Performance of the tsunami forecast system for the Indian Ocean

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The Indian Tsunami Early Warning System (ITEWS) at the Indian National Centre for Ocean Information Services, Hyderabad, is responsible for issuing tsunami bulletins in India. The tsunami centre operates on a 24 × 7 basis and monitors seismological stations, bottom pressure recorders and tidal stations throughout the Indian Ocean to evaluate potentially tsunamigenic earthquakes and disseminating tsunami bulletins. The end-to-end capabilities of this warning system have been well proven during all the tsunamigenic earthquakes that occurred since September 2007. Comparison of the earthquake parameters estimated by ITEWS with other international seismological agencies suggests that the system is performing well and has achieved the target set up by the Intergovernmental Oceanographic Commission.

Keywords: Bottom pressure recorders, Indian Tsunami Early Warning System, tidal stations, tsunami modelling and bulletins.

THE great Sumatra–Andaman earthquake[1,2] of 26 December 2004 of magnitude *Mw* 9.2, the second largest instrumentally recorded earthquake in the world[3], generated a devastating tsunami which caused unprecedented loss of lives and damage to properties in the Indian Ocean rim countries[4–9]. This tsunami was considered as one of the deadliest natural hazards in the history, killing over 230,000 people in 14 countries. In India, it claimed about 10,745 lives, according to official estimates of the Ministry of Home Affairs, Government of India[4]. In response to this disaster, India has established the Indian Tsunami Early Warning System (ITEWS) at Indian National Centre for Ocean Information Services (INCOIS), Hyderabad (Figure 1).

The functions of ITEWS include 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 and dissemination of the notification to all concerned. A database of all possible earthquake scenarios for the Indian Ocean is used to identify the regions under risk at the time of the event. Significant changes in sea level are monitored at the time of occurrence of tsunamigenic earthquakes. Timely tsunami bulletins (categorizing coastal areas under Warning/Alert/Watch/Threat Passed) are disseminated to the vulnerable community following a standard operating procedure (SOP) by means of various available communication methods[10]. The ITEWS is operational since October 2007 and has been issuing accurate tsunami advisories for all under-sea earthquakes of magnitude $M \geq 6.5$. The warning centre is capable of issuing tsunami bulletins in less than 10 min after any major earthquake in the Indian Ocean.

The ITEWS comprises a real-time network of seismic stations, bottom pressure recorders (BPRs), tide gauges and 24 × 7 operational tsunami warning centre to detect tsunamigenic earthquakes, monitor tsunamis and provide timely advisories to the vulnerable community using the latest communication methods with back-end support of a pre-run model scenario database and decision support system (DSS)[10–15]. The important components of the ITEWS are given below.

(1) Seismic and sea-level observation system: About 300 global seismic data are received in real-time from IRIS Global Seismographic Network and GEOFON Extended Virtual Network, including data from 17 broadband seismic stations in India established by India Meteorological Department. The seismic parameters (origin time, location, depth and magnitude) are being processed through autolocation software, namely Seiscomp and Response Hydra. The sea-level observation is monitored through two types of sea-level gauges: BPRs and coastal tide gauges. BPRs are used to detect the propagation of tsunami waves in the open ocean. A network of tide gauges helps to monitor the progress of tsunami and validate the tsunami model. The ITEWS is monitoring sea level using 25 tide gauges along the coast and four BPRs in the Indian Ocean.

(2) Tsunami modelling: The TUNAMI-N2 (Tohoku University's Numerical Analysis Model for Investigation of Near-field Tsunamis, version-2) model[16], customized for the Indian Ocean, is used for estimating possible tsunami travel times and run-up heights for different earthquakes. This model uses available earthquake parameters and assumes worst slip[17]. The tsunami centre maintains a large database of pre-run scenarios for timely dissemination of the advisories. The surge heights and travel times at nearly 1800 coastal points along the Indian Ocean can be picked up easily from the database for early warning purpose.

(3) Decision support system (DSS): An exclusive DSS has been built to pickup the closest scenario from the database that helps in generating the tsunami advisories at the time of an event. That is, the DSS picks up the nearest earthquake scenario and the associated Tunami N2 model estimates of possible water levels and arrival times along the Indian Ocean. This enables the centre to assess the possibility of tsunami generation, and the likely severity due to the rise in water level at various

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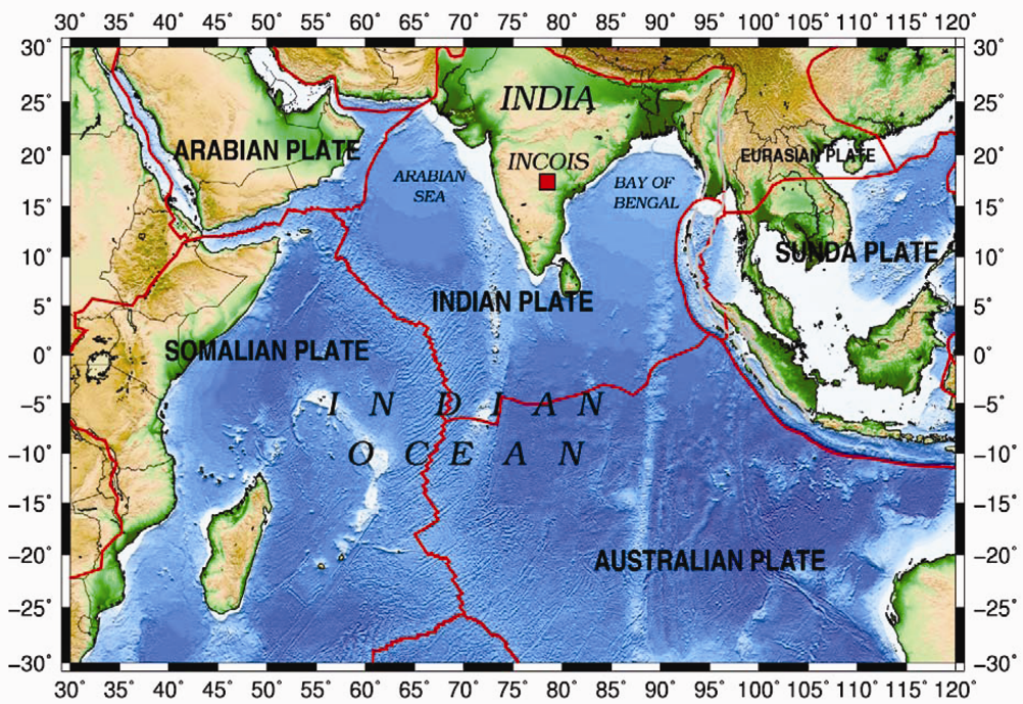

Figure 1. Regional tectonic setting of the Indian Ocean. The location of Indian Tsunami Early Warning System (ITEWS) at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad is shown by a red square in the map of India.

Table 1. Summary of the performance levels achieved by the Indian National Centre for Ocean Information Services as criteria given by International Oceanographic Commission (IOC)

Parameter	Targets	Achievements
Elapse time from earthquake origin time to initial earthquake information issuance (local/distant)	10/15 min	6 min
Probability of detection of Indian Ocean earthquakes with $Mw \geq 6.5$	100%	100%
Accuracy of hypocentre location (with respect to USGS)	Within 30 km	9.5 km
Accuracy of hypocentre depth (with respect to USGS)	Within 25 km	22.5 km
Accuracy of earthquake *Mw* magnitude (with respect to USGS)	0.2	0.2
Reliability of RTWP operations (power, computer, communication)	99.5%	Achieved

locations along the coasts of the Indian Ocean, and the generation of appropriate advisories for use by the disaster management authorities.

The services of the warning centre for an earthquake event commence whenever earthquakes with magnitude ≥ 6.5 within the Indian Ocean and magnitude ≥ 8.0 outside Indian Ocean are recorded by the seismic network. Analysis of the events includes automatic and interactive processes for determining the epicentre, depth, origin time, and magnitude of an earthquake. The tsunami warning centre issues two types of products (bulletins), namely Public and Exchange tsunami bulletins. The Public products contain earthquake information (origin time, location, magnitude and depth) and tsunami-genesis potential of the earthquake. The Exchange products contain coastal forecast zones (CFZs) tagged with results of a forecast model such as estimated wave amplitude, estimated time of arrival and threat level. The CFZs are high-resolution spatial boxes of 100 km × 50 km, extrapolated to district-level information. As the Exchange products need an expert interpretation, they are provided only to authenticated agencies through secured means.

Since May 2010, the tsunami warning centre monitored and reported 73 earthquakes of magnitude ≥ 6.5 covering the entire globe. A summary of the performance of the warning centre against key performance indicators (set up by IOC-ICG/IOTWS-V/13)[18] for the above events is given in Table 1. It may be noted that the desired targets have been achieved. Since the inception of the warning centre in October 2007 till date, it has monitored and reported 24 tsunamigenic events (under-sea earthquakes with magnitude ≥ 6.5) in the Indian Ocean region. The model simulations were analysed, real-time water levels were closely monitored and earthquake/tsunami forecasts were issued according to the SOP. The forecast issued by the ITEWS, the Pacific Tsunami Warning Center

Table 2. Comparison of threat level issued by the Indian Tsunami Early Warning System (ITEWS), the Pacific Tsunami Warning Center (PTWC) and the Japan Meteorological Agency (JMA) to the tsunamigenic events in the Indian Ocean during the period September 2007 to April 2011

Date and time (UTC)	*M*	Region	ITEWS	PTWC	JMA
3 April 2011 20:06:42	6.7	South of Java, Indonesia	Tsunami threat does not exist for India	Tsunami information bulletin – A very small possibility of a local tsunami	Tsunami information bulletin – A very small possibility of a destructive local tsunami
25 October 2010 14:42:20	7.5	Southern Sumatra, Indonesia	Tsunami threat does not exist for India	Local tsunami watch for Indonesia	Local tsunami watch for Sumatra, Java (Indonesia) and Cocos Island (Australia)
12 June 2010 19:26:47	7.5	Nicobar Island, India	No tsunami threat for the Indian mainland Tsunami Watch for Nicobar, Komatra and Katchal Islands Cancelled after 1 h 30 min	Regional tsunami watch for India/Indonesia/Sri Lanka/ Myanmar/Thailand/ Malaysia	Regional tsunami watch – possibility of destructive regional tsunami
9 May 2010 11:29:44	7.4	Northern Sumatra	Tsunami threat does not exist for India	Local tsunami watch for Indonesia	Local tsunami watch – possibility of destructive local tsunami
6 April 2010 22:15:03	7.7	Northern Sumatra	Tsunami threat does not exist for India	Local tsunami watch for Indonesia	Local tsunami watch – possibility of destructive local tsunami
30 March 2010 16:54:50	6.9	Andaman and Nicobar (A&N) Islands, India	No tsunami threat for the Indian mainland Tsunami Watch for West and land-fall islands, Flat Islands, North Sentinel Islands, Port Blair Cancelled after 1 h 20 min	Tsunami information bulletin – A very small possibility of a local tsunami	Tsunami information bulletin – A very small possibility of a destructive local tsunami
30 September 2009 10:16:11	8.0	Southern Sumatra, Indonesia	Tsunami threat does not exist for India	Regional tsunami watch for Indonesia/India/Thailand/ Malaysia	Regional tsunami watch – possibility of destructive regional tsunami
2 September 2009 07:55:03	7.8	Java, Indonesia	Tsunami threat does not exist for India	Local tsunami watch for Indonesia	Local tsunami watch – possibility of destructive local tsunami
16 August 2009 07:38:28	7.0	Southern Sumatra, Indonesia	Tsunami threat does not exist for India	Tsunami information bulletin – A very small possibility of a local tsunami	Tsunami information bulletin – A very small possibility of a destructive local tsunami
10 August 2009 19:55:38	7.6	A&N Islands, India	No tsunami threat for India	Regional tsunami watch for India/Myanmar/Indonesia/ Thailand/Bangladesh. It was cancelled after 3 h	Regional tsunami watch – possibility of destructive regional tsunami
25 February 2008 08:36:35	7.2	Kepulauan Mentawai region, Indonesia	No tsunami threat for India	Local tsunami watch for Indonesia	Local tsunami watch – possibility of destructive local tsunami
20 February 2008 08:08:30	7.3	Coast of Northern Sumatra	No tsunami threat for India	Local tsunami watch for Indonesia	Local tsunami watch – possibility of destructive local tsunami
24 October 2007 21:02:49	7.1	Southwest of Sumatra, Indonesia	No tsunami threat for India	Local tsunami watch for Indonesia	Tsunami information bulletin – A very small possibility of a destructive local tsunami
12 September 2007 23:49:05	7.8	Kepulauan Mentawai region, Indonesia	No tsunami alert for the Indian mainland Tsunami Watch for A&N Islands Cancelled after 3 h	Regional tsunami watch for Indonesia/Australia/ Thailand/Malaysia/ Singapore	Regional tsunami watch
12 September 2007 11:10:26	8.5	Southern Sumatra, Indonesia	Tsunami Watch for A&N Islands, Odisha, Andhra Pradesh, Tamil Nadu, Kerala Cancelled after 5½ h	Indian Ocean-wide tsunami Watch	Indian Ocean-wide tsunami watch

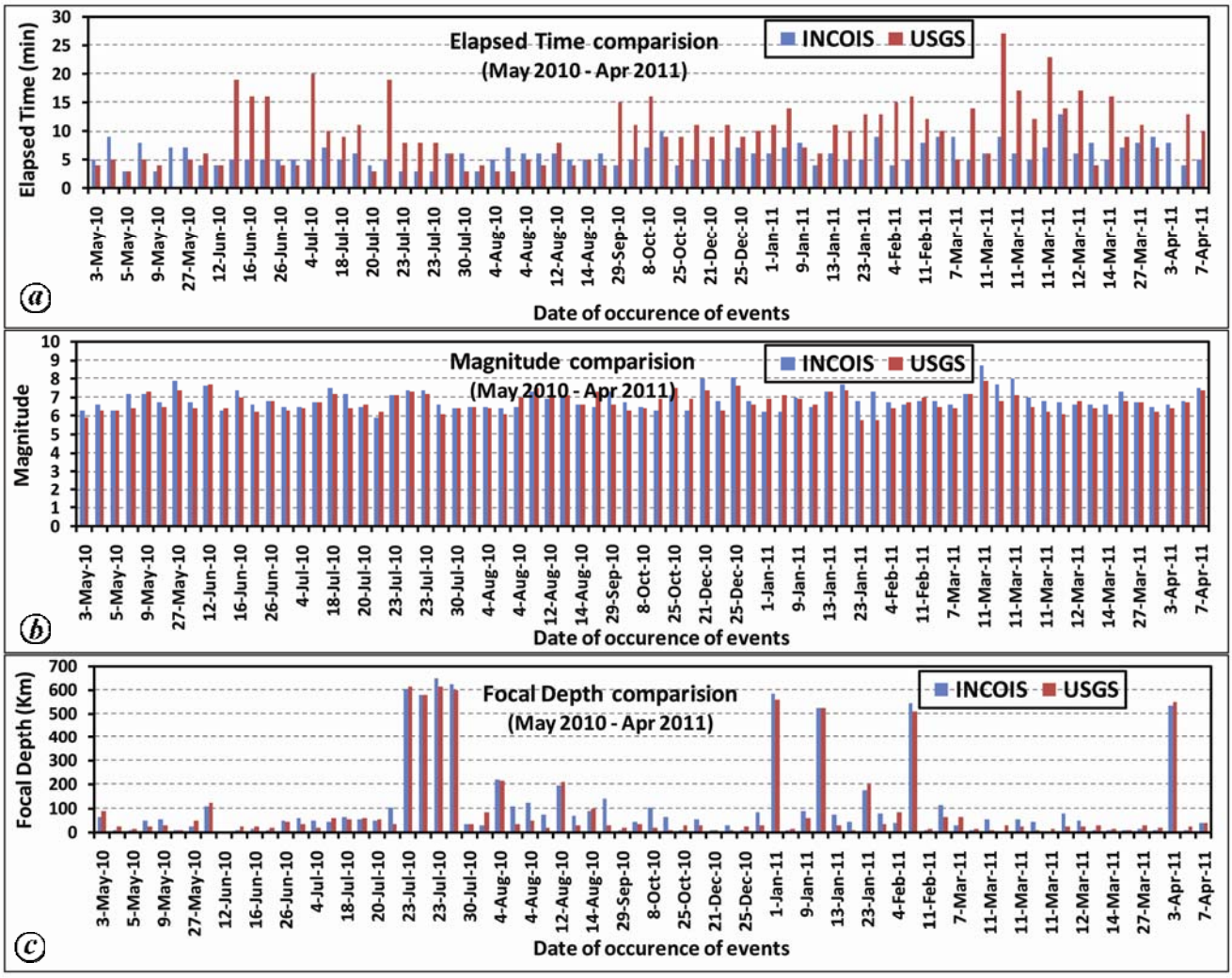

Figure 2. Comparison of earthquake parameters: (***a***) elapsed time, (***b***) magnitude and (***c***) focal depth of earthquakes of magnitude $M \geq 6.5$ recorded and computed by INCOIS during the period May 2010 to April 2011 with those of USGS.

(PTWC) and the Japan Meteorological Agency (JMA) for a few tsunamigenic events are listed in Table 2. It may be noted that, only for four occasions, a tsunami Watch/ Alert was issued by the centre, that too only for selected near-source areas in the Andaman and Nicobar Islands; whereas other centres issued local/regional/ocean-wide tsunami watches for all the events. In addition to these Indian Ocean earthquakes, ITEWS has also monitored three global ocean earthquakes: (1) Chile Earthquake (*M* 8.6) on 27 February 2010, 06:34:11 (UTC), (2) Vanuatu Islands Earthquake (*M* 7.6) of 25 December 2010, 13:16:38 (UTC) and (3) Honshu, Japan Earthquake (*M* 8.9) of 11 March 2011, 05:46:23 (UTC). For all these earthquakes 'No Threat' bulletins were issued for the Indian Ocean.

A comparison of earthquake parameters (elapsed time, magnitude, focal depth and location) estimated by INCOIS has been made with other international agencies, like the US Geological Society (USGS). The performance comparison has been made for 73 earthquakes with magnitude ≥ 6.5 that occurred in the Indian as well as Global Ocean during the period May 2010–April 2011 (Figure 2). The main aim is that the parameters estimated by the INCOIS seismic network should be within the target set up by IOC-ICG/IOTWS-V/13. Elapsed time is the time span between origin time of the earthquake and initial earthquake information issuance. It is observed that average elapsed time of INCOIS is 6 min, which is within the target of 10/15 min, while USGS has an elapsed time 10 min. The average difference in magnitude of INCOIS estimate with USGS is 0.20, which also achieves the target of 0.2. The average focal depth difference with USGS is 22.5 km, which is within the target value of 25 km. A comparison of earthquake location estimated by INCOIS with USGS indicates that the average difference in location is within the target of 30 km. The above statistics indicates that the earthquake parameters estimated by INCOIS are comparable with those estimated by international agencies and fall within the target set up by IOC-ICG/IOTWS-V/13.

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Photosynthetically active radiation, a critical parameter for mass coral bleaching in the North Indian Ocean

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The Gulf of Mannar (GOM) and Kadamat Island (KI) are two major coral reefs that were severely bleached en masse in the North Indian Ocean (NIO) during 1998. Mass coral bleaching took place once again in NIO during 2002, which severely affected the GOM corals but not the KI corals. This contrasting phenomenon prompted us to re-examine parameters such as surface sea temperature (SST), photosynthetically active radiation (PAR), hotspots, heat content, sea-surface height anomaly (SSHA) and North Indian Ocean Dipole (NIOD) events. The analysis indicates that the above mass bleaching events are associated with high PAR (47 Einstein/m^2/day) with minimum SST of 30°C, which was probably critical for mass bleaching in NIO during 1998 and 2002. However, the above bleaching events do not show any direct link with SSHA, hotspots and NIOD.

Keywords: Coral reefs, hotspots, mass bleaching, photosynthetically active radiation.

CORAL bleaching is the whitening of corals caused by expulsion of zooxanthellae, the photosynthetic pigments in corals. Regardless of the geographic location, mass bleaching occurs worldwide due to elevated temperature[1] and thermal stress[2,3] under changing climatic scenarios such as greenhouse warming, El Niño and El Niño Southern Oscillation (ENSO). Earlier studies have shown that tolerance of corals to thermal stress varies regionally[4–6] and high photosynthetically active radiation (PAR) causes stress to the corals[7]. Thermal stress reduces reproductive capacity, growth and resistance to diseases of corals[7,8]. Sporadically, local fluctuations in critical parameters such as temperature, salinity, excessive sedimentation and diseases also affect the coral communities[9]. In general, a temperature of 29°C and salinity range 34–39 PSU are set as threshold for healthy corals[10]. High sediment attenuates light needed for the symbiotic algae growth[11] and sustained sedimentation of >0.2 kg/m^2/day causes stress to the corals[12].

The Gulf of Mannar (GOM) and Kadamat Island (KI) are two major coral reefs in the North Indian Ocean (NIO). Both GOM and KI corals had severely bleached en masse in 1998, causing extensive deaths up to 60% in GOM and 90% in KI[8]. These mass bleaching events are attributed to elevated temperatures[13–16]. During 2002,

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