunami hazard assessment. This earthquake, with a moment magnitude of M_w 8.3 and a return period of about 1000 years, was moved along the Makran subduction zone (MSZ) and its possible tsunami wave height along various coasts was calculated via numerical simulation. Both seismic hazard analysis and numerical modeling of the tsunami were validated using historical observations of the Makran earthquake and tsunami of the 1945. Results showed that the possible tsunami may reach a maximum height of 9.6 m in the region. The distribution of tsunami wave height along various coasts is presented. We recommend the development of a tsunami warning system in the region, and emphasize the value of education as a measure to mitigate the death toll of a possible tsunami in this region.

Key words: Northwestern Indian Ocean, Makran subduction zone (MSZ), deterministic tsunami hazard assessment (DTHA), maximum regional earthquake, near-field effects, numerical modeling.

1. *Introduction*

The great Sumatra–Andaman tsunami of 2004 has awakened the attention of the scientific community to tsunami hazard in the Indian Ocean basin (OKAL and SYNOLAKIS, 2008). This mega-tsunami was fresh evidence that lack of tsunami hazard understanding in any tsunami-prone coastline can have serious consequences. According to CLAGUE *et al*. (2003), tsunami hazard is normally evaluated by the maximum wave runup, which can be measured as either the elevation reached by the water, or the horizontal distance the wave floods inland. Throughout this paper, the term *tsunami hazard* is considered as referring the vertical runup.

Different methods have been employed by researchers to assess tsunami hazards in various tsunamigenic zones around the world including: (1) analysis of historical tsunami

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(e.g., Dominey-Howes *et al.*, 2007), (2) deterministic modeling (e.g., Okal and Synolakis, 2008), and (3) probabilistic modeling (e.g., Rikitake and Aida, 1988).

Compilation and analysis of historical data of tsunamis is of primary importance for tsunami hazard assessment. The compiled data yield important information about the return period of tsunamis, the different types of potential tsunamis in the region, the possible tsunami wave heights, and the most vulnerable coastlines to the impact of tsunamis (Dominey-Howes *et al.*, 2007). Such catalogs have been developed for many tsunami-prone coastlines around the world such as Italy (e.g., Tinti and Maramai, 1999), Japan (e.g., Abe, 1985), the Mediterranean (e.g., Ambraseys, 1962), U.S.A. (e.g., Lander *et al.*, 1993), and other regions.

When data of historical tsunamis for a particular site are insufficient, tsunami hazard can be calculated using a deterministic method. This method is based on adopting characteristic scenarios considering the largest event known to have hit the area of interest and to simulate this event through numerical modeling (Geist and Parsons, 2006). This technique has been used to assess tsunami hazards in some vulnerable coastlines (e.g., Okal *et al.*, 2006a; Tinti and Armigliato, 2003).

The probabilistic method is based on the idea underlying seismic hazard assessment (Lin and Tung, 1982). This method uses a combination of probability analysis for offshore earthquake occurrence and numerical modeling of tsunamis to determine the probability of having a tsunami whose maximum water elevation exceeds a certain value at a coastal site. The method has been employed by some authors (e.g., Rikitake and Aida, 1988).

In this study, we aim at evaluating the tsunami hazard in the Makran subduction zone (MSZ) in the northwestern Indian Ocean (Fig. 1) using a deterministic method. As shown, the MSZ is formed by the northward subduction of the Arabian plate beneath the Eurasian one. This zone extends east from the Strait of Hormoz in Iran to near Karachi in Pakistan with a length of about 1000 km. This region is prone to large subduction tsunamigenic earthquakes from the MSZ. The last tsunami in the region occurred on November 28, 1945, and was produced by an M_w 8.1 earthquake claiming more than 4000 lives (Heck, 1947).

Heidarzadeh *et al.* (2008a, 2008b) studied historical tsunamis in the MSZ and presented a preliminary estimation of tsunami hazard for this region. Heidarzadeh *et al.* (2008b) moved a 1945-type earthquake along the MSZ and calculated the maximum positive tsunami wave height along the various coasts in the region. Although their work is of importance for the Makran region whose tsunami hazard had not been studied before, it is believed that more studies should be performed on the seismicity of the region to more accurately estimate its tsunami hazard. In fact, this study is the continuation of the preliminary work performed by Heidarzadeh *et al.* (2008a, 2008b) on the Makran tsunami hazard assessment to provide a better understanding of the level of tsunami threat faced in this region.

For regions like Makran where the historical record of tsunamis and earthquakes is both short and insufficient, a more accurate tsunami hazard assessment can be performed

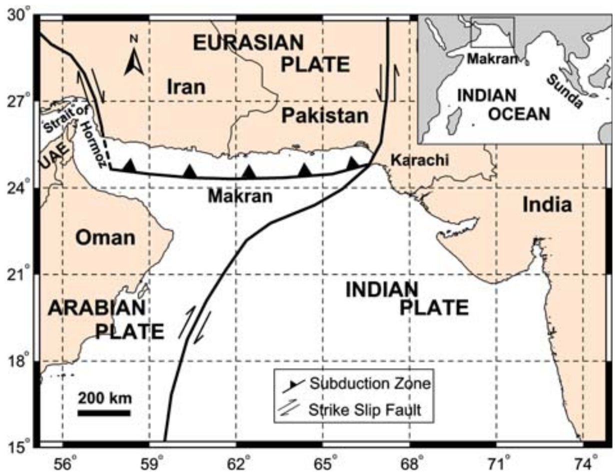

Figure 1
Location map and tectonic setting of the Makran Subduction Zone (MSZ). The inset shows the MSZ compared to the entire Indian Ocean region.

by application of probabilistic seismic hazard analysis to calculate the maximum regional earthquake, followed by the application of sophisticated hydrodynamic models to calculate possible tsunami wave heights. In this context, we calculated here the maximum magnitude of earthquakes in the MSZ using probabilistic seismic hazard analysis. Subsequently, it was used as the tsunami source in the present deterministic method. Six tsunami scenarios along the MSZ were considered and for each scenario numerical modeling of the tsunami was performed. Also, we discuss the magnitude of the worst possible earthquake in this region and its possible tsunami. The results presented here may assist in developing tsunami preparedness strategies in the northwestern Indian Ocean where the tsunami hazard has been inadequately understood.

2. *Probabilistic Seismic Hazard Analysis and Validation*

The motivations for performing probabilistic tsunami hazard assessment are to calculate the maximum regional magnitude of earthquake in the region, which will then be used as the tsunami source in the next section, and also to estimate the return period of large earthquakes in the region.

The area surveyed for assessing the seismicity comprised a rectangle limited between 23° to 28°N, and 57° to 70°E. A variety of sources was used to compile an earthquake catalog for the MSZ which can be classified as belonging to one of two categories: Historical (non-instrumental) or modern (instrumental). All data concerning events prior to 1900 are of historical type. Modern data consist of hypocenters and instrumentally recorded arrival times from worldwide stations that are reported in various catalogs,

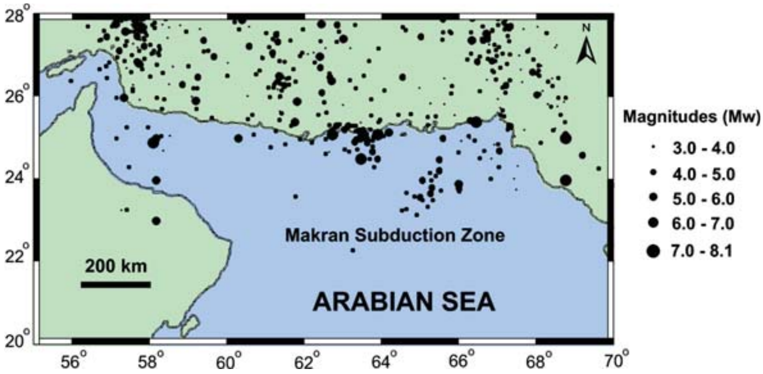

Figure 2
The epicenters and magnitudes of earthquakes in the Makran region.

books and journals. The epicenters and magnitudes of the compiled earthquakes are shown in Figure 2. The maximum observed earthquake in the region is the event of November 28, 1945 with a moment magnitude of 8.1.

The assessment of the recurrence parameters for the MSZ was performed by making use of the procedure developed by Kijko and Sellevoll (1992). Also, the method developed by Kijko (2004) was employed to calculate the maximum regional earthquake magnitude. Here, we divided the catalog of Makran earthquakes into four parts. The first part contains historical large events (non-instrumental events). The other three parts were complete catalogs including instrumental data each having certain threshold magnitude and standard deviation. The results of seismic hazard assessment for the MSZ are shown in Figure 3. Estimates of the earthquake return periods in the MSZ are shown in Figure 3a. Also, Figure 3b presents the probability of earthquakes with certain magnitudes in the next 1, 50, 100 and 1000 years. For example, based on the results shown in Figure 3, the return period of an M_w 8.1 earthquake is about 250 years in the MSZ, and the probability of having such an earthquake in the next 50 years is about 17.5% in this region. Figure 3 shows that the maximum regional earthquake magnitude in the MSZ is about 8.3 which will be used as the tsunami source in the following sections. The return period of this earthquake is about 1000 years, and the probability of having such an earthquake in the next 50 years is about 5%.

To validate the results of the seismic hazard analysis, we compared our results with previous estimates of the return period of large earthquakes in the MSZ. Byrne *et al.* (1992) believed that, if all of the plate motion between Eurasia and Arabia occurred during earthquakes like the 1945 event (M_w 8.1), such events would be expected to repeat about every 175 to 300 years in the eastern Makran. By calculating the average uplift rate along the Makran coast, Page *et al.* (1979) estimated that the recurrence of a 1945-type earthquake along the MSZ is approximately 125 to 250 years. Our results presented in Figure 3a suggest a return period of about 250 years for a 1945-type earthquake (M_w 8.1), which is in agreement with the previous estimates made of Page *et al.* (1979) and Byrne *et al.* (1992).

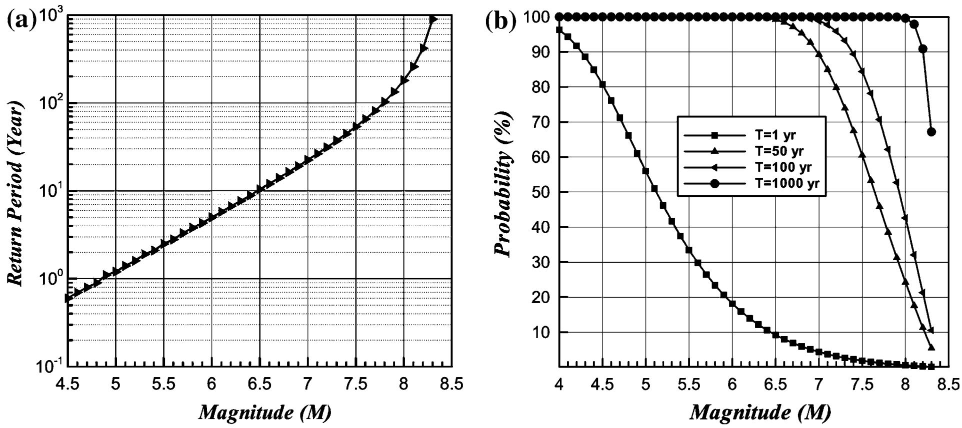

Figure 3
Estimation of earthquake return periods in the MSZ (a), and the probability of earthquakes with certain magnitudes in the next 1, 50, 100 and 100 years (b).

3. *Tsunami Modeling and Verification*

The Makran earthquake and tsunami of 1945, which was the only instrumentally recorded tsunami in the northwestern Indian Ocean, was used for validation of our tsunami modeling. Some authors (e.g., AMBRASEYS and MELVILLE, 1982; PAGE *et al.*, 1979) reported that the ocean floor experienced about 2 m of uplift due to this earthquake. The data of the Makran 1945 tsunami wave heights on the coastlines are rather poor and no tide gauge data are available. However, there are some limited data pertaining to tsunami wave heights on some Makran coasts. AMBRASEYS and MELVILLE (1982) reported that the tsunami wave height was approximately 4–5 m in Pasni, about 1.5 m in Karachi, and 2 m in Mumbai. Also, they reported that the tsunami caused extensive flooding of low-lying areas along the Iranian coastline, but no details were presented. PENDSE (1946) reported:

> *"Karachi, which is at a distance of about 276 miles from the epicenter, experienced waves affecting the harbor at 5–30 AM, 7 AM, 7–50 AM and 8–15 AM. The last one was the largest and its height was estimated to be 4.5 ft above normal."*

Other authors reported 12–15 m wave height at Pasni due to the 1945 tsunami (e.g., BERNINGHAUSEN, 1966). HEIDARZADEH *et al.* (2008a) presented evidence that the Makran tsunami of 1945 was associated with other phenomena such as landslides and attributed the large runup of 12–15 m to it. Based on their detailed runup modeling, HEIDARZADEH *et al.* (2008a) concluded that the tectonic source of the 1945 tsunami was capable of producing 4–5 m runup in the near-field (i.e., Pasni), as reported by AMBRASEYS and MELVILLE (1982). Some authors (e.g., AMBRASEYS and MELVILLE, 1982; BILHAM *et al.*, 2007) reported that the largest tsunami wave (i.e., wave of 12–15 high) arrived at Pasni about 1.5–2 hours after the earthquake, which supports HEIDARZADEH *et al.*'s (2008a) interpretation of it as belonging to another phenomenon like a submarine landslide.

Table 1

Seismic parameters of the Makran tsunami of 1945 and the maximum regional earthquake (M_w 8.3) used in this study.

Name of event	Dip (°)	Slip (°)	Strike (°)	Depth (km)	Length (km)	Width (km)	Slip (m)	Moment (N m)[a]	Uplift (m)
Maximum Regional Earthquake (M_w 8.3)	7	89	270	27	200[b]	80[b]	8.5[b]	4.08×10^{21}	2.8
1945 Makran Earthquake (M_w 8.1)	7	89	246	27	130	70	6.6	1.80×10^{21}	2.0

[a] The rigidity of the earth is about 3.0×10^{10} N/m^2 in the Makran region; after Bayer *et al.* (2006).
[b] Estimated using empirical relations of Wells and Coppersmith (1994) and calibrated using the data of the Makran earthquake of 1945.

Here, the algorithm of Mansinha and Smylie (1971) was used to calculate the seafloor deformation due to the earthquake. This algorithm calculates the ground deformation using input seismic parameters that include the strike, dip, and slip angles, the amount of slip, the dimensions of the rupture area (length and width), and the earthquake depth (Synolakis, 2003). The seismic parameters estimated in the study by Byrne *et al.* (1992) and calibrated by Heidarzadeh *et al.* (2008b), were used for tsunami generation modeling which were: 246°, 7°, 89°, 6.6 m, 130 km, 70 km, and 27 km, respectively (Table 1). The maximum calculated uplift using these seismic parameters was about 2 m which was in agreement with the actual observed uplift during the 1945 event.

The numerical model TUNAMI-N2 was used for simulation of propagation and coastal amplification of long waves. The model was originally authored by Nobuo Shuto and Fumihiko Imamura of the Disaster Control Research Center in Tohoku University (Japan) through the Tsunami Inundation Modeling Exchange (TIME) program (Goto *et al.*, 1997). TUNAMI-N2 is one of the key tools for developing studies for propagation and coastal amplification of tsunamis in relation to different initial conditions (Yalciner *et al.*, 2002). Also, a similar methodology is used in the numerical model MOST (Method of Splitting Tsunami) developed by Titov and Synolakis (1998). TUNAMI-N2 and MOST are the only two existing nonlinear shallow water codes, validated with laboratory and field data (Yeh et al., 1996).

In this study, we applied bathymetry data provided through the GEBCO (General Bathymetric Chart of the Oceans) digital atlas (IOC *et al.*, 2003). The total number of grid points in the computational domain was 369852, which was 833 × 444 points. The time step was selected as 3.0 s to satisfy the stability condition. The duration time of wave propagation was 4 h in our simulations. Figure 4 presents the results of the numerical modeling of tsunami for the Makran earthquake of 1945. As shown, the distribution of the tsunami wave height along various Makran coasts reproduces most features of the historical observations during this event. Our numerical model successfully reproduces the wave height of about 4–5 m at Pasni as well as 1.5 m in Karachi. The modeling results showed that the largest wave arrives in Karachi about

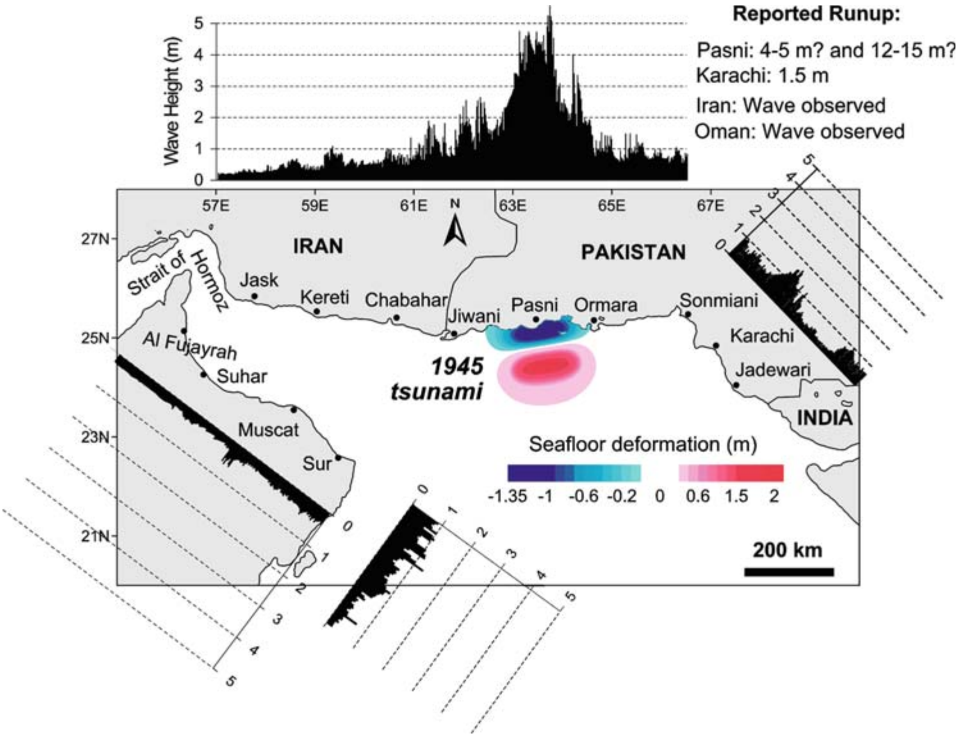

Figure 4
Distribution of the maximum positive tsunami wave heights along the Arabian Sea coasts due to the Makran tsunami of 1945 (after Heidarzadeh *et al*., 2008b).

120 min after the earthquake, which is in approximate agreement with the historical reports. In addition, Figure 4 shows that the simulated wave heights at the southern coasts of Iran and northern coasts of Oman are less than 1 m, thus it is reasonable since there is scant information regarding the effects of the Makran tsunami of 1945 on these coasts. Also, this is consistent with the results of Okal *et al*. (2006b) who attempted to find eyewitnesses of the 1945 tsunami in Oman, but found none, although Okal (2008, personal communication) found one eyewitness who reported 3 m runup in Sur.

4. *Tsunami Scenarios*

The maximum regional earthquake magnitude (M_w 8.3) in the MSZ, estimated in the Section 2, was used for tsunami hazard assessment. Empirical relations proposed by Wells and Coppersmith (1994) were employed to relate the moment magnitude of the earthquake (M_w 8.3) to the fault parameters (rupture length, rupture width and fault displacement). Other seismic parameters were the same as those of the 1945 event (Table 1). However, we used a strike angle of 270° for our source scenarios as the MSZ is

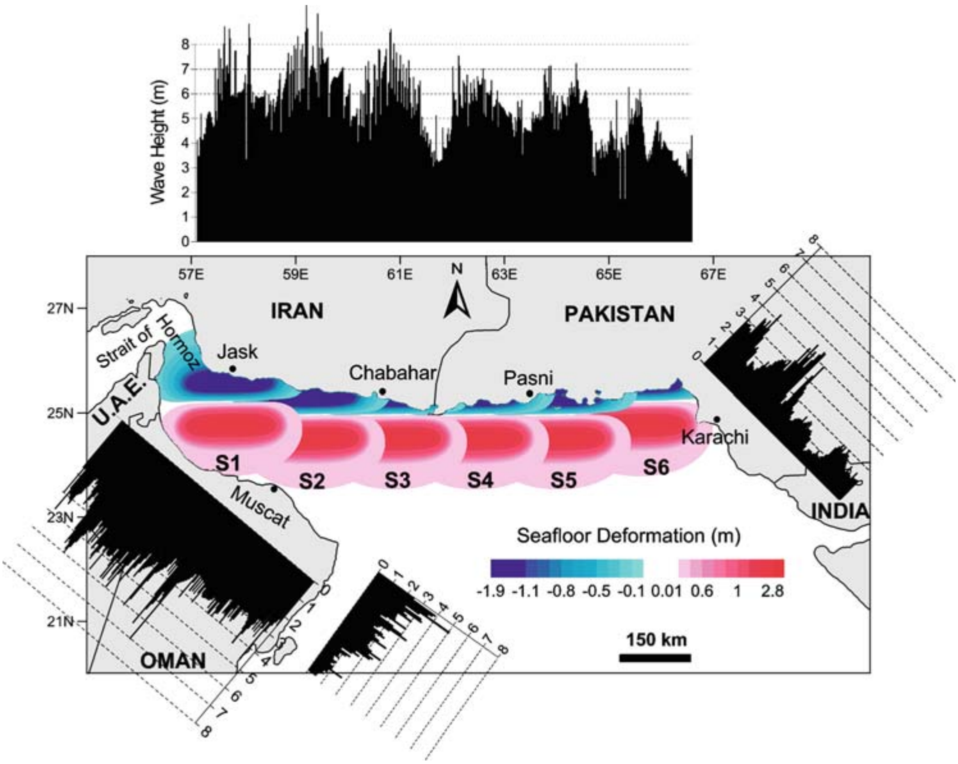

Figure 5
Results of simulations for six tsunami scenarios showing the distribution of maximum positive tsunami wave heights along various coasts.

nearly straight. We note that the predictions made by Wells and Coppersmith's (1994) relations were not directly used here, but we calibrated them using the actual seismic parameters of the Makran earthquake of 1945. As shown in Table 1, the maximum regional earthquake (M_w 8.3) features a seismic moment of about 4.08×10^{21} N m (4.08×10^{28} dyne $\times$ cm).

As the entire length of the MSZ is about 1000 km and since every M_w 8.3 earthquake is capable of rupturing about 200 km of the plate boundary, we considered 6 tsunami scenarios with a 25 km overlap between adjacent scenarios (Fig. 5).

5. *Results of Deterministic Modeling*

The results of tsunami modeling for all of the tsunami scenarios are presented in Figure 5. Also, Figure 6 presents the maximum wave height of the scenario tsunamis as they travel across the Arabian Sea for the case of S4 (Fig. 6a) and S5 (Fig. 6b) along with

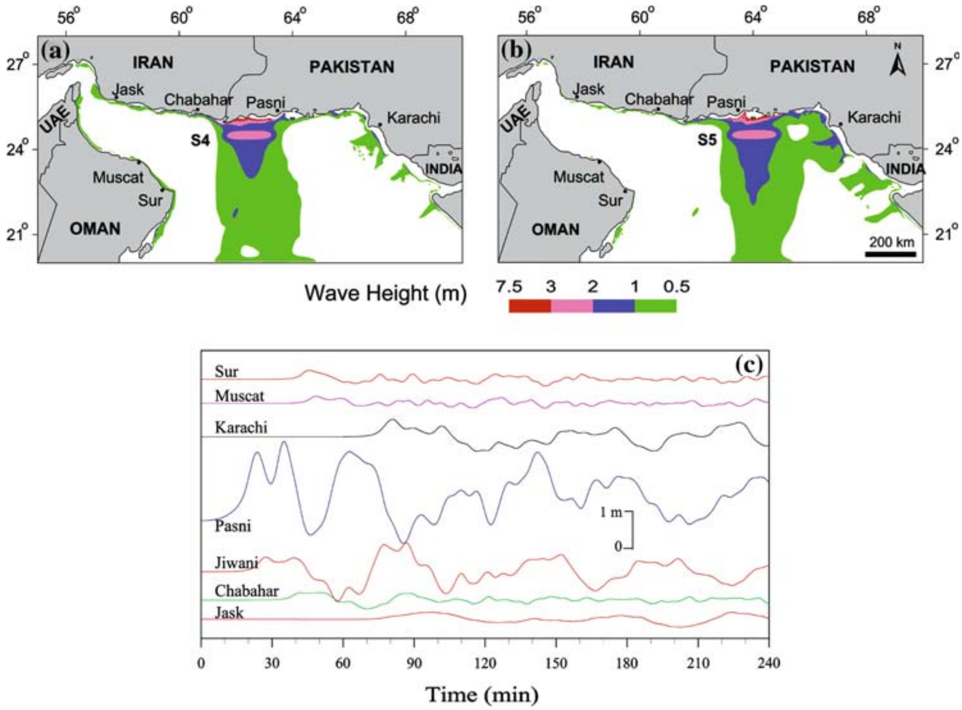

Figure 6
Maximum wave height of the scenario-tsunami as it travels across the Arabian Sea for the case of scenarios S4 (a) and S5 (b), along with the time histories of tsunamis in selected coastlines for the case of S5 scenario (c).

the time histories of the tsunami waves in selected offshore gauges for the case of scenario S5 (Fig. 6c).

Based on Figure 5, the maximum calculated tsunami wave height was about 9.6 m which was due to scenario S2 along the southern coast of Iran. Results showed that, by moving the maximum regional earthquake (M_w 8.3) along the MSZ, the tsunami will reach a height of 4–9.6 m along the southern coasts of Iran and Pakistan, 3–7 m along the northern coast of Oman, 1–5 m along the southern coast of Oman, and 1–4.4 m along the eastern coast of Makran. In their preliminary estimation of the tsunami hazard associated with the MSZ, HEIDARZADEH *et al*. (2008b) concluded that the southern coasts of Iran and Pakistan will experience the largest wave heights and thus are the coasts with the highest hazard in the northwestern Indian Ocean. However, our results based on the current more comprehensive study, revealed that the northern coast of Oman has hazard as high as the southern coasts of Iran and Pakistan.

Figures 6a,b show that most of the tsunami's energy travels perpendicular to the strike of the fault segment which is evident from the theory of directivity (BEN-MENAHEM and ROSENMAN, 1972). HEIDARZADEH *et al*. (2008b) showed that tsunamis originating from the middle and eastern part of the MSZ due to a 1945-type earthquake (M_w 8.1), have minor effects on the Omani and Emirian coasts. Our results, based on an M_w 8.3 earthquake as the tsunami source, support their conclusion, since the maximum wave heights generated by the S4 and S5 scenarios were less than 1 m on the Omani and Emirian coasts (Figs. 6a,b). Therefore, we may conclude that the directivity of tsunami is an important factor when dealing with the tsunami hazard in the northwestern Indian Ocean. Heidarzadeh *et al*. (2008b) reported up to 2 m of tsunami wave height along the Emirian coast due to a 1945-type earthquake. Our simulations showed a wave height of up to 5 m along this coast. Hence, we repeat the statement made by Heidarzadeh *et al*. (2008b) that the tsunami hazard of the Emirian coast cannot be neglected.

According to Figure 6c, the tsunami for case S5 will reach the nearest coast (e.g., Jiwani and Pasni) within about 15 min. However, the tsunami travel times to more distant coasts are longer, e.g., about 45 min for the Omani coast, 35 min for Chabahar, and 75 min for Karachi and Jask. Regarding such a short travel time, we believe that the only warning available will be the ground shaking for the nearest coast to the tsunami source, and it is unlikely that a local tsunami warning system could be effective in warning the nearest coast, e.g., Jiwani and Pasni in this case. However, such a system can be used to warn (or to sound an 'all clear' for, which is also an important function of a warning system) the coasts located far to the east, west, or south of the rupture zone, e.g., Jask, Muscat, and Karachi in this case. Therefore, we recommend the development of a tsunami warning system in the northwestern Indian Ocean.

We emphasize that public education is a must. According to Synolakis and Bernard (2006), in an era of global citizenship, more comprehensive educational efforts on tsunami hazard mitigation are necessary worldwide. Synolakis and Kong (2006) reported that simply educating the local populations and training emergency managers in countries at risk in the Indian Ocean region is not enough. In any coastline vulnerable to a tsunami attack, it is important that everyone can identify the precursors of a tsunami attack and knows to evacuate to high ground or inland as quickly as possible, or, if necessary, how to more safely vertically evacuate to well-built structures that are likely to survive (Synolakis and Kong, 2006). Synolakis and Okal (2005) reported that the 1999 Vanuatu tsunami was a milestone in tsunami hazard assessment, showing the value of education as a mitigating factor of the death toll during near-field tsunamis. However, we note that the public must be informed clearly about the level of an expected tsunami threat and about areas at risk.

6. *Discussion*

The present tsunami hazard assessment was performed by considering the maximum regional earthquake (M_w 8.3) as the tsunami source whose return period is about

1000 years. However, we believe that this earthquake does not represent the worst possible earthquake in the MSZ. Following the 2004 Indian Ocean tsunami and taking into account the lessons learned from this mega-tsunami, OKAL (2007) proposed that the maximum earthquake size expected from a subduction zone depends on the length over which a fault system extends continuously along a convergent plate boundary. This continuous segment is about 500 km for the MSZ as the segmentation of this subduction zone was confirmed by BYRNE *et al*. (1992). By applying the empirical relations of WELLS and COPPERSMITH (1994), the corresponding earthquake magnitude will be about 8.6 in moment magnitude scale. It is evident that such an earthquake and consequent tsunami will be a very rare event, having a far longer return period than that of the maximum regional earthquake (M_w 8.3).

As discussed by HEIDARZADEH *et al*. (2008b), we note that TUNAMI-N2 treats the coastline as a vertical wall, and hence flooding was not permitted in our simulations. In other words, runup calculations were not performed, however the maximum positive tsunami heights along the coast were calculated which provide a reasonable approximation of the runup heights (TINTI *et al*., 2006; YALCINER *et al*., 2002). Therefore, it is possible that our results (Fig. 5) underestimate or overestimate the runup heights in some areas where the actual beach topography may have a pronounced influence on the hydrodynamics of tsunami runup.

7. Conclusions

To more accurately evaluate tsunami hazard in the northwestern Indian Ocean, a series of tsunamis each resulting from the maximum regional earthquake (M_w 8.3) were simulated. The main findings are:

(1) Based on the results of seismic hazard analysis, the maximum regional earthquake magnitude in the MSZ is M_w 8.3 with a return period of about 1000 years.
(2) The maximum calculated tsunami wave height was about 9.6 m which was obtained along the southern coast of Iran.
(3) The tsunami will reach a height of 4–9.6 m along the southern coasts of Iran and Pakistan, 3–7 m along the northern coast of Oman, 1–5 m along the southern coast of Oman, and 1–4.4 m along the eastern coast of Makran.
(4) As was previously reported by HEIDARZADEH *et al*. (2008b), our results showed that the tsunami hazard of the Emirian coast cannot be neglected.
(5) Our results confirmed HEIDARZADEH *et al*.'s (2008b) conclusion that tsunamis originating from the middle and eastern part of the MSZ have minor effects on the Omani and Emirian coasts.
(6) We recommend the development of a tsunami warning system in the northwestern Indian Ocean.

(7) We emphasize the value of education as an essential measure for mitigating the possible death toll from tsunamis in the northwestern Indian Ocean.

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