Successful monitoring of the 11 April 2012 tsunami off the coast of Sumatra by Indian Tsunami Early Warning Centre

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The Indian Tsunami Early Warning Centre (ITEWC) in Hyderabad monitored the 11 April 2012 tsunami off the coast of Sumatra, which was generated by a shallow strike–slip earthquake and it largest aftershock of magnitude M_w (mB) 8.5 and 8.2 respectively, that occurred inside the subducting slab of the Indian plate. The earthquake generated a small ocean-wide tsunami that has been recorded by various tide gauges and tsunami buoys located in the Indian Ocean region. ITEWC detected the earthquake within 3 min 52 s and issued six advisories (bulletins) according to its Standard Operating Procedure. The ITEWC performed well during the event, and avoided false alarms and unnecessary public evacuations, especially in the mainland part of India region.

Keywords: Buoys, earthquake, subducting slab, tide gauges, tsunami monitoring.

A great shallow strike–slip earthquake of magnitude M_w (mB) 8.5 occurred off the west coast of northern Sumatra, Indonesia, on 11 April 2012 at 14:08 IST (08:38 UTC) with its epicentre at 2.40°N and 93.07°E and focal depth of 10 km (Figure 1). The earthquake was followed by another great shallow strike–slip earthquake (aftershock) of magnitude M_w 8.2 at 16:13 IST (10:43 UTC), with its epicentre at 0.87°N, 92.49°E and focal depth of 10 km towards SW of the main shock. Both earthquakes were located within the subducting oceanic lithosphere of the Indian Ocean. They were located more than 100 km to the SW of the major subduction zone that resulted due to the collision between Indo-Australia and Sunda plates. The main earthquake was situated about 300 km west of the giant earthquake of 26 December 2004 of magnitude M_w 9.2 that caused a ocean-wide major tsunami in the Indian Ocean and killed more than 230,000 people in the Indian Ocean rim countries[1–3] (Figure 1). At the location of earthquake, the Indo-Australian plate was found to move towards the NNE direction with a velocity of 52 cm/yr with respect to the Sunda plate[4]. The triple junction formed by the Indian, Australian and Sunda plates, at the location of the earthquake, makes this region unstable and also causes frequent occurrences of large earthquakes there[5]. The occurrence of large strike–slip earthquakes is unprecedented in the diffuse plate boundary region that separates the India and Australia plates towards the SW of the Sumatra subduction zone. This region recently experienced three strike–slip earthquakes near to the main shock on 19 April 2006 (M_w 6.2), 4 October 2007 (M_w 6.2) and 10 January 2012 (M_w 7.2). The focal mechanisms of these earthquakes are consistent with the 11 April 2012 earthquakes, implying that each earthquake could have occurred as the result of either left-lateral slip on a north-northeast striking fault or right-lateral slip on a south-southwest striking fault[6].

The 11 April 2012 earthquake (M_w (mB) 8.5) generated a small ocean-wide tsunami that was monitored by the Indian Tsunami Early Warning Centre (ITEWC) at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad. Since the establishment of ITEWC in 2007, it has been serving as the primary source of tsunami advisory for India and, after October 2011, as the Regional Tsunami Advisory Service Provider (RTSP) for the whole Indian Ocean region along with Australia and Indonesia[3,7]. The operational procedure of ITEWC includes detection, location and determination of the magnitude of potentially tsunamigenic earthquakes occurring in the Indian Ocean, estimation of travel time and run-up heights of tsunamigenic waves using pre-run tsunami simulation models and dissemination of bulletins/notifications[3]. The pre-run tsunami simulation model consists of 5000 possible earthquake scenarios for the Andaman–Sumatra–Java and Makran subduction belts. After detection of a tsunamigenic earthquake in the region, the scenario nearest to the actual earthquake is extracted from the database and tsunamigenic wave heights

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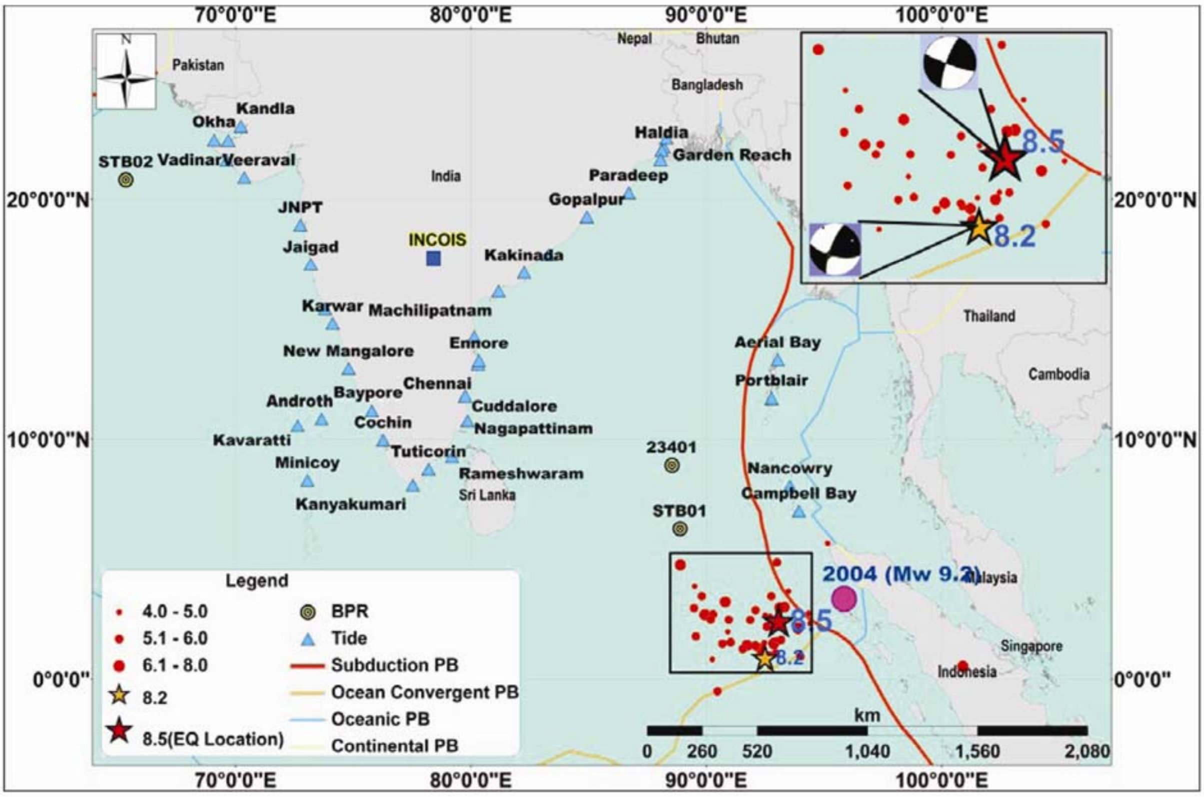

Figure 1. Location of earthquake of magnitude 8.5, its largest aftershock of magnitude 8.2 and other small aftershocks. The devastating Sumatra earthquake of 2004, of magnitude M_w 9.2, is shown by a red solid circle. The tsunami buoys (BPR; bottom pressure recorder) and tide gauge locations are shown with double circles and triangles respectively. (Inset) Location of the main earthquake and its aftershocks. The style of faulting of the main earthquake (8.5) and its largest aftershock (8.2) is also shown on lower equal-area hemisphere projection revealing the strike–slip faulting for these earthquakes.

Table 1. Threat-level status criteria for considering an area under different threat levels

Pre-run model scenario results			
ETA ≤ 60 min		ETA > 60 min	
EWA (M)	Threat status	EWA (M)	Threat status
>2	Warning	>2	Alert
0.5–2	Alert	0.5–2	Watch
0.2–0.5	Watch	0.2–0.5	Watch

ETA, Estimated time of arrival; EWA, Estimated wave amplitude.

are scaled to suite the scenario that must have emerged due to the event. This procedure helps in quickly identifying the regions under risk at the time of tsunamigenic events. Significant changes in the sea level, if any, are monitored at the time of occurrence of tsunamigenic earthquakes using tsunami buoys and tide gauges installed in the Indian Ocean. Timely tsunami bulletins (categorizing coastal areas under Warning/Alert/Watch/Threat Passed) are disseminated to the vulnerable communities and authorities in various government departments following a Standard Operating Procedure (SOP) by means of multiple communication channels (Table 1).

The SOP followed at ITEWC is unique and capable of differentiating between near-source and far-source coastal regions and generate bulletins with different threat levels (based on the response time and estimated wave height); thus reducing the number of false alarms. Details of SOP followed by ITEWC during tsunamigenic earthquakes are available in Kumar *et al.*[3]. In the present article, an attempt has been made to examine the efficiency and effectiveness of SOP followed by ITEWC in monitoring the tsunamigenic earthquake on 11 April 2012 off the west coast of northern Sumatra and issuing meaningful information to the authorities in India and tsunami warning focal points in the Indian Ocean rim countries.

The SOP followed at ITEWC

According to SOP of the ITEWC, the Centre issues Bulletin-1 for the Indian Ocean earthquakes, that contains preliminary earthquake information and a qualitative statement on its tsunamigenic potential based on the criteria given in Table 1. Based on preliminary earthquake parameters, the nearest matching scenario from pre-run model scenario database is selected. If the pre-run model scenario indicates estimated wave amplitude (EWA) <

0.2 m, then Bulletin-2 is issued with 'No Threat' information. However, the monitoring of sea-level observations continues. If EWA > 0.2 m, then Bulletin-2 is issued with the estimated time of arrival (ETA), EWA and threat category (Warning/Alert/Watch) for each of the coastal forecast zones. The criteria for the generation of different threat types (Warning/Alert/Watch) for a particular region of the coast are based on the available warning time (i.e. time taken by the tsunamigenic wave to reach the particular coast). The threat criteria of National Tsunami Warning Centre (NTWC) are based on the premise that coastal areas falling within 60 min travel-time from a tsunamigenic earthquake source need to be warned based solely on earthquake information and model estimates, since sufficient time may not be available for confirmation of water levels from the bottom pressure recorders (BPRs) and tide gauges. Coastal areas falling outside the 60 min travel-time from a tsunamigenic earthquake source could be put under Alert/Watch status and upgraded to an Alert/Warning status only upon confirmation from water-level data. The criteria for considering an area under different threat levels (Warning/Alert/Watch) are given in Table 1.

When the revised earthquake parameters become available, or when the earthquake elapsed time exceeds > 60 min, but still no real-time sea-level data are available even from the nearest sea-level gauge or BPR, then a supplementary to the Bulletin-2 (Bulletin-2 Supplementary-xx) is issued with revised threat (Warning/Alert/Watch) information. When the data on sea level become available, and if they confirm the generation of a tsunami, the Warning Centre issues Bulletin-3 with revised threat (Warning/Alert/Watch) information from model scenario together with the observed water levels. As and when subsequent real-time observations become available or after 60 min from the time of issue of the previous bulletin, Bulletin-3 Supplementary-xx is issued. The Bulletin-3 Supplementary-xx messages also may contain the 'Threat Passed' information, if any, for the individual coastal zones. The Final Bulletin withdrawing the Warning/Alert/Watch is issued when there are no significant water level changes reported by multiple sea-level gauges or 120 min after the last exceedance of 0.5 m threat threshold at last coastal zone on the Indian coast. However, as local conditions would cause a wide variation in tsunamigenic wave action, the 'All Clear' determination needs to be made by the local authorities.

Monitoring of the 11 April 2012 tsunami

The ITEWC detected this earthquake within 3 min 52 s, and located it within 7 min from its occurrence with the help of 'SeiscomP' auto-location software. The initial magnitude of this earthquake was estimated as M_w (mB) 8.7 with a focal depth of 10 km. The first National (NTWC) and Regional (RTSP) bulletins with earthquake information (location, magnitude, focal depth and origin time) were issued after 8 min of the occurrence of the earthquake which is within the target of 10/15 min prescribed by Intergovernmental Oceanographic Commission (IOC)-Intergovernmental Coordination Group (ICG)/Indian Ocean Tsunami Warning and Mitigation System (IOTWS)-V/13 (ref. 8). The initial qualitative evaluation in the first bulletin stated that 'Earthquake of this size sometimes has the potential to generate ocean-wide tsunami that can be destructive along the entire coastline of the Indian Ocean'. Then, it was noted that the Indian Tsunami Buoy (STB-01) and Thailand Buoy (23401) in the Bay of Bengal got triggered into tsunami mode soon after the earthquake, due to the seismic Rayleigh waves.

According to SOP of ITEWC (Table 1), the second bulletin with tsunami threat information based on pre-run model simulations of Sumatra–Sunda subduction zone was issued to NTWC and RTSP contacts after 12 min of the occurrence of the earthquake. In the initial tsunami simulation, ITEWC considered this event as a thrust fault mechanism, as a worst case, since at that time the style of faulting for the earthquake was not available. The directivity and travel-time maps were generated using the above-mentioned earthquake information and pre-run tsunami simulation scenarios (Figure 2). The second bulletin for NTWC revealed that the estimated wave height at Indira Point, Car Nicobar and Komatra and Katchal islands of the Andaman and Nicobar Islands was about 3–6 m. These three regions were kept under 'Warning' status, since they fell within the less than 60 min arrival of the tsunamigenic wave with an expected height of more than 2 m (Table 1). The remaining islands of the Andaman and Nicobar and the east coast regions of India like Andhra Pradesh and Tamil Nadu were kept under 'Alert' status, as the estimated wave arrivals at these regions were more than 60 min and the estimated water levels were in the 0.5–2.0 m range (Figure 3 *a*). The west coast of India was kept under 'Watch' mode, as the estimated water level was less than 0.5 m. The second bulletin for RTSP revealed that the Sumatra region, Oman, Somalia, Kenya, the east coast of Madagascar and west coast of Australia were under 'Threat' status along with some other regions, as shown in Figure 3 *b*.

The third bulletin was issued 74 min (09:52 UTC) after the occurrence of the earthquake with a revised earthquake magnitude of M_w (mB) 8.5 and confirmation of tsunami generation based on the first available sea-level observations at tsunami buoy STB01. At that time, the style of faulting of the earthquake, estimated as strike–slip, was available from USGS and GEOFON. Using the revised earthquake magnitude of 8.5 and nature of faulting (strike–slip), the tsunami simulation model was re-run to revise the directivity map, travel-time map and threat maps for national and regional (RTSP) levels. The revised estimates put only two regions, namely Indira Point

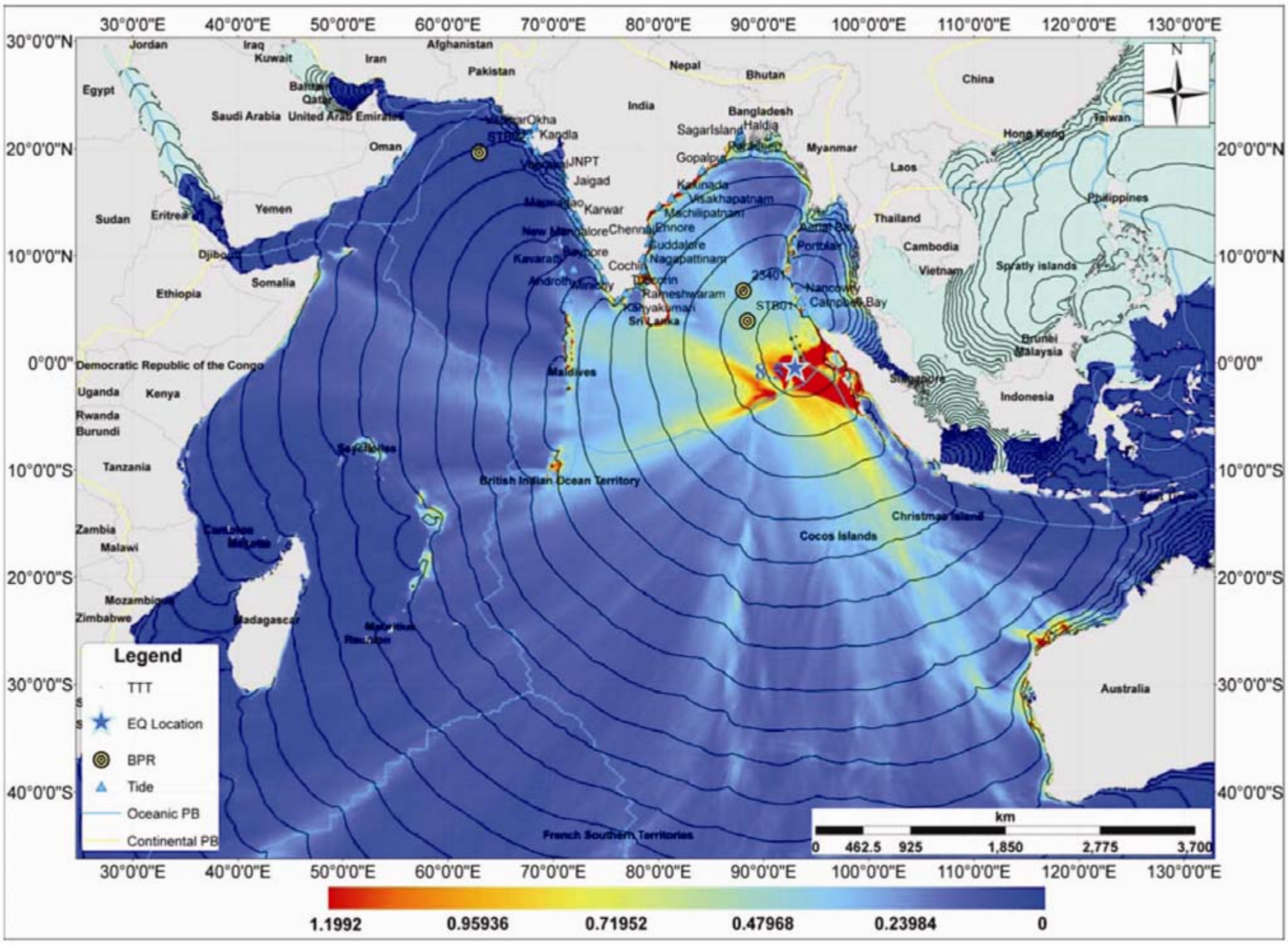

Figure 2. Directivity and travel-time maps for the 11 April 2012 main earthquake of magnitude 8.5, revealing the threat levels due to the tsunami and expected arrival time of the tsunami at varrious locations in the Indian Ocean.

and Komatra and Katchal Islands of the Andaman and Nicobar Islands under warning. The real-time water-level observations (Figure 4) showed the arrival of tsunamigenic wave at STB01 at 09:17 UTC with maximum wave height of 0.06 m (Table 2, Figure 4). At 23401 DART buoy, the first tsunamigenic wave reached at 09:47 UTC with maximum wave height of 0.04 m. Since the water-level observations had confirmed the generation of a tsunami, regions where the estimated water-level height from model simulation exceeded 0.5–2 m (Odisha, Andhra Pradesh, Tamil Nadu, Kerala, Lakshadweep) were kept under ‘Alert’ status and those where the estimated wave heights were less than 0.5 m (West Bengal, Karnataka, Goa, Maharashtra and Gujarat) were kept under ‘Watch’ status.

The fourth bulletin was issued 1 h 40 min (10:20 UTC) after the occurrence of the earthquake reporting the observed water-level changes at Campbell-Bay (India) and Sabang (Indonesia). The first tsunamigenic wave at Campbell-Bay tide gauge (India) reached at 9:42 UTC with maximum wave height of 0.30 m. At Sabang tide gauge (Indonesia), first tsunamigenic wave reached at 09:44 UTC with maximum wave height of 0.35 m. On the basis of these real-time water-level observations, previous threat levels for NTWC and RTSP were kept as such and ‘Warning’ was effective for Indira Point and Komatra and Katchal islands of the Andaman and Nicobar Islands.

The fifth bulletin was issued 2 h 54 min (11:33 UTC) after the occurrence of the earthquake reporting water-level changes observed at more locations, namely Telukdalam, Meulaboh and Nancowry tide gauges (Table 2, Figure 4). In this bulletin also, the threat levels were kept the same as in the previous bulletin, since water-level observations confirmed the occurrence of a tsunami. Though this is an over cautious approach, it is necessary to avoid the unexpected damages due to higher second, third or subsequent waves. The maximum tsunamigenic wave height of 1.06 m was observed at Meulboh tide gauge (Indonesia), where the first tsunamigenic wave had reached at 09:51 UTC. The Telukdalam tide gauge (Indonesia) showed the first tsunamigenic wave arrival at

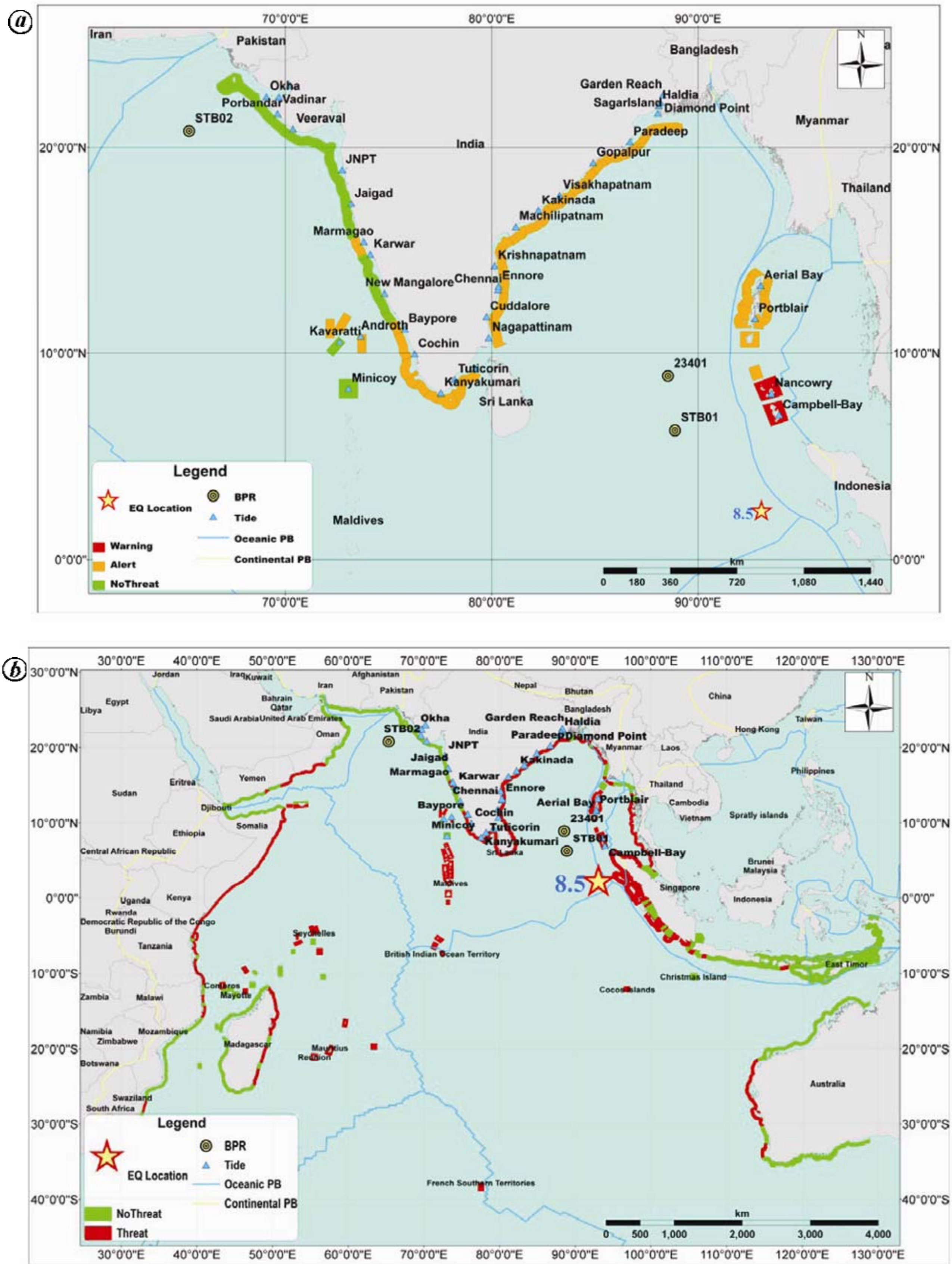

Figure 3. Threat levels for (***a***) National Tsunami Warning Centre (NTWC) and (***b***) RTSP estimated according the standard operating procedure. For NTWC, three levels of threat are shown, i.e. Warning, Alert and Watch; while for RTSP only two levels, i.e. 'Threat' and 'No Threat' are shown.

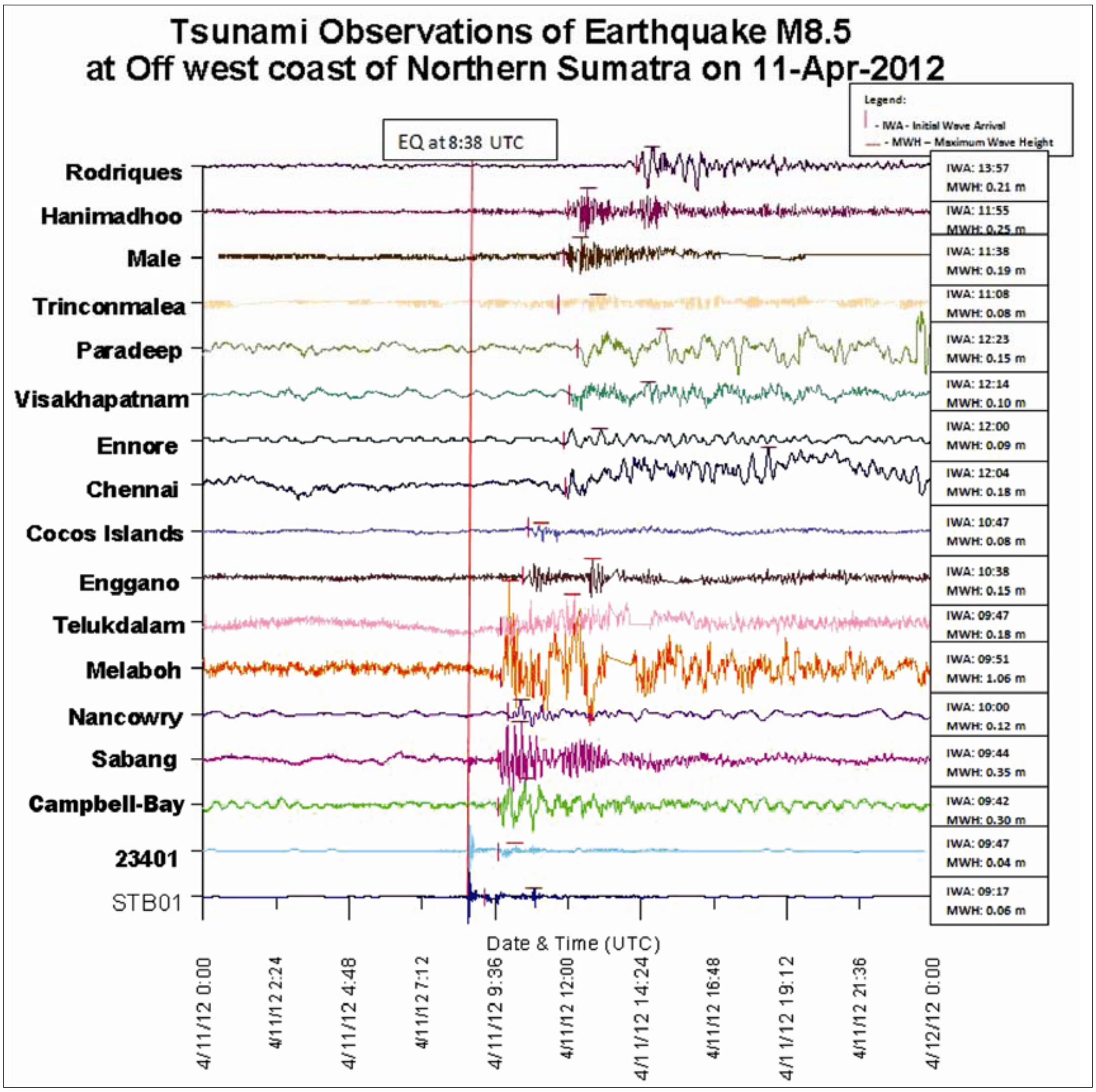

Figure 4. Observations at different tsunami buoys and tide gauges installed in the Indian Ocean region showing water-level variations during the 11 April 2012 tsunami.

Table 2. Water-level observations at various tide gauges and tsunami buoys situated in the Indian Ocean

Station	Latitude (°)	Longitude (°)	Observed maximum wave arrival (UTC)	Observed maximum wave height (m)
STB01 (BPR)	6.25N	88.80E	09:17	0.06
23401 (BPR)	8.90N	88.50E	09:56	0.04
Campbell-Bay	6.90N	93.70E	09:42	0.30
Nancowry	7.96N	93.53E	10:10	0.12
Sabang	5.83N	95.33E	09:45	0.35
Meulaboh	4.31N	96.21E	10:00	1.06
Telukdalam	0.60N	97.80E	10:35	0.18
Enggano	5.34S	102.27E	10:47	0.15
Cocos Island	12.11S	96.80E	11:02	0.08
Chennai	13.10N	80.30E	18:20	0.18
Ennore	13.25N	80.33E	12:00	0.09
Visakhapatnam	17.71N	83.32E	12:19	0.10
Paradeep	20.24N	86.64E	14:47	0.15
Trinconmalae	8.60N	81.20E	11:16	0.08
Male	4.19N	73.52E	12:16	0.19
Hanimadhoo	6.76N	73.16E	12:30	0.25
Rodrigues	19.68S	63.42E	14:24	0.21

Table 3. Performance comparison between different tsunani warning centres (TWCs)

TWC bulletins	ITEWC, India	InaTEWS, Indonesia	JATWC, Australia	PTWC, USA	JMA, Japan
First bulletin (earthquake information)	Issued: 8 min*; magnitude: 8.7 M_w (mB)	Issued: 20 min*; magnitude: 8.3 M_{wp}	Issued: 10 min*; magnitude: 8.5 M_{wp}	Issued: 7 min*; magnitude: 8.7	Issued: 17 min*; magnitude: 8.7
Second bulletin (expected threat information)	Issued: 12 min* Evaluation: 'Warning' – Indira Point, Car-Nicobar and Komatra and Katchal Islands of Andaman and Nicobar Islands. 'Alert' – Tamil Nadu, Andhra Pradesh and rest of the Andaman Islands. 'Watch' – Few areas of the mainland	Issued: 25 min* Evaluation: Andaman and Nicobar Islands, Tamil Nadu, Andhra Pradesh, Odisha, Kerala, Karnataka and Maharashtra are under 'Threat' (EWH ≥ 0.5 m)	Issued: 18 min* Evaluation: Andaman and Nicobar Islands and Tamil Nadu are under 'Threat' (EWH ≥ 0.5 m)	Issued: 67 min* Evaluation: Entire Indian coast under tsunami 'Watch'[#]	Issued: 122 min* Evaluation: Entire Indian coast under tsunami 'Watch'[#]
Third bulletin (sea-level observations)	Issued: 74 min*	Issued: 273 min*	Issued: 133 min*	Issued: 96 min*	–
Final bulletin (cancellation)	Issued: 250 min*	Issued: 628 min*	Issued: 466 min*	Issued: 238 min*	–

*Bulletin issued time is in minutes from earthquake origin time.
[#]PTWC and JMA issue tsunami watches for the Indian Ocean (region outside their area of responsibility for which they provide interim services). 'Watch' in this case represents areas under 'Tsunami Threat'.

09:47 UTC, with maximum wave height of 0.18 m. At Nancowry tide gauge (India), the first tsunamigenic wave reached at 10:00 UTC, with maximum wave height of 0.12 m. The second tsunamigenic wave with heights as of 0.3 and 0.2 m was observed at Sabang and Campbell-Bay tide gauge stations respectively.

The sixth bulletin (final) was issued 4 h and 10 min (12:50 UTC) after the occurrence of the earthquake with 'All clear' information confirming that the tsunami threat had passed for the Indian mainland and the island region. The bulletin also included additional water-level observations at Cocos Island (Australia), Ennore, Chennai and Visakhapatnam (India). The maximum wave height observed at these stations was only 0.1 m. The ITEWC monitored the tsunami generated by the earthquake very well and issued bulletins according to SOP. All the systems, i.e. automatic location of the earthquake, estimation of tsunami arrival time and height, dissemination of messages through SMS, e-mail, fax, GTS and website, as well as BPRs and tidal gauges to record sea-level changes have performed as envisaged. All the six bulletins were disseminated to both the national and regional contacts in the form of public and exchange bulletins. It might also be noted that ITEWC disseminated regional tsunami advisories to 23 countries in the Indian Ocean region (Australia, Bangladesh, Comoros, Reunion Islands, Indonesia, Iran, Kenya, Madagascar, Malaysia, Maldives, Mauritius, Mozambique, Myanmar, Oman, Pakistan, Seychelles, Singapore, South Africa, Sri Lanka, Thailand, Timor Leste, Tanzania and Yemen) as part of its RTSP operations.

Concluding remarks

A tsunami early warning centre, established at INCOIS with all the necessary computational and communication infrastructure, has performed well under all circumstances during the 11 April 2012 tsunami off the coast Sumatra. The end-to-end performance of capabilities of this warning system has been well proven during this tsunamigenic earthquake. If warning were generated for this event solely based on earthquake parameters, as is the case with many traditional warning systems (Table 3), it would have called for an Indian Ocean-wide tsunami warning. However, by use of pre-run model simulations and the unique SOP of ITEWC, only three zones in the Nicobar Islands were placed under warning, that called for evacuation of public to higher grounds. The Andaman Islands as well as the east coast of India were placed under 'Alert' status that implicated a marine threat and hence only clearing the beaches. Thus, the timely advisories generated for the above event avoided false alarms and unnecessary public evacuations in the mainland part of the India region. There are a lot of lessons (technical as well as logistic) learnt from this event, which ITEWC should incorporate into its warning system to further improve its capabilities. The water-level data inversion, real-time inundation modelling, real-time estimation of focal mechanism of the earthquake to show style of faulting and incorporation of GPS data into the warning chain are a few key issues that ITEWC needs to take up on a priority basis, to improve its accuracies. The web infrastructure also needs to be enhanced to handle bursts of large traffic during such events.

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