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The Great 26 December 2004 Tsunami

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ABSTRACT

Before the occurrence of the 26 December 2004 mega-tsunami caused by the Mw 9.2 Sumatra earthquake, there was no tsunami warning facility in the Indian Ocean, and one depended on the tsunami advisories being issued by the Pacific Tsunami Warning Center and the Japan Meteorological Agency. Many of these issued advisories were later withdrawn, causing a lot of inconvenience to a large population residing along the east coast of India. From a study of past tsunami sources, we discovered that there are only two areas, which can host tsunamigenic earthquakes in the Indian Ocean. This finding was accepted in the 2nd International Coordination Meeting during 14–16 April 2005 for the Development of an Indian Ocean Tsunami Warning and Mitigation System, held at Grand Baie, Mauritius. This provided the foundation of setting up of the Indian Tsunami Early Warning System (ITEWS). Global network of seismic stations permits determination of the location and the magnitude of the earthquake within 5 minutes or so of its occurrence. If an earthquake has a magnitude $\geq$7 and if it is located within the two identified tsunamigenic earthquake generating areas, there are chances of generation of a tsunami. However, whether a tsunami has been really generated and what is its magnitude cannot be determined, which is necessary to issue appropriate advisories. This issue was resolved by placing ocean bottom pressure recorders in the immediate vicinity of the two regions capable of hosting a tsunamigenic earthquake. India undertook a very ambitious project to set up a state of art tsunami warning capability in a short time of 30 months. ITEWS was functional by end of August 2007. The tsunami advisories, issued for the first time by ITEWS for the 12 September 2007 earthquake, were found to be accurate. Over the past 17 years the system has worked very efficiently. It is now assessed as among the best tsunami warning systems in the world.

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Research Highlights

- Discovery that there are only two areas in the Indian Ocean that can host a tsunamigenic earthquake.
- These are a stretch of 4000 km from Sumatra to Andaman and an area of ~500 km radius off the Makaran Coast.
- Placing ocean bottom pressure recorders in the vicinity of these two areas have eliminated false alarms.
- ITEWS was set up in 28 months by August 2007. Over the past 17 years the system has worked well. No false alarms.
- INCOIS is identified as one of the key tsunami service providers for the Indian Ocean Tsunami Warning and Mitigation System.

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1 Introduction

Among the natural hazards, tsunamis are one of the worst. We have just completed the first 24 years of the 21st Century. In these years, two mega tsunamis have occurred. The 26 December 2004 Mw 9.2 Sumatra earthquake and the resultant tsunami claimed ∼250,000 human lives in south and south-east Asia. India lost close to 15000 lives. Just seven years later, on 11 March 2011, the Mw 9.0 Tohoku earthquake off Japan coast caused a tsunami claiming around 20,000 human lives and causing a nuclear emergency. The word *Tsunami* has its origin from Japan. It is pronounced as *tsoo-nah-mee.* Literally, it means harbor waves. It is called so because in the open ocean tsunamis have very small amplitude. However, as it progresses to shallower sea in the harbors, the amplitude increases, reaching several meters. The Japanese fishermen out in the sea for fishing, would not notice the occurrence of a tsunami, but when they returned, they found their villages wiped off by tsunamis, and hence the name harbor waves. Only a few other languages have an equivalent of tsunami. It is *beuna* or *alôn buluël* in Acehnese language, spoken in Aceh, Sumatra, Indonesia; *smong* and *emong* in Defayan and Sigulai languages of spoken in western coast of Sumatra, Indonesia.

Tsunamis are mostly caused by the occurrence of an earthquake below the sea. Under favorable-geological conditions, when an earthquake occurs below the sea bottom and the displacement on the earthquake generating fault causes a vertical displacement on the sea bottom, the water column above it gets displaced causing the tsunami. In the open oceans the tsunami wave length could be up to 100 km. However, the amplitude is no more than 30 cm in most cases. Tsunami waves in the open ocean get lost in the natural waves which have much larger amplitudes. The tsunamis travel with velocity of up to 1000 km/h in the open ocean. As the tsunami approaches the seacoast, the velocity decreases and amplitude increase.

Based on the paleo-tsunami records, the earliest tsunami is dated 426 BC. Among the past tsunamis, the 1 November 1755 Lisbon, Portugal tsunami is the most significant (Fuchs, 2008; Gupta and Gahalaut, 2013). The 1 November 1755 Lisbon earthquake was later estimated to have a magnitude ∼ Mw 9 (Johnston, 1996). The resultant tsunami claimed ∼90,000 lives in Lisbon and ∼1000 lives in Morrocco. In 1755, population of Lisbon was ∼260,000. The tsunami caused deaths amounted 1/3 of the population of Lisbon. The 1755 Lisbon earthquake was felt over North Africa and Europe. According to Johnston (1996), the felt area was spread over 14 million square km.

2 The 26 December 2004 Mw 9.2 Sumatra Earthquake and the resultant Tsunami

The 26 December 2004 would be known in the annals of natural hazards as one of the most significant days. A Mw 9.2 earthquake occurred at 00.59 Universal Time off the west coast of Sumatra Island, Indonesia and the resultant tsunami claimed an estimated 250,000 human lives. The brunt of lives lost was in Sumatra (over 200,000), followed by Sri Lanka (∼35000), India (∼15000), and Thailand (∼6000).

Following are the earthquake details:

Date	26th December 2004
Origin Time	00.59.00 Universal Time
Magnitude	Mw 9.2
Epicenter	Latitude: 3.7° North
	Longitude: 95.0° East
Region	Off west coast of Sumatra Island (Indonesia)

It is important to realize that earthquake magnitude scale is logarithmic. With the increase of one unit magnitude, the energy release increases 31 time. Table 1 gives the annual number of earthquake occurrence in different magnitude ranges. Earthquakes of Mw ∼ 9 occur rarely. During the preceding 100 years of the 11 March 2011 Mw 9 Tohoku earthquake in Japan, only 4 earthquakes of Mw ≥ 9 earthquakes had occurred. To have an idea about the amount of energy released in an earthquake, it may be noted that one magnitude Mw 6 earthquake releasees energy equivalent to Hiroshima/Nagasaki 2nd World War atom bombs. So, a magnitude 7 would be equivalent to 31 such bombs, and so on. The energy released by the 26 December 2004 earthquake was equivalent to some 40,000 Hiroshima/Nagasaki atom bombs. The earthquake fault rupture had extended to some 1500 km! Historically, it is the 3rd largest recorded earthquake with the longest rupture length (Ishii et al., 2005).

Descriptor	Magnitude	Annual frequency in the world
Great	8 and higher	1
Major	7–7.9	18
Strong	6–6.9	120
Moderate	5–5.9	800
Light	4–4.9	6200
Minor	3–3.9	49000
Very minor (micro)	2–2.9	About 1000 per day
	1–1.9	About 8000 per day

Table 1. Approximate annual frequency of earthquake occurrence in the world.

In India, the word tsunami was not usually known to the public. 26 December 2004 was a Sunday. People were having a leisurely walk on the Marina Beach in Chennai. When the crest of the tsunami first reaches the beach, flooding occurs. However, when the trough of the tsunami first reaches the beach, it causes a withdrawal of water. For the 26 December 2004 tsunami, the trough first reached the Marina Beach, and the sea receded (Fig. 1). The people walking on the Marina Beach, unaware of this phenomenon of receding of the water when the trough reaches

Fig. 1. A scene at around 8.40 am Indian Standard Time on the 26 December 2004 morning at the Marina Beach, Chennai, India. It may be noted that due to the arrival of the '*trough*' of the tsunami first, sea withdrew. Ignorant of tsunami people walked into bared sea to pick fish and shells.

the beach, just walked into the bared sea-floor to collect shells and fish, unaware than soon the crest would arrive drowning them. This is exactly what happened at the Marina Beach. The trough had arrived at 08.40 am Indian Time, and the crest arrived about 25 minutes later flooding the entire Marina Beach when people were drowned, and cars were washed away (Fig. 2). The height of the wave in Chennai was 3.2 m.

3 Tsunamis in the Indian Ocean

Tsunamis rarely occur in the Indian Ocean. In the entire 20th Century, there were only 3 tsunamis reported in the Indian Ocean as can be noted from Table 2 (Updated from Srinivasa Kumar et al. (2014)). As against this small number, there were close to 900 small and big tsunamis in the Pacific Ocean. Before the occurrence of the 26 December 2004 mega-tsunami caused by the Mw 9.2 Sumatra earthquake, there was no tsunami warning facility in the Indian Ocean, and one depended on the tsunami alerts being issued by the Pacific Tsunami Warning Center and the Japan Meteorological Agency. Many of the advisories were later withdrawn, causing a lot of inconvenience to a large population residing along the east coast of India.

3.1 Discovery of the two sources of Tsunamis in the Indian Ocean

Fig. 3 provides (after Gupta, 2005) the global distribution of earthquakes, and major plate boundaries. Globally, the Circum-Pacific Earthquake Belt accounts for more than 75% of earthquake energy release. The Alpine-Himalaya Earthquake Belt accounts for 20% of the earthquake energy release, and the remaining 5% is accounted for by the mid-oceanic ridges and the stable continental regions. It was discovered that as far as the tsunamis in the Indian Ocean are concerned, their sources are limited to two regions: a stretch of 4000 km from Sumatra to Andaman-Nicobar group of Islands, and small area of 500 km radius off Makaran Coast in the Arabian Sea.

3.2 Intergovernmental oceanographic commission meetings

India was keen to set up a tsunami-warning system for the Indian Ocean. There were proposals from global agencies. However, India was concerned about the issue of tsunami warnings and their withdrawal after some time. After the 26 December 2004, there were cases where a

Fig. 2. At around 09.05 am Indian Standard time, the crest of the tsunami arrived and swept away vehicles and drowned people who had walked into the bared sea floor caused by the arrival of the trough of the tsunami, first, on the Marina Beach, Chennai, India.

tsunami advisory was issued and millions of citizens from the east coast of India moved away from the coastal areas, and later these advisories were withdrawn. This caused immense inconvenience and a worry that the population may not pay heed to these advisories in the future. The reason behind this situation is the fact that the entire Pacific Earthquake Belt is very close to the well populated coasts around the Pacific Ocean, as can be seen from Fig. 3. When a possible tsunamigenic earthquake occurs near the coast of the Pacific Ocean, an advisory is issued, as the tsunami reaches within a few minutes to the populated coastal areas. There is no time available to verify whether the earthquake has indeed generated a tsunami. People living in these areas are habituated to receiving advisories and their withdrawal. Fortunately for India, the Sumatra-Andaman source is far off and it takes over an hour for tsunami to reach the India mainland. Occurrence of a magnitude ≥ 7 earthquakes in the two zones capable of hosting a tsunamigenic earthquake is established within 5 minutes of the occurrence of the earthquake. However, whether the earthquake has generated a tsunami or not is not known for quite sometimes with the absence of desired sensors in the immediate vicinity of two tsunami source zones. So, if one plants ocean-bottom pressure recorders in the immediate vicinity of the two known-sources of the tsunamigenic earthquakes, it is possible to find out whether an earthquake has indeed generated a tsunami or not.

India underscored both these issues, namely, avoidance of false alarms and the fact that there are only two sources of tsunamigenic earthquakes for the entire Indian Ocean in the International Coordination Meeting during 3–8 March 2005 for the Development of an Indian Ocean Tsunami Warning and Mitigation System organized by the Inter-Governmental Commission on Oceanography at Paris. The first issue was accepted with the following Communiqué:

"*Noting it is important to improve the science of issuing tsunami warnings to reduce false alarms given the inordinate inconvenience and disruptions to normal life caused by false alarms, especially given the high population densities and intensive operations in coastal areas in the Indian Ocean, and also to continuously improve forecasting*".

However, there was a long discussion on the point made by India that there are only two broad areas of tsunamigenic earthquake sources for the entire Indian Ocean. At that stage India requested that the participants

Date	Remarks
326 BC	Army of Alexander the Great suffered
Between 1 April and 9 May 1008	Tsunami on the Iranian coast from a local earthquake
27 August 1883	Krakatoa: 1.5 m tsunamis at Madras, 0.6 m at Nagapattinam, 0.2 m at Arden
1884	Earthquake in the western part of the Bay of Bengal, tsunamis at Port Blair, Dublet (mouth of Hooghly River)
26 June 1941	8.1 earthquake in the Andaman Sea at 12.9° N, 92.5° E, tsunamis on the east coast of India with amplitudes from 0.75 to 1.25 m
27 November 1945	8.25 earthquake 70 km south of Karachi at 24.5° N, 63.0° E, tsunami amplitude at Kutch was 11.0–11.5 m
19 August 1977	8.0 earthquake in Sunda Islands of Indonesia at 10.5° S, 118.8° E, tsunami heights were 5–8 m at Lunyuk on Sumbawa Island, and 5 m at Leterua on the south coast of Sumba Island
26 December 2004	9.2 earthquake off coast of Northern Sumatra, Indonesia, at 3.3° N, 95.8° E. Amplitudes of 4.5 and 3.2 m were estimated at Port Blair and Chennai
28 March 2005	8.6 earthquake off coast of Northern Sumatra, Indonesia, at 2.1° N, 97.0° E, tsunami run-up about 2–4 m observed on southern Nias and Simeulue Islands, Indonesia
12 September 2007	8.5 earthquake off coast of Southern Sumatra, Indonesia, at 4.5° S, 101.3° E, tsunami amplitude about 0.60 m at Padang, Indonesia; 0.08 m at Portblair and 0.18 m at Chennai, India
11 April 2012	8.6 earthquake off west coast of Northern Sumatra, Indonesia, at 2.3° N, 93.1° E, tsunami amplitude about 1.06 m at Meulaboh, Indonesia, 0.30 m at Campbell-Bay and 0.18 m at Chennai, India

Table 2. Tsunamis in the Indian Ocean (after Murty and Bapat, 1999; Ramana Murthy et al., 2005; Nayak and Srinivasa Kumar, 2008; Borrero et al., 2011; Srinivasa Kumar et al., 2012b).

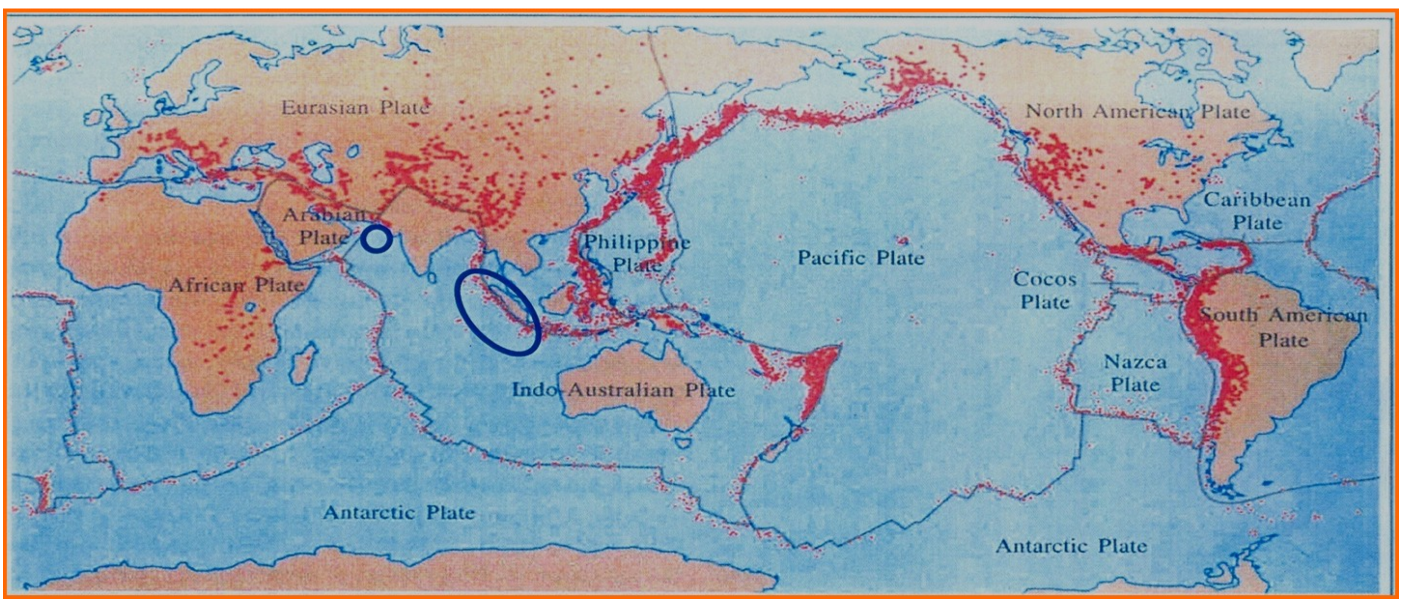

Fig. 3. Diagram showing the distribution of earthquakes and major plate boundaries. It may be noted that globally, more than 75% of earthquake energy is released in the circum-Pacific belt, about 20% in the Alpine-Himalayan belt, and remaining 5% through the mid-oceanic ridges and other Stable Continental Region earthquakes. For a tsunami to hit Indian coast, it is necessary that a tsunamigenic earthquake occurs and its magnitude should be larger than M 7, and the possible locations of such events are enclosed in blue circle and ellipse (after Gupta, 2005).

be given time to find a source of a tsunami in the Indian Ocean that got generated by a source located outside the two identified areas. Mr. Patricio Bernal, the IOC-UNESCO Executive, who was chairing the session, decided to take this issue in meeting to be organized after a few weeks, giving time to the participants to find a source of tsunami outside the areas defined by India for the occurrence of a tsunami in the Indian Ocean.

The 2nd International Coordination Meeting was held at Grand Baie, Mauritius, during 14–16 April 2005. There was quite a bit of discussion. No one could come up with a tsunami having been generated in the Indian Ocean with its source earthquake lying outside the two demarcated zones by Gupta (2005). This led to the following declaration:

MAURITIUS DECLARATION

"*Recognize the unique tectonic plate structure of the Indian Ocean, and that there are primarily two tsunamigenic sources that could affect the coastlines of the Indian Ocean, namely the Indonesian seismic zone and its extensions, about 4000 km in length, and the Makram source".*

This provided the foundation of setting up of the Indian Tsunami Early Warning System. As mentioned earlier, the global network of seismic stations permits determination of the location and the magnitude of the earthquake within 5 minutes or so of its occurrence. If this earthquake has a magnitude ≥ 7 and if it is located within the two identified tsunamigenic earthquake generating areas, there are chances of generation of tsunami. However, whether a tsunami has been really generated and what is its magnitude, cannot be determined immediately, which is necessary to issue appropriate advisories. This issue was resolved by placing ocean bottom pressure recorders in the immediate vicinity of the two regions capable of hosting a tsunamigenic earthquakes.

4 Setting up of the Indian Tsunami Early Warning System (ITEWS)

Setting up of the Indian Tsunami Early Warning System is well documented (Gupta, 2008; Srinivasa Kumar et al., 2014). Here the salient features are briefly commented up on. Having identified that there are only two areas in the Indian Ocean that host the tsunamigenic earthquakes, Indian program was focused on monitoring of these two areas. One of the major components was deploying of the ocean bottom pressure recorders in the immediate vicinity of these two seismogenic earthquake source zones. The Government of India approved a program with a direct cost of US $ 30 million for this mission in early 2005. The mission was scheduled to be completed in 30 months' time.

4.1 Seismic Network

ITEWS makes use of the global and local seismic stations that monitor seismicity in the two specified tsunamigenic earthquake zones in near real time. 17 broadband stations were specifically installed towards this goal in addition to the getting data from $\sim$300 global seismic stations in real time. Earthquakes are located within $\sim$5 minutes of their occurrence.

4.2 Sea-level network

To find whether an earthquake has generated a tsunami, changes in the water level needs to be monitored with high accuracy. A network of ocean bottom pressure recorders (BPRs) is deployed in the close vicinity of the two tsunamigenic earthquake source zones. These BPRs can detect 1 cm change at water depths of up to 6 km. These BPRs send data to the Indian Tsunami Early Warning Centre (ITEWC) via satellite. The data from BPRs is supplemented with the data from tide gauges in real time. ITEWC has developed the necessary software for real-time reception, display and archiving the sea level data.

4.3 Quantitative tsunami forecast

ITEWC adopted tsunami pre-run simulations using TUNAMI-N2 (Tohoku University's numerical analysis model for investigation of near-field tsunamis, version 2) for the Indian Ocean. A complete knowledge from tsunami generation to propagation and inundation is required for proper tsunami forecasts. The initial water level changes are computed using the earthquake parameters such as location, fault length and width, slip, dip, rake and depth using Mansinha and Smylie's (1971) approach. This helps in simulating wave propagation, tsunami travel time and runup heights. These are done for 1800 coastal forecast points along the entire Indian ocean rim countries. A large data base is maintained by ITEWC for pre-run scenarios for possible earthquakes in the two tsunamigenic earthquake zones. After the occurrence of an undersea earthquake, the closest scenario is picked up from the pre-run scenario data base to generate tsunami scenarios at spatial units called 'coastal forecast zones (CFZs)'.

4.4 12 September 2007 Mw 8.4 earthquake

By August 2007, ITEWS was totally operational. At 11: 10: 26 Universal Time on the 12 September 2007, an earthquake of Mw 8.4 occurred at 4.521° S, 101.370° E off the west coast of Sumatra, Indonesia. The earthquake was large enough and located in the Sumatra-Andaman zone of tsunamigenic earthquakes. The displaced sea water generated a tsunami. This was the first case for the issue of tsunami advisory by the ITEWS. Table 3 provides the forecasted times of arrival and amplitudes at several of the locations in the Indian Ocean-rim countries. It may be noted that the tsunami forecast was reasonably accurate. So, with in 28 months, the mega project of setting up of the Indian Tsunami Early Warning System was completed successfully.

Location	Estimated arrival time (h)	Estimated water level (cm)	Observed arrival time (h)	Observed water level (cm)
Padang	1751	80	1754	60
Coco's Island	1748	40	1748	50
Sabang	1903	20	1903	30
TB 3	1903	2	1913	1
TB10A	1931	1	1941	2
TB10	1930	2	1945	1
Port Blair	2010	10	2013	8
Chennai	2105	20	2110	18

Table 3. INCOIS generated a database of Model Scenarios considering various earthquake parameters. For the September 12, 2007 event scenario Ids 28.2 & 29.2 were picked from the scenario database. They were used to calculate the estimated travel time and run up heights at various coastal locations and water level sensors (Tide gauges & BPRs and tidal stations as evident from the table).

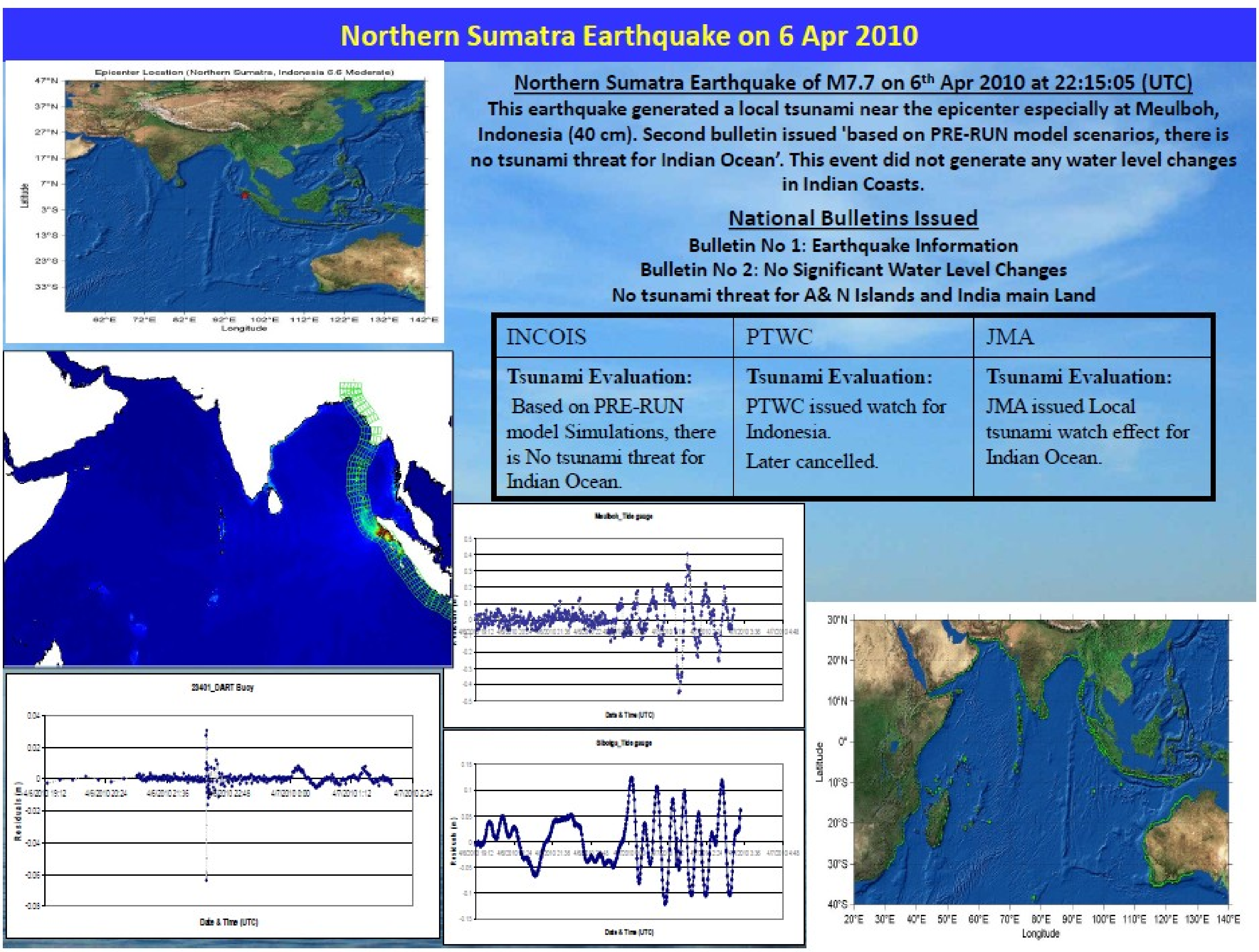

Fig. 4. Figure depicts the forecasts of tsunamis issued by INCOIS, PTWC and JMA for the 6 April M 7.7 northern-Sumatra earthquake. 'No tsunami threat' by INCOIS; PTWC issued a 'Watch' advisory for Indonesia that was later withdrawn, while JMA advised for a local tsunami watch. This earthquake had caused no tsunami.

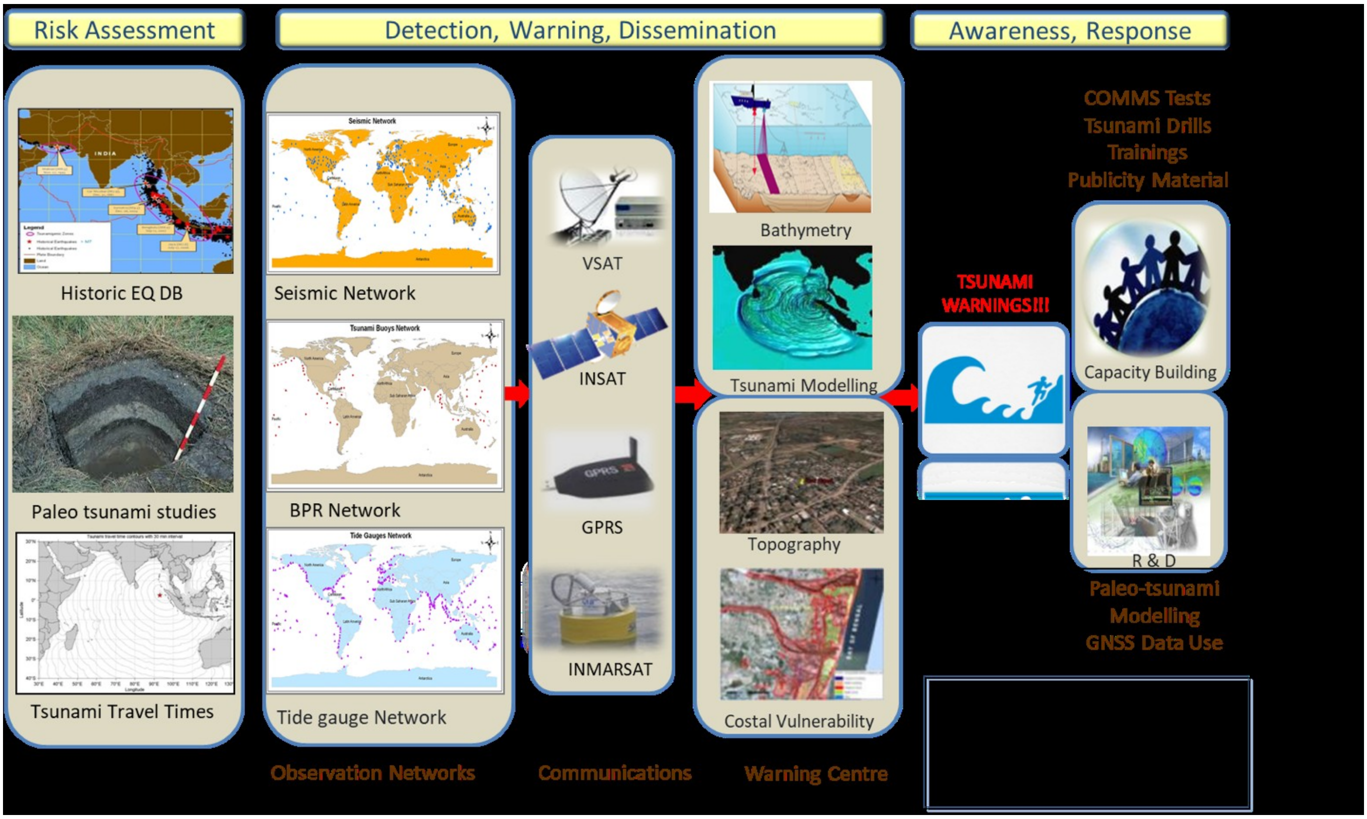

Fig. 5. The three major components of the Indian Tsunami Early Warning System (ITEWS).

4.5 Performance since September 2007

Over the years the ITEWS has performed very well. An example of the advisory issued for the Mw 7.7 earthquake that occurred in northern Sumatra is provided in Fig. 4. It may be noted that while Pacific Tsunami Warning Centre (PTWC) and Japan Meteorological Agency (JMA) issued advisories for a mild tsunami, ITEWS advised of no tsunami, which was found to be true.

Fig. 5 provides the three major components of ITEWS, which are self-explanatory.

5 Concluding remarks

Recent developments concerning ITEWS have been reported by Srinivasa Kumar et al. (2012a, 2014); Nayak et al. (2021); Srinivasa Kumar and Francis (2024). Contribution of space missions to improve tsunami science has been very well addressed by Hebert et al. (2020).

India completed, indigenously, a very ambitious project to set up a state of art Tsunami Warning capability for the entire Indian Ocean warning in a short time of 30 months. This was achieved by end of the August 2007 and tested by the 12 September 2007 earthquake.

ITEWS has performed exceptionally well since its commissioning in 2007.

- Over the years ITEWS has issued bulletins for over 700 earthquakes of magnitude Mw 6.5 and above.
- Only 7 of these earthquakes had the possibility of generating a tsunami. Only one of these seven earthquakes merited issue of a tsunami advisory.
- The very timely and accurate advisories generated by ITEWS have saved the entire Indian Ocean rim countries from false alarms and subsequent evacuation, as had been the case before the installation and commissioning of ITEWS.
- In true sense, ITEWS has served the purpose of its creation.

Over the past 17 years the system has worked very efficiently. It is now assessed among the best in the world.

With the outstanding contributions over the years, INCOIS is identified as one of the key tsunami service providers for the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS).

The credit goes to Ministry of Earth Sciences, Government of India, and particularly the Indian National Centre for Ocean Information and Services (INCOIS), for this extraordinary achievement.

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Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit author statement

Harsh K. Gupta: Conceptualization; Visualization; Writing—original draft; Writing—review & editing.

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