IOTWS – Operations and Limitations

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1 Introduction

This document provides a description of the real-time monitoring and alerting activities of the Indian Ocean Tsunami Warning and Mitigation System (IOTWS), considered in the context of the other actions which are required for effective warning and mitigation of tsunamis. These other activities, such as emergency response, planning, education and risk assessment are generally the responsibility of national and local authorities, and will be most effective when carried out with awareness of the capabilities and limitations of the international tsunami service providers.

The Regional Tsunami Service Providers (RTSPs) of the IOTWS have been fully operational since 31 March 2013, but have been developing and testing their capabilities since 2009. They now provide an advanced tsunami forecasting service based on earthquake detection, sea-level measurements and oceanographic modeling, which includes detailed threat information for almost 800 coastal zones around the Indian Ocean.

The three centres currently acting as RTSPs each cover the whole area of responsibility of the Indian Ocean and have aligned their coastal forecast zones, accuracy and timeliness targets, and output product formats to ensure that National Tsunami Warning Centres (NTWCs) can readily use the forecasts from any or all of the RTSPs.

The tsunami models used by the RTSPs are similar but differ in their detailed configurations. This leads to some differences, generally small, in the forecasts produced by the centres, so it is important that NTWCs understand the basis for the forecasts and the significance of any differences. The RTSP products include tsunami arrival and cessation times and maximum wave amplitudes for all threatened coastal zones, and so can be rather complex. Some of the issues involved in interpreting the products are discussed here, including the potential to use modeled tsunami forecasts to improve risk assessment for local areas.

Although the real-time operation of the IOTWS is working well, there are several limitations and areas of potential improvement, most of which are currently being addressed. Several of the current limitations are discussed here.
2 History and Overview of the IOTWS

2.1 History

When the magnitude 9.1 (Mw) earthquake\(^1\) occurred off the west coast of northern Sumatra on 26 December 2004, no ocean-wide tsunami warning system existed for countries with Indian Ocean coasts. Many people were killed on Sumatra within minutes of the earthquake, but many others died hours later because they were unaware as the tsunami waves radiated across the Indian Ocean, with deadly impact on 14 nations, particularly Indonesia, Sri Lanka, India and Thailand. The enormous loss of life caused by that tsunami and the obvious potential value of an early warning system triggered a rapid response from the global community. Planning commenced almost immediately for an Indian Ocean Tsunami Warning and Mitigation System (IOTWS) to be built using a framework similar to that already established for the Pacific Ocean by UNESCO’s Intergovernmental Oceanographic Commission (IOC).

While the IOTWS was being designed and built, an Interim Advisory Service (IAS) was put in place jointly by Japan, through the Japan Meteorological Agency (JMA), and the USA, through its Pacific Tsunami Warning Center (PTWC). The IAS commenced operation in April 2005 and continued to provide tsunami alerts and information to Indian Ocean countries until 31 March 2013, when three centres, in Australia, India and Indonesia became fully operational IOTWS Regional Tsunami Service Providers (RTSPs). The operational characteristics of the RTSPs are described in detail in a later section.

The implementation and operation of both the IAS and IOTWS have been coordinated under the IOC by participating countries in and around the Indian Ocean, organized as the Intergovernmental Coordination Group for the IOTWS (ICG/IOTWS). The ICG/IOTWS was established by IOC Resolution XXIII-12 in 2005 as a primary subsidiary body of the IOC, and has held nine sessions since 2005.

A total of 21 earthquakes\(^2\) of magnitude 7.0 or greater occurred under the sea or within 200 km of the coast of the Indian Ocean between January 2005 and March 2013, and 4 of those earthquakes generated tsunamis resulting in a large number of casualties and property loss. Although alerts were provided for those damaging events by the IAS, some lives were lost, due largely to the proximity of the earthquakes to the affected populations and the resultant short tsunami travel time. This problem of “near-field” earthquakes illustrates the importance of the other elements of the IOTWS, such as public education and local response planning, which must be based on realistic local risk assessments.

Since the IOTWS became fully operational, replacing the IAS in April 2013, the only earthquake of magnitude 7.0 or greater to occur under the ocean or nearby was located in Pakistan, almost 200 km from the coast and generated only a small tsunami. This does not mean that the RTSPs are untested. From 2009 the three centres began issuing tsunami advice bulletins to National Tsunami Warning Centres (NTWCs) as their capabilities developed. In particular, a large earthquake (Mw 8.9) and aftershock west of Sumatra on 11

\(^1\) USGS estimate of magnitude. Some sources suggest the moment magnitude (Mw) may have been as high as 9.3.

\(^2\) USGS earthquake archive
April 2012 caused the RTSPs and IAS to issue initial tsunami bulletins, but no tsunami was generated and the event did not escalate further. This earthquake and other smaller events provided effective tests of the RTSP systems and procedures.

In addition, RTSP capabilities were tested in two ocean-wide exercises, in 2009 and 2011. The IOWave11 exercise, in October 2011, marked the formal commencement of IOTWS operation in parallel with the IAS. During the following 12 months, the three centres measured and reported on their performance against a set of indicators which are described below. The ICG/IOTWS, at its ninth session, held in November 2012, considered the performance of the RTSPs and decided that the centres were ready to become fully operational, replacing the IAS from 31 March 2013.

The RTSPs are activated and issue bulletins for earthquakes of magnitude 6.5 or greater around the Indian Ocean, and magnitude 8.0 or greater in the Pacific or southern Atlantic Oceans. Since the formal commencement of their operations in October 2012, there have been 7 earthquakes of sufficient magnitude in the Indian Ocean region to require RTSP bulletins to be issued. Although most of the earthquakes were assessed as not posing a tsunami threat, this frequency of about 4 events per year provides useful opportunities to exercise and familiarise with the service.

With the evolution of the IOTWS, its supporting frameworks have also evolved. Initially the ICG/IOTWS progressed its activities principally through six working groups with very focused areas of interest. These working groups were:

1. Seismic Measurement, Data Collection and Exchange
2. Sea Level Measurement Data Collection and Exchange
3. Risk Assessment
4. Modelling, Forecasting & Scenario Development
5. A System for Interoperable Advisory & Warning Systems
6. Mitigation, Preparedness & Response

In 2010, ICG/IOTWS-VII reviewed the working group structure and decided to combine some functions to form three new working groups. The current working groups are:

1. Tsunami Risk Assessment and Reduction
2. Tsunami Detection, Warning and Dissemination
3. Tsunami Awareness and Response

2.2 Concept of Operations

As a regional body, the ICG/IOTWS is comprised of UNESCO/IOC Member States in the Indian Ocean, with other countries outside the region and other organisations considered Observers. Each Member State is represented by a Tsunami National Contact (TNC) who serves as the intergovernmental contact person for the coordination of international tsunami warning and mitigation activities.

During a tsunami event, messages and information from the RTSPs are available to each Member State through the officially designated national Tsunami Warning Focal Point (TWFP), which is usually associated with the National Tsunami Warning Centre (NTWC) and/or National Disaster Management Office (NDMO). The TWFP is a 24x7 point of contact,
who has the responsibility of notifying the national emergency authority of the event and its characteristics. The maintenance of up-to-date contact information for TWFPs and TNCs is a critical element of the operation of the IOTWS, and it is in the interests of each Member State to ensure that its contact information is promptly updated if a change occurs.

The IOTWS achieves operational robustness through the existence of multiple RTSPs operating as a “system-of-systems”. Rather than dividing the area of the Indian Ocean between them, each RTSP covers the entire area of service of the IOTWS, providing redundancy in case of failure of any single centre. The system-of-systems approach requires all RTSP tsunami information to be interoperable. This means that RTSPs use agreed, common formats for information exchange, address common service requirements, follow agreed, high-level Standard Operating Procedures (SOPs), and share information on procedures and processes. Differences do exist between the RTSPs, in tsunami model formulation, for example, which means that there are quantitative differences (usually small) in the advice provided to NTWCs.

The area of service of the IOTWS is shown in the diagram below (formerly referred to as Area of Responsibility or AOR). One important point to note is that the area of the Banda and Java Seas is currently served jointly by the IOTWS and the Pacific Tsunami Warning System. The diagram also illustrates the fact that some segments of coast in Australia, South Africa and northern parts of Indonesia are not currently included in the IOTWS area of service, but will be added in the future as the RTSPs extend their tsunami model domains.

![Figure 1: Area of service of the IOTWS (IOC/TOWS-WG-VII/15, 2014)](image-url)
RTSPs do not issue warnings; they provide advisory information and data on tsunami threats to NTWCs. It remains the responsibility of the NTWC, operating within the legal framework of its country, to provide warnings, watches, and advisories to its citizens and agencies. NTWCs will do so after reviewing the information received and considering their independent assessment of the ground situation based on national investigations. NTWCs are also encouraged to feed back to the RTSPs information on the warning status in their country during a tsunami event, so that region-wide summaries of the warning situation can be compiled.

As they each have responsibility for the whole Indian Ocean, the RTSPs provide services to several NTWCs, and each NTWC may elect to utilise services from more than one RTSP. The RTSPs issue their products in identical formats, to help the NTWCs in comparing and assessing their information, but each NTWC must establish a procedure for making decisions on the basis of a range of tsunami forecasts.

Because the authority for issuing tsunami warnings and instructions to the public resides with the NDMO/NTWC and its national partners, the RTSPs do not make their bulletins publicly available. Instead, secure dissemination methods are used to deliver RTSP information direct to NTWCs. These methods are discussed in detail in the section below on the RTSPs.

The only publicly-accessible information provided by the RTSPs consists of earthquake characteristics, tsunamigenic potential and sea level observations and a website showing the real-time tsunami warning status across the Indian Ocean, based on advice from NTWCs on their local situation.

The implementation of the IOTWS has been based on a number of operational targets, the most important of which are the minimum earthquake magnitude which triggers RTSP activation, the maximum elapsed time from earthquake to issuance of initial bulletins, and the probability of detection of significant earthquakes. Other RTSP performance targets, relating to accuracy in earthquake and tsunami data are described later.

Following widespread international practice, the IOTWS is activated for earthquakes of magnitude Mw 6.5 or greater in or near the Indian Ocean. At this magnitude a tsunami might impact the local area (within approximately 100 km), but is unlikely to cause danger elsewhere.

The world’s oceans are connected, so it is possible for a severe tsunami in the Pacific or Atlantic Oceans to impact Indian Ocean coasts. For this reason, the RTSPs monitor earthquakes in a region wider than the Indian Ocean, as shown in the diagram below. However, only strong earthquakes are able to cause significant tsunami waves at a great distance, so the magnitude threshold used for earthquakes outside the Indian Ocean is Mw 8.0.
Consistent with the IOTWS focus on large, long-duration events, the RTSP target for issuance of an initial bulletin is 10 minutes elapsed time from the occurrence of an earthquake which meets the magnitude threshold. The initial bulletin may be confined to earthquake information, and is followed by the first bulletin containing tsunami threat information, which must be issued within 20 minutes elapsed time.

Perhaps the most important of the RTSP targets is the probability of detection of earthquakes of Mw 6.5 or greater. The target is 100%, which means that the IOTWS has been designed to guarantee that all potentially tsunamigenic earthquakes will be detected and alerts issued. This imperative of never missing a tsunamigenic earthquake, combined with the need to issue advices very quickly, creates the possibility of false alarms, which can be costly and damaging to confidence in the warning system. The RTSP product suite minimizes the potential impact of false alarms through a staged approach, moving towards greater certainty and more detail with time.

When a potentially tsunamigenic earthquake occurs, the RTSPs issue their advisories to NTWCs in the following sequence, adding detail as more information becomes available:

- **Notification Message** - issued within 10 minutes of the earthquake, providing an alert that an RTSP Bulletin has been issued, plus the earthquake parameters.
• **Bulletin Type 1** - Earthquake Bulletin: providing details of earthquakes which have the potential to cause tsunamis. Issued within 10 minutes of the earthquake. The bulletin may also provide advice as to whether the earthquake has the potential to generate a tsunami or not, based only on earthquake magnitude, location and depth, pending more detailed tsunami forecasts based on scenario modelling.

• **Bulletin Type 2** - Tsunami Forecast: issued within 20 minutes of the earthquake, providing an initial forecast of tsunami threat, including arrival times and wave amplitude. This type of bulletin contains either:
  - Advice that there is no threat to any coastal zone in the Indian Ocean;
  - Details of the forecast tsunami threat to coastal zones, based on tsunami modelling.

• **Bulletin Type 3** - Tsunami Forecast and Observations: providing the same information as the Tsunami Forecast Bulletins, with the addition of information on observed sea-level anomalies, confirming the existence of a tsunami.

• **Bulletin Type 4** - Tsunami Service Finalisation: advice on the end of the tsunami threat.

When a tsunami occurs the damaging waves are not uniformly distributed around the coasts of the Indian Ocean or even across a single country. Some locations will experience destructive waves while others will see very small sea-level anomalies or none at all. Current limitations on tsunami modeling and prediction have been considered in deciding how precisely the IOTWS can describe the differences in tsunami characteristics along a coastline. This resolution or “granularity” of the IOTWS service is based on the division of all of the coasts around and in the Indian Ocean into 571 zones which average about 100 km long and extend 50 km seaward from the coast. A recent development in the IOTWS has been to refine the coastal zones to match administrative boundaries as an aid to local warning formulation. These Coastal Forecast Zones (CFZ) are used by all of the RTSPs to describe the geographical extent of a tsunami threat. A threat is deemed to exist in any zone if tsunami waves of 50 cm or more positive amplitude are forecast to occur at the beach (1 metre water depth).
The methods used by RTSPs to produce their tsunami forecasts are discussed in the section below.

2.3 Exercising of the System

An important element of the IOTWS is the regular exercising of the system through regular ocean-wide exercises. These “IOWave” exercises, coordinated by the ICG/IOTWS, are generally held every 2 years. All RTSPs are involved and all NTWCs and NDMOs are encouraged to participate. The exercises are designed to simulate an ocean-wide tsunami threat, and each nation chooses how extensive its simulated response will be, ranging from NTWC-only involvement (receiving and acknowledging RTSP bulletins) through to full activation of the NDMO and simulated evacuations and emergency response. A detailed survey of participants is carried out after each exercise, and a full report is published, providing guidance for the further development of the IOTWS.

The communications networks and procedures which are vital to the successful delivery of RTSP services are also tested routinely, usually twice per year.
The Regional Tsunami Service Providers

Three centres are currently filling the role of RTSPs for the Indian Ocean. They are:

- **RTSP Australia:**
  Joint Australian Tsunami Warning Centre (JATWC), operated by the Australian Government Bureau of Meteorology (BoM) and Geoscience Australia (GA)
  Melbourne and Canberra, AUSTRALIA

- **RTSP India:**
  Indian Tsunami Early Warning Centre (ITEWC), operated by the Indian National Centre for Ocean Information Services (INCOIS)
  Hyderabad, INDIA

- **RTSP Indonesia:**
  Indonesia Tsunami Early Warning System (InaTEWS), operated by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) in cooperation with BAKOSURTANAL (National Coordinating Agency for Survey and Mapping) and BPPT (Agency for Assessment and Application of Technology)
  Jakarta, INDONESIA

The ICG/IOTWS has identified the capabilities and process required for an operational centre to be recognised as an RTSP of the IOTWS. Each RTSP must:

- Adopt the common Coastal Forecast Zones (CFZs), harmonised RTSP webpage layout, and bulletin formats and content as established by Working Group 2 (WG2).
- Make a presentation to WG2 demonstrating the attainment of capability requirements as agreed by the ICG/IOTWS
- Begin exchanging bulletins with other RTSPs
- Participate in Communications Tests and IOWave Exercises
- Have its performance reviewed by WG2 and presented to the ICG/IOTWS
- Begin providing RTSP threat information to NTWCs upon agreement of the ICG/IOTWS (Ref: ICG/IOTWS-IX/12)

All of the RTSPs are government agencies, operating 24x7 and possessing seismic and oceanographic expertise, which allows them to monitor and detect earthquakes and tsunamis, and to use computer modeling to forecast tsunami timing and intensity. Each RTSP has implemented a sophisticated decision support system to help operational staff to rapidly assess seismic and sea-level data and generate RTSP products. Each centre is also the NTWC for its own country and is therefore responsible for issuing national warnings.

The ICG/IOTWS has agreed on a set of key performance indicators (KPIs) and targets which define the level of service which NTWCs can expect from the RTSPs. These indicators and targets are summarized in the table below.
<table>
<thead>
<tr>
<th>KPI</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elapsed time from EQ to initial EQ information issuance</td>
<td>10 min</td>
</tr>
<tr>
<td>Probability of detection of IO earthquakes with Mw&gt;=6.5</td>
<td>100%</td>
</tr>
<tr>
<td>Accuracy of EQ hypocenter location</td>
<td>30 kms</td>
</tr>
<tr>
<td>Accuracy of EQ hypocenter depth</td>
<td>25km</td>
</tr>
<tr>
<td>Accuracy of initial earthquake magnitude</td>
<td>0.3</td>
</tr>
<tr>
<td>Elapsed time from EQ to issuance of first bulletin containing tsunami threat info</td>
<td>20 min</td>
</tr>
<tr>
<td>Accuracy of the tsunami forecast amplitude/height</td>
<td>factor of 2</td>
</tr>
<tr>
<td>Probability of detection of tsunami above threat threshold</td>
<td>100%</td>
</tr>
<tr>
<td>Accuracy of time arrival of tsunami (0.02m amplitude)</td>
<td>within 5% of travel time</td>
</tr>
<tr>
<td>Accuracy of time arrival of 1st significant wave (0.1m)…</td>
<td>within 5% of travel time</td>
</tr>
<tr>
<td>Accuracy of threat threshold exceedance</td>
<td>within 5%</td>
</tr>
<tr>
<td>Percent of IO countries issued a timely product as defined above</td>
<td>100%</td>
</tr>
<tr>
<td>Elapsed time from any product issuance to potential receipt by TWFPs</td>
<td>5 mins</td>
</tr>
<tr>
<td>Percent of time RTSP is operating and able to issue products</td>
<td>99.5%</td>
</tr>
<tr>
<td>Percent of regular Comms tests participated in</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 1:** RTSP Key Performance Indicators and Performance Targets (ICG/IOTWS-IX/12)

### 3.1 Monitoring and Detection Networks

Detection of earthquakes and measurement of tsunamis are central to the operation of the IOTWS, so the seismic and sea-level observing networks used by the RTSPs are crucial to their operations. The core of the seismic monitoring network used in the IOTWS is the IRIS Global Seismographic Network (GSN). The RTSPs augment this network extensively with other sources, such as the stations of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), the GFZ Geofon Extended Virtual Network and stations from other national and regional networks. An overview of the seismic network used by RTSPs is shown in Figure 4.
There are two basic types of sea level gauges: coastal tide gauges and open ocean buoys (tsunameters). Coastal tide gauge stations are operated by a number of countries and organizations, including the Global Sea Level Observing System (GLOSS) of the IOC, that share their data for tsunami warning purposes. In addition, the RTSPs receive data from several deep-ocean tsunameters located off the major seismic zones of the Indian Ocean. Many of the current set of sea-level stations whose data are available to the RTSPs can be seen in Figure 5 below, which shows the locations of Indian Ocean stations accessible through the IOC Sea-Level Station Monitoring Facility.
3.2 Tsunami Forecasting Methodology

The three RTSPs all employ similar tsunami forecasting methodologies, but there are differences in the details of their models and processes. The common core of the forecasting approach is to pre-calculate ocean-wide tsunami characteristics in deep water (20-30 metre depth or greater) for a large number of earthquake scenarios, using an oceanographic model based on fluid dynamics and bathymetry data. From the model’s grid of forecast tsunami parameters, each centre extracts for each coastal forecast zone representative values, such as tsunami arrival time and maximum tsunami amplitude. Using the representative values for each zone, each centre extrapolates from the deep water model predictions to 1 metre depth to determine if the threat threshold (50 cm positive wave amplitude) will be crossed, and the height of the maximum forecast wave.

When a significant earthquake occurs, each RTSP selects from its library the scenario which best matches the real earthquake, and uses the forecast data from that run of the model in its advice to the NTWCs. Sea-level monitoring networks are then used to confirm that a tsunami was generated and to assess the accuracy of the model predictions.

The extrapolation of wave amplitude from deep to shallow water is an approximation based on simplifying assumptions about the slope of the sea floor and the orientation of the coast. All centres use the Green’s Law\(^3\) approximation for this crucial step, and NTWCs should be aware of the inaccuracies which are likely to result. This issue is discussed further in the section on limitations and uncertainties.

Within the bounds of the common methodology just described, the RTSPs differ in some technical details of their forecasting process, such as:

- the location and spacing of earthquake scenarios on which the library of model forecasts are based
- the assumptions about earthquake rupture geometry and energy transfer to the ocean
- the method of selecting representative values for each forecast zone.

The libraries of earthquake scenarios used by the RTSPs are composed of many model runs based at a large number of likely earthquake locations. At each location it is necessary to carry out several model runs, each at a different earthquake magnitude, so that when a real earthquake occurs a scenario which closely matches the observed location and magnitude can be selected. The location/magnitude combinations used by the three centres are as follows:

- Australia – Total = 522 locations x 4 magnitudes
- India – Total = 1462 locations (unit magnitude used to calculate any observed Mw)
- Indonesia– Total = 715 locations\(^4\) x 6 to 8 magnitudes

The tsunami models which the RTSPs run to produce their libraries of scenario forecasts are similar in their physics, but differ in their configurations, which are summarised in the table below.

\(^3\) Green’s Law: \(h_1 = 4\sqrt{\frac{d_0}{d_1}} \times h_0\) where \(h_1\) = wave amplitude at 1m depth, \(h_0\) = forecast wave amplitude at 30m depth, \(d_1\) = water depth at the beach (1m), and \(d_0\) = deep water depth (30m)

\(^4\) InaTEWS scenario library has a high concentration of closely-spaced locations near Indonesia due to the need to provide a detailed national warning service in addition to the RTSP role.
The grid length used in the RTSP models is less than the length of most of the coastal forecast zones, so model data is usually available for several grid points within a zone. The procedures by which the RTSPs select the appropriate forecast values of wave amplitude and arrival times from these grid points varies to some extent among the RTSPs, but is generally intended to lean towards the safest choices (earliest likely arrival times and maximum likely wave amplitudes).

The process of selecting representative values for a zone is based on a network of 2174 Coastal Forecast Points (CFPs) which has been agreed on by the RTSPs and which is independent of their individual model grids. The number of CFPs in a zone varies, but is generally three to four. RTSPs determine representative values of maximum tsunami amplitude, and arrival times of first, maximum and last waves (see Section 4.1.8 below) from the values at their model grid points surrounding each CFP. The general form of this selection process is as follows:

- Identify the CFPs in each coastal forecast zone
- Identify the model grid points (usually 4) surrounding each CFP
- From the surrounding grid point values for each CFP identify the maximum forecast value of tsunami amplitude and earliest arrival times.
- From the values associated with each CFP select for each zone representative values of maximum tsunami amplitude and earliest arrival times.

Because the coastal forecast zones lie at the boundary between shallow water and the deep water where the models are applicable, care must be taken in identifying and rejecting grid points which lie in shallow water and so may not have valid forecasts.

Some different strategies can be applied in the selection process. For example, all of the forecast values for a zone might reasonably be taken from the grid points surrounding the CFP which has the largest forecast maximum tsunami amplitude. However, other CFPs within the same zone may be associated with earlier arrival times, so another approach is to choose the earliest arrival times from all CFPs in a zone. With this strategy the arrival times and maximum wave amplitudes issued for a zone might derive from different points within the zone, but the safest forecast is provided. There are some differences in the details of the selection strategies used by the RTSPs, but they are continuing to collaborate on refining and standardising this process.

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5 Greenslade et al, 2009
6 Imamura et al, 2006
7 Behrens et al, 2010
If an earthquake does generate a tsunami, the RTSPs are able to utilize the sea-level observation network to compare the wave amplitudes with their model predictions. The models are designed for deep water (greater than 20 to 30 metres depth), so tsunameters located well away from coastal shallows provide the most reliable comparisons with the model predictions. In theory it is possible to “invert” the tsunami model, using observed wave amplitudes to calculate the magnitude of the generating earthquake. This method could be used to correct the magnitude determined by seismic measurements, but is not currently used operationally by the RTSPs. However, RTSPs do currently compare their forecast tsunami amplitudes with tsunameter observations and, if necessary, make appropriate adjustments to the coastal zones forecast to be under threat, particularly where the amplitude forecast is close to the threat threshold.
4 The RTSP Products

The full suite of products which RTSPs provide to the NTWCs comprises:

- **Notification messages** - sent to NTWCs when RTSP bulletins are issued, via the World Meteorological Organization (WMO) Global Telecommunication System (GTS), e-mail, SMS and fax. The notification messages do not contain detailed tsunami forecasts, since this information is not intended for public dissemination, but provide an immediate “heads-up” to NTWCs.

- **Detailed tsunami threat information and bulletins** – accessible to NTWCs on each RTSP’s password-protected website.

- **Graphical products** - such as threat assessment maps and wave-height/travel-time maps, also made available to NTWCs on the RTSPs’ websites.

- **Spatial data files** - containing threat assessment and wave forecast data for use in mapping applications, also made available to NTWCs from password-protected web/FTP sites.

Other, more detailed country-specific information or products may be arranged through bilateral agreement between the country requiring the service and an individual RTSP.

The Global Telecommunications System (GTS) is operated by the WMO primarily to exchange weather information between National Meteorological and Hydrometeorological Services (NMHSs). Because the GTS has 24x7 support and a high reliability record, it is a preferred method for receiving the critical first notification of the issuance of RTSP products. NMHSs subscribe to products based on each product’s WMO identifier. In countries where the NTWC is not also the NMHS, the agencies should coordinate to ensure rapid delivery of the Notification Messages to the appropriate operational office.

4.1 Bulletin Structure

All RTSPs use the same layout and structure for their bulletins, which consist of some or all of these component sections, depending on the bulletin type:

- **Header** – Indicates the issuing authority, bulletin number, which is sequential throughout an event, type of bulletin and the date and time in UTC that the bulletin was issued.

- **Earthquake Parameters** – comprising Magnitude (Mw), Depth (km), Date and Time of earthquake (UTC), Latitude and Longitude of earthquake epicentre, and Location Name of earthquake epicentre

- **Tsunami Evaluation Statement** - Based on preliminary earthquake parameters, the first bulletin may contain qualitative information on tsunamiogenic potential of the earthquake (local / regional / ocean-wide). If model results indicate a THREAT, the evaluation message indicates that investigation is underway. If any sea-level gauge subsequently confirms the existence of a tsunami that is reported in this section, from the third bulletin
onwards.

- **Tsunami Threat Information** – If model results indicate a THREAT, this section is included from the second bulletin onwards and includes a list of countries where a THREAT is forecast to exist. For each threatened country the coastal zones under THREAT are listed with the expected wave arrival time in UTC for the first wave greater than the 0.5 m threshold, and the expected maximum wave amplitude in metres for that zone.

- **Advice** - Indicates that the bulletin is issued as an advice only and that the condition of the alert and determination of action based on threat status is up to national or local authorities.

- **Updates** - A statement indicating when the next bulletin will be issued, or in the case of Type 4 Bulletins indicating that no further bulletins will be issued for the event. Also information about additional information which may be issued by other RTSPs.

- **Contact Information** – Details on how to contact the RTSP

This structure is illustrated in the sample bulletin below. This example shows the most complex bulletin (type 3, which includes sea-level tsunami observations and coastal zone forecasts, with the sections separated for illustrative purposes.

### 4.1.1 Header

<table>
<thead>
<tr>
<th>RTSP-INDIA-20110615-0600-005 (TYPE – III Supplementary 05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSUNAMI BULLETIN NUMBER 5</td>
</tr>
<tr>
<td>REGIONAL TSUNAMI ADVISORY SERVICE PROVIDER RTSP INDIA (ITEWC)</td>
</tr>
<tr>
<td>issued at: 0632 UTC Wednesday 15 June 2011</td>
</tr>
<tr>
<td>... CONFIRMED TSUNAMI THREAT IN THE INDIAN OCEAN ...</td>
</tr>
</tbody>
</table>

### 4.1.2 Earthquake Parameters

1. **EARTHQUAKE INFORMATION (Revised)**
   - RTSP INDIA issuing earthquake with the following preliminary parameters:
   - Magnitude: 9.0 M (Great)
   - Depth: 10 km
   - Date: 15 Jun 2011
   - Origin Time: 0600 UTC
   - Latitude: 7.2 N
   - Longitude: 92.9 E
   - Location: Nicobar Islands, India

### 4.1.3 Tsunami Evaluation Statement

2. **EVALUATION**
   - Sea level observations have confirmed that a TSUNAMI WAS GENERATED.
   - Maximum wave amplitudes observed so far:
     - CampbellBay(India) 6.9 93.7 0605Z 15 Jun 2011 12.5m
     - Nancowry(India) 8.0 93.5 0618Z 15 Jun 2011 2.5m
     - Kamorta(India) 8.1 93.5 0619Z 15 Jun 2011 14.7m
     - Sabang (Indonesia) 5.8 95.3 0627Z 15 Jun 2011 8.5m
   - Based on pre-run model scenarios, the zones listed below are POTENTIALLY UNDER THREAT.
4.1.4  Tsunami Threat Information

3. TSUNAMI THREAT FOR THE INDIAN OCEAN
The list below shows the forecast arrival time of the first wave estimated to exceed 0.5m amplitude at the beach in each zone, and the amplitude of the maximum beach wave predicted for the zone. Zones where the estimated wave amplitudes are less than 0.5m at the beach are not shown.
The list is grouped by country (alphabetic order) and ordered according to the earliest estimated times of arrival at the beach.
Please be aware that actual wave arrival times may differ from those below, and the initial wave may not be the largest. A tsunami is a series of waves and the time between successive waves can be five minutes to one hour.
The threat is deemed to have passed two hours after the forecast time for last exceedance of the 0.5m threat threshold for a zone. As local conditions can cause a wide variation in tsunami wave action, CANCELLATION of national warnings and ALL CLEAR determination must be made by national/state/local authorities.

AUSTRALIA
---
COCOS ISLAND (AU) 0834Z 15 Jun 2011 1.1m
NORTHWEST CAPE TO CARNARVON 1114Z 15 Jun 2011 2.2m

BANGLADESH
---
KHULNA 0846Z 15 Jun 2011 1.8m
COXS BAZAR 0853Z 15 Jun 2011 3.4m

4.1.5  Advice

4. ADVICE
This bulletin is being issued as advice. Only national/state/local authorities and disaster management officers have the authority to make decisions regarding the official threat and warning status in their coastal areas and any action to be taken in response.

4.1.6  Updates

5. UPDATES
Additional bulletins will be issued by RTSP INDIA for this event as more information becomes available. Other RTSPs may issue additional information at:
RTSP INDONESIA: http://rtsp.bmkg.go.id
In case of conflicting information from RTSPs, the more conservative information should be used for safety.

4.1.7  Contact Information

6. CONTACT INFORMATION
Indian Tsunami Early Warning Centre (ITEWC)
Indian National Centre for Ocean Information Services (INCOIS)
Address: “Ocean Valley”, P.B No.21, IDA Jeedimetla P.O, Hyderabad - 500 055, India.
35
Tel: 91-40-23895011
Fax: 91-40-23895012
Email: tsunami@incois.gov.in
Website: www.incois.gov.in

4.2  Detailed Tsunami Forecast Data

So that the text bulletins can be contained to a practical length, the presentation of the detailed tsunami forecast information from the RTSPs’ models is limited in these products. The most critical values, arrival time of the first wave over the threat threshold and the
expected maximum wave amplitude (which is often after the first wave), are included in the bulletins, but much more information is made available in tables on the RTSP web pages.

In addition to a graphical overview of the Indian Ocean showing, by colour-coding, which coastal zones are forecast to be under threat, the RTSP web pages also give these details of their model forecasts for each threatened zone:

- Maximum wave amplitude at the coast at water depth 1m (included in text bulletins)
- Time of arrival of first tsunami wave ($t_1$)
- Time of arrival of first tsunami wave amplitude over 50 cm ($t_2$) (included in text bulletins)
- Time of arrival of maximum tsunami wave ($t_3$)
- Time of arrival of last wave amplitude over 50 cm ($t_4$) (Ref: JATWC, 2011)

The diagram below shows an example of an RTSP webpage table containing tsunami forecast details.

---

**Figure 6:** RTSP tsunami forecast table from web page
Other useful graphical products which the RTSPs provide on their webpages are tsunami travel time isochrone maps, and diagrams showing the distribution of forecast maximum tsunami amplitude (in deep water), often referred to as energy or directivity maps.

**Figure 7:** Tsunami travel time (black contours – hours) and maximum wave amplitude/directivity map (colour – cm)

Those NTWCs with Geographic Information System (GIS) capabilities can also download from the RTSP websites a DBF file containing spatial data for each event.
5 Limitations and Uncertainties

The IOTWS has led the world in the implementation of an advanced, modeling-based tsunami forecasting service, but the system is not yet perfect or comprehensive. The limitations discussed below are well recognized by the ICG/IOTWS and the RTSPs, and many are currently being worked on. The system will continue to evolve and improve, but in the meantime, NTWCs should take the uncertainties into consideration in the design of their planning and response systems.

5.1 Non-earthquake sources

Tsunamis can be generated by mechanisms other than major earthquakes of magnitude 6.5 or greater. Less intense earthquakes, volcanoes and undersea landslides and certain meteorological events can also generate tsunami waves, but the impacts of these events are usually confined to the local area (approximately 100 km radius). The short tsunami travel time over these short distances means that the IOTWS cannot provide an effective alerting service for these mechanisms. Other, less common events, such as meteorite/asteroid impact in the ocean also have the potential to create tsunami waves, but the IOTWS forecasting system has not been designed to respond to such events.

5.2 Near-field earthquakes

As a regional service for the entire Indian Ocean, the IOTWS has not been designed to address the problem of near-field earthquakes in which the tsunami travel time to coastal communities is less than about 15 minutes. The RTSP target for issuance of an initial earthquake bulletin to NTWCs is 10 minutes elapsed time from the earthquake, and 20 minutes for issuance of the first bulletin containing tsunami threat information.

RTSPs cannot provide alerts or forecasts quickly enough to warn communities which are less than 15-20 minutes tsunami travel time from an earthquake source region. The high density of seismic observations required to identify and respond to earthquakes in less than 5 minutes cannot be utilized by the RTSPs over their ocean-wide area of responsibility. Those communities which are less than 15-20 minutes tsunami travel time from potential source zones are also those which will feel a significant earthquake as it occurs. Effective community education which prioritises moving to safety even before official warnings are received is therefore essential. In the Indian Ocean many such locations are also now served by well-developed national warning systems, such as in Indonesia.

5.3 Simplified rupture geometry

Tsunami models generally assume simple sea-floor rupture geometry. The exact size and shape of the movement of the sea-floor during a tsunamigenic earthquake cannot be deduced quickly enough to meet the short timeframes required for tsunami warning, so simplifying assumptions have been made in the RTSP oceanographic models. These assumptions can introduce errors into the directionality of the forecast maximum waves. Further, the tsunami models assume the maximum possible transfer of energy from sea-
floor to the ocean for a particular earthquake magnitude and so may overestimate the magnitude of tsunami waves to some degree.

5.4 Non-real-time model scenarios

Use of pre-run model scenarios introduces some errors due to the differences between the real-time earthquake characteristics and the pre-run scenario. RTSPs are moving towards real-time running of tsunami models, so that observed real-time earthquake location, magnitude and geometry can be used to initialize the tsunami forecasts. However, at present in general real-time earthquake locations are rarely more than about 50 km distant from the closest pre-run scenario in the RTSPs’ library of model runs.

5.5 Delays in magnitude estimation

Great earthquakes involve ruptures which can extend for many hundreds of kilometres. Such ruptures do not occur instantaneously, but can take several minutes, eg. the 2004 Indian Ocean earthquake took 8 minutes to fully rupture. Because tsunami warning systems are designed to detect and respond very quickly, it is usually the case that the first estimates of magnitude during major tsunamigenic events are made before the rupture is complete and so are lower than the final value. RTSPs will issue updated bulletins and model forecasts as soon as magnitude estimates are revised by seismologists. NTWCs should expect and be prepared for an escalation in the number of threatened coastal zones in RTSP advices during the first 30 minutes or more of severe events.

5.6 Extrapolation of deep-water model forecasts to the beach

Most deep water propagation models cannot be used in water less than 20 to 30 metres deep, so simple extrapolations using Green’s Law are used to forecast wave amplitude on the beach. Coastal inundation models can be coupled to the broadscale deep-water models to produce detailed coastal wave forecasts, but these require very high-resolution inshore bathymetry and considerable computing power. Generally this is not practical at present for the RTSPs.

While shallow water wave amplitude is being forecast by extrapolation from deep-water modeling, the effect of small coastal features such as headlands, bays and sand-bars cannot be quantified in RTSP products. These features can introduce very large variations in the observed tsunami wave amplitude and run-up within a single coastal forecast zone. There is considerable scope for national agencies to add value to the RTSP service by carrying out risk analyses and high-resolution inundation modeling for critical or vulnerable coastal zones.

5.7 Communications network latency

Time is of the essence during a tsunami event, and the RTSP performance targets reflect this. Although modern communications networks are generally very reliable and prompt, it should be remembered that the time to receipt of notifications from time of issuance by the RTSPs is dependent on network performance.
5.8 False alarms

The IOTWS has been designed to minimize the impact of false alarms. Many earthquakes of magnitude 6.5 or greater occur without generating a tsunami, but the RTSPs cannot wait for confirming sea-level observations before alerting NTWCs of a potential threat. The first bulletins issued therefore act as alerts for national agencies to begin preparations without committing to action. Over years many of these alerts will not move into the confirmed tsunami phase, but NTWCs should take care to ensure that Bulletins Type 1 and 2 (before confirmation) continue to be carefully monitored and assessed.

5.9 Coastal sea-level gauge network deficiencies

The coastal sea-level gauge network is generally not dense enough to capture a full picture of the distribution of tsunami waves and impact during a major tsunami. RTSPs provide tsunami forecasts for coastal zones which are about 100 km long or less, but the spacing between verifying sea-level gauges around the Indian Ocean is much greater. In some events it is possible that the sea-level gauge network will suggest that no tsunami waves over the threat threshold were generated, even though larger waves went unobserved in some zones without gauges.

5.10 Simplified inversion techniques

Deep-ocean tsunameters can provide reliable early observations of tsunami amplitude, but RTSP systems cannot currently make full use of this information to calculate refined quantitative tsunami forecast parameters. RTSPs currently use tsunameter data to confirm tsunami generation and to make qualitative adjustments to their forecasts. Numerical techniques are available to utilise reliable tsunami measurements to “invert” the tsunami model to refine the initial earthquake assessment and so correct the model’s forecasts. All RTSPs are working on implementing this technique.
6 Interpretation of RTSP Products

6.1 Using advice from multiple RTSPs

During a major tsunami event, the RTSPs issue a large number of notification messages, bulletins and graphical products. NTWCs can choose to monitor and assess the products from all three RTSPs, but need to ensure that their procedures protect their operational staff from being overwhelmed or confused by the volume of information.

Because of the differences in tsunami models between the RTSPs there will be some differences among the centres in the number of coastal zones forecast to be under threat. Figure 8, below, illustrates the high degree of similarity between the coastal zone threat forecasts from two RTSPs for a simulated earthquake of Mw 9.0 in the Sunda Strait.

![Figure 8: Coastal zone threat forecasts from RTSP Indonesia (left) and RTSP Australia (right) for a simulated earthquake of Mw 9.0 in the Sunda Strait. Red zones (left) and orange zones (right) are forecast to receive tsunami waves above the threat threshold.](image)

Tsunami travel times are usually very consistent between models, but the forecast maximum wave amplitudes will differ to some degree. The performance targets for RTSPs reflect this, with wave amplitude accuracy aiming to be within a factor of two of the observed values.

Two obvious strategies for NTWCs in managing the differences in RTSP forecasts are to either select one RTSP as the basis for local decisions, or to use the most conservative (earliest arrival/most severe) of the three RTSP forecasts. The former strategy has the advantages of simplicity and speed. However, it risks subsequent criticism if local warnings did not cover affected coastal zones which were correctly forecast to be under threat in RTSP products which were not used. The RTSP bulletins recommend that “in case of conflicting information from RTSPs, the more conservative information should be used for safety”.

RTSPs measure their performance using the key performance indicators described earlier, and NTWCs are able to monitor the indicators from a website maintained by the RTSPs. In addition, at the meetings of the ICG/IOTWS (held every two years), the RTSPs provide
detailed reports on their performance against the KPIs. The reports are available in the meeting documents published on the IOC website.

6.2 Interpreting forecast arrival times and maximum wave amplitudes

The detailed forecast information included in the RTSP text bulletins and tables is complex and requires some interpretation to be correctly used. The specific forecast values were listed above and are discussed in more detail here.

**Maximum wave amplitude at the coast at water depth 1m** - This forecast wave height is included in the RTSP text bulletins and the detailed table of forecast values. The forecast is based on a model forecast of tsunami wave amplitude forecast in deep water within the coastal zone. The deep-water value is extrapolated to a representative value at the beach (1 metre depth) using Green’s Law. The extrapolation does not take into account local bathymetry or the geometry of the coast. A single forecast value represents the whole coastal zone and determines whether the zone is assessed as being under threat or not.

**Time of arrival of first tsunami wave \( t_1 \) –** Tsunami travel time forecasts are generally quite accurate, although discrepancies between the source location in the chosen scenario and the actual location of the real earthquake can introduce a small error. The first tsunami wave in this context means the first model forecast of a wave amplitude of 2 cm or more. This time is not the time of arrival of the maximum wave, which will usually be later.

**Time of arrival of first tsunami wave amplitude over 50 cm \( t_2 \) –** This forecast arrival time is included in text bulletins with the maximum wave amplitude, but NTWCs should understand that the maximum wave arrival time will be different. The arrival of the first wave over 50 cm amplitude is significant because this is the threshold for determining if a coastal zone is under threat.

**Time of arrival of maximum tsunami wave \( t_3 \) –** The highest tsunami wave is usually not the first wave to arrive, so this time will generally be later than \( t_1 \) or \( t_2 \). This forecast can be useful after a tsunami has begun to impact a coastal zone in determining if the impact has reached its peak or will continue to intensify.

**Time of arrival of last wave amplitude over 50 cm \( t_4 \) –** Finalisation of tsunami warnings requires careful consideration. It is possible that local effects in bays, harbours, estuaries and other features, which are not included in the RTSP tsunami models, can cause seiching and currents which could be dangerous for an extended period after the tsunami waves have ceased to arrive at a coastal zone. The RTSPs provide the forecast time of arrival of the last wave over the threat threshold, and base the timing of their final (cancellation) bulletin on this forecast. The final bulletin is issued 2 hours after the last \( t_4 \) in any coastal zone. NTWCs will consider a variety of local factors, including community reaction, as well as the forecast \( t_4 \), in deciding when to finalise their local warnings.

These four forecast time values are illustrated in Figure 9, below, using a modeled time series from RTSPAustralia’s scenario library.
Figure 9: Time series forecast of tsunami amplitude in deep water, from RTSP Australia’s scenario library, illustrating $t_1$ (time of first tsunami wave arrival), $t_2$ (time of first wave over threat threshold), $t_3$ (time of maximum wave amplitude) and $t_4$ (time of last tsunami wave over threat threshold) (Coburn and Leggett, 2013).

6.3 Meaning of the energy/directivity maps

For every earthquake which meets the magnitude/location criteria for RTSP assessment, each RTSP generates a graphical product which summarises the maximum waves forecast by its tsunami model. This product is also called an energy or directivity map, since it clearly shows the directions in which the largest waves develop away from the earthquake source.

The product is an integrated picture of the largest forecast waves throughout the run-time of the model, which is around 24 hours from the time of the earthquake. It is not a snapshot at a particular instant, but a plot of the distribution of the worst waves over the 24-hour period.

Usually the maps clearly show focusing of the largest waves near the earthquake in the directions perpendicular to the alignment of the fault which has ruptured. Further from the source, the effects of bathymetry (islands and undersea ridges and mountains) are also apparent in local maxima in the forecast wave amplitude. It must be remembered that these maxima are not coincident in time, but can be separated by many hours.
6.4 Using RTSP spatial data in local GIS

For NTWCs and NDMOs with GIS capabilities the most convenient format in which to receive the RTSP products may be the DBF files which are available from the password-protected websites. When combined with local vulnerability or administrative maps in a GIS, the RTSP coastal zones and associated forecast amplitudes and arrival times could be used to prioritise and expedite response and evacuation activities. RTSP India also provides geo-referenced forecast data in KML format, for use with Google Maps.

The shape file which defines all of the coastal forecast zones is permanently available from the RTSP websites. During an event a DBF file which is readable by GIS such as ArcReader is created and made accessible from the websites. The DBF file contains the geo-referenced forecast wave amplitudes and arrival times from the tsunami models.

6.5 Using local inundation modeling with RTSP forecasts

The broadscale nature of the RTSP model forecasts has been discussed above. Until computing power develops sufficiently to allow the RTSPS to carry out real-time high-resolution inundation modeling for the whole Indian Ocean area of responsibility, the IOTWS service can be augmented by research into local inundation modeling. These models can be
nested in broadscale boundary conditions which would be expected in selected earthquake scenarios. The scenarios and databases used to create the RTSP forecast libraries could be used as an initial filter to identify the most dangerous earthquake events for selected coastal zones.

As well as allowing better localized risk assessment, local inundation modeling also forms the best basis for planning emergency response and designing NTWC/NDMO procedures. During a real event, when RTSP threat forecasts are issued, experience with local modeling would allow the broad threat/no threat zone forecasts to be refined by the NTWC to focus on particularly vulnerable areas within each affected zone.
7 Glossary

**Amplitude (tsunami)** - Vertical distance from normal sea-level to tsunami wave crest

**Coastal Forecast Points (CFP)** - Network of 2174 points covering all Indian Ocean coasts, used by RTSPs to represent tsunami forecasts for coastal forecast zones.

**Coastal Forecast Zones (CFZ)** – 571 zones covering the coasts around the Indian Ocean, including islands, with default dimensions of 100 x 50 km, but modified to match local provincial or other administrative boundaries where known.

**GIS** – Geographic Information System

**GTS** - Global Telecommunication System operated by WMO

**ICG** – Intergovernmental Coordination Group

**InaTEWS** - Indonesia Tsunami Early Warning System

**INCOIS** – Indian National Centre for Ocean Information Systems

**IOC** – Intergovernmental Oceanographic Commission of UNESCO

**IOTWS** – Indian Ocean Tsunami Warning and Mitigation System

**JATWC** – Joint Australian Tsunami Warning Centre

**MOST** – Method of Splitting Tsunami model used by JATWC

**NDMO** – National Disaster Management Office

**NTWC** – National Tsunami Warning Centre

**PTWS** – Pacifici Tsunami Warning System

**RTSP** – Regional Tsunami Service Provider

**TsunAWI** - Tsunami forecast model used by InaTEWS

**TUNAMI N2** – Tsunami forecast model used by INCOIS

**USGS** – United States Geological Survey

**WMO** – World Meteorological Organization
References


Coburn, P., and Legget, T.: RTSP Tsunami Arrival Times, NTWC Workshop, Jakarta, September 2013


ICG/IOTWS-IX/12: WG2 Report to ICG/IOTWS-IX, 2012

