Ocean Decade Tsunami Programme

Research & Development Implementation Plan

2nd Draft Report

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List of Acronyms

CAP	Common Alerting Protocol
CARIBE-EWS	Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions
CNN	Convolutional Neural Network
COTS	Commercially off the Shelf
CPA	Civil Protection Agency
CTBTO	Comprehensive Nuclear-Test Ban Treaty Organisation
CTIC	Caribbean Tsunami Information Centre
DART	Deep-ocean Assessment and Reporting of Tsunamis
DAS	Distributed Acoustic Sensing
DMO	Disaster Management Office
DONET	Dense Ocean Floor Network system for Earthquakes and Tsunamis
FDSN	Federation of Digital Seismographic Networks
GADRRRES	Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
ICG	Intergovernmental Coordination Group
IFREE	Institute for Frontier Research on Earth Evolution
IOC	Intergovernmental Oceanographic Commission IOTIC Indian Ocean Tsunami Information Centre
IODE	International Ocean Data and Information Exchange
IOTWMS	Indian Ocean Tsunami Warning and Mitigation System ITIC International Tsunami Information Center
IRIS	Incorporated Research Institutions for Seismology
ITST	International Tsunami Survey Team
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
LDC	Least Developed Country
NEAMTIC	North-Eastern Atlantic, Mediterranean and connected seas Tsunami Information Centre
NEAMTWS	North Eastern Atlantic, Mediterranean and connected seas Tsunami Warning and Mitigation System

NEPTUNE	North-East Pacific Time-series Undersea Networked Experiments
NTWC	National Tsunami Warning Centre
ODTP	Ocean Decade Tsunami Programme
ORFEUS	Observatory and Research Facility for European Seismology
OTGA	Ocean Teacher Global Academy
PGD	Peak Ground Displacement
PSHA	Probabilistic Seismic Hazard Assessment
PTHA	Probabilistic Tsunami Hazard Assessment
PTWC	Pacific Tsunami Warning Center
PTWS	Pacific Tsunami Warning and Mitigation System
SIDS	Small Island Developing State
SLR	Sea Level Rise
SMART	Science Monitoring And Reliable Telecommunications
SOP	Standard Operating Procedure
TEMPP	Tsunami Evacuation Maps, Plans and Procedures
TEMPP	Tsunami Evacuation Mapping Planning and Procedures
THA	Tsunami Hazard Assessment
TIC	Tsunami Information Centre
TNC	Tsunami National Contact
TOWS-WG	Working Group on Tsunamis and Other Hazards related to Sea Level Warning and Mitigation System
TRA	Tsunami Risk Assessment
TSP	Tsunami Service Provider
TT-DMP	Task Team on Disaster Management and Preparedness
TT-TWO	Task Team on Tsunami Watch Operations
TWS	Tsunami Warning System
UNDRR	UN Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WMO	World Meteorological Organisation

1 Introduction

1.1 Purpose of the Ocean Decade Tsunami Programme Research, Development and Implementation Plan

In 2016, IOC-UNESCO initiated the concept "from the Ocean we have to the Ocean we want" and in December 2017, this concept culminated in the proclamation of the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030), also referred to as the Ocean Decade. The Ocean Decade's primary objective is to harness, stimulate and empower interdisciplinary ocean research at all levels to support the timely delivery of the data, information and knowledge needed to support all Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.

In June 2021, IOC-UNESCO approved the Ocean Decade Tsunami Programme (ODTP) in response to the call to action by the Ocean Decade to reduce the uncertainty and warning time for the tsunami forecast and preparedness of coastal communities.

The **first objective of the ODTP** is to develop the warning systems' capability to issue actionable and timely tsunami warnings for tsunamis from all identified sources to 100 percent of coasts at risk. Most urgently, the ODTP will provide tsunami confirmation within 10 minutes or less of origin for the most at-risk coastlines. This is challenging, as current warning systems depend upon quick detection and characterisation of tsunamigenic earthquakes using only seismic sensors. This objective would require expanding existing monitoring systems and implementing further scientific and technological advances, and to also include non-seismic tsunami sources (Sumy et al., 2022).

The **second objective of the ODTP** is that 100 percent of communities at risk be prepared and resilient to tsunamis by 2030 through programmes like the IOC-UNESCO Tsunami Ready Recognition Programme (TRRP), which was approved by the IOC-UNESCO Executive Council in 2022. It embodies 12 Assessment, Preparedness and Response Indicators that support communities at risk to build capacities to effectively respond to warning and tsunami threats.

The purpose of the research, development and implementation plan is to highlight how to address the following areas to achieve the objectives of the ODTP:

(i) Enhance tsunami risk assessments and the research on technologies for it, so the countries know their expected threat and vulnerability, and are able to identify and prioritise the at-risk communities.

(ii) Expand and improve existing detection and monitoring systems, including seismographs, coastal tide gauges, and deep ocean tsunameters, to fill identified gaps, and deploy new technologies to address observational gaps that cannot be covered by existing networks.

(iii) Ensure all National Tsunami Warning Centres (NTWCs) have access to data, tools and communication platforms, protocols and training to timely and effectively warn coastal and maritime communities threatened by tsunamis and other coastal hazards that are integrated into a multi-hazard framework

(iv) Emphasise the importance of building tsunami resilient communities through the IOC-

UNESCO Tsunami Ready Recognition Programme, which is achieved through involvement of stakeholders at all levels.

In addition, this research, development and implementation plan addresses the needs for capacity development, governance and pathways to implementation. Its intended audience is, among others, the governing bodies of IOC, relevant UN bodies, ODTP programme leads, Intergovernmental Coordination Groups (ICGs), Member States, tsunami practitioners, Research and Development scientists and funding agencies.

Implementation of the Research and Development Plan also addresses special consideration and priority to the needs of Small Island Developing States (SIDS) and Least Developed Countries (LDCs).

1.2 Background

The world's oceans and coasts are fundamental components of humanity's life-support system. Their productive ecosystems and rich biodiversity provide wide-ranging social and economic benefits, including food-security for large populations. However, many coastal areas face decline due to increasing population pressures and economic development, in turn increasing the demand for food, water, energy and other services. Numerous economic activities are connected to the ocean. Marine transportation plays a crucial role in global trade; 80–90 percent of all trade is carried out by about 50,000 ships worldwide (Schnurr and Walker, 2019). Approximately 40 percent of the world's population live within 100 km of the coast with approximately 680 million people living in low-lying areas (less than 10 m above sea level) that are exposed to varying degrees of oceanic hazards including tsunamis (UN Ocean Conference, 2017).

The Indian Ocean Earthquake of 26 December 2004 caused one of the largest and most disastrous tsunamis ever experienced. An estimated 230,000 people lost their lives in 14 countries and resulted in damages of an estimated USD10 billion. The highest death toll, of about 130,000, was reported from Banda Aceh and Meulaboh along the north-western coast of Sumatra where the tsunami run-up heights exceeded 30 m. Within hours the tsunami propagated to all directions of the Indian Ocean affecting Thailand, Sri Lanka, India, Maldives and as far as east Africa. A few years later, on 11 March 2011, a major earthquake ruptured offshore Northeast (NE) Japan in the Pacific Ocean and generated a tsunami, which devastated the NE coastal zone of Japan, particularly the Tohoku region where the wave runup reached up to about 40 m, while the tsunami penetrated inland up to about 5 km. An estimated 19,508 people lost their lives including missing persons, nearly all of them due to the tsunami. The tsunami also caused major damage to the Fukushima nuclear power station. Within hours the tsunami propagated throughout the Pacific Ocean affecting as far remote regions as California, where damage occurred in Crescent City and several other harbours (Borrero et al., 2013; Admire et al., 2014).

The 2018 Palu and Anak Krakatoa, and 2022 Hunga Tonga - Hunga Ha'apai events further illustrated the challenges for the current Tsunami Warning Systems locally and globally. These three events are catalogued as "non-seismic tsunamis" as they were not caused by submarine earthquakes, and thus posed a challenge for the current tsunami warning protocols. The 2018 events in Indonesia had a local impact only, but the tsunami caused by the eruption of the

Hunga Tonga - Hunga Ha'apai volcano in 2022 affected the entire Pacific basin, causing two deaths in Peru. These events call for enhanced coordinated national and international efforts for the Tsunami Warning Systems to account for all types of tsunamis and to prepare people to respond to them.

The global tsunami warning services are provided by regional tsunami warning systems operating in different ocean basins: the Pacific Tsunami Warning and Mitigation System (PTWS), the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS), the North-eastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning System (NEAMTWS), and the Caribbean and Adjacent Regions Early Warning System (CARIBE-EWS), each coordinated by a regional ICG. The regional warning systems are the building blocks of the end-to-end tsunami warning and mitigation system, coordinated by IOC-UNESCO as a global "system of systems". One of the primary goals of all ICGs is to improve existing earthquake and tsunami monitoring and early warning systems, and to provide effective international exchange of information and data.

The core governance principles that apply to all IOC regional Tsunami Warning Systems are that: 1) they are fully owned by the Member States of the region, 2) they are based on international and multilateral cooperation, 3) they are based on the free and open exchange of data, 4) they are designed to protect all countries in the region, and 5) that each Member State has the sovereign responsibility for issuing warnings in their respective territories and for protecting their own populations.

A global Working Group on Tsunamis and Other Hazards (TOWS-WG) has been established by IOC for global coordination and has been key to the establishment of the ODTP. The ODTP addresses the four pillars of Early Warning Systems described in the Early Warnings for All Action Plan (WMO, UN, COP 27, 2022): (i) Tsunami Disaster Risk Knowledge, (ii) Detection, Monitoring, Analysis and Forecasting of the tsunami hazard and possible consequences (iii) Warning Dissemination and Communication and (iv) Preparedness and Response Capabilities. These four components are underpinned by capacity development, governance, including collaboration mechanisms, and financing.

2 Risk Knowledge

Tsunami risk reduction is based on a combination of various actions including operation of early warning systems, public education and awareness, preparedness and emergency planning. However, understanding the physical processes that govern the generation, propagation, and inundation of tsunamis as well as the assessment of the tsunami hazard and risk for specific locations are of crucial importance for an effective development of the various tsunami risk reduction actions at those locations.

2.1 Advance Risk Knowledge

The concept of risk as related to earthquakes was defined by UNESCO in the 1970s as a function of three main elements: hazard, vulnerability, and value exposed to hazard (see for example UNESCO, 1978). This definition was later generalised and applied to other types of risks including tsunamis. The above definition of risk is consistent with recent terminologies and glossaries adopted in the framework of international organisations such as the United Nations Office for Disaster Risk Reduction (UNDRR), the European Union (EU) and IOC-UNESCO. According to the IOC Tsunami Glossary (IOC, 2019a), tsunami hazard is defined as the *possibility* that a tsunami of a particular size may strike a particular section of coast, while tsunami risk is the *probability* of a particular coastline being struck by a tsunami, multiplied by the likely destructive effects of the tsunami and by the number of potential victims. In general terms, tsunami risk is considered as hazard multiplied by vulnerability and exposure. Tsunami risk can be approached qualitatively or quantitatively and this again depends on the data availability and on the kind of risk that is being assessed.

2.2 Tsunami Hazard

Tsunami runup, inundation area, flow depth and arrival time are essential parameters for tsunami preparedness at all levels. By 2030, tsunami hazard zones should be mapped for all at-risk locations, specific “hot spots” of the strongest expected tsunamis have to be identified including maximum values of runup, inundation area and flow depth, and minimum values of arrival times should be known by emergency planners, responders and communities exposed to tsunami hazard.

In some cases, it is desirable to have forecasts of other parameters before or during an event, such as maximum expected flow velocities and tsunami driven coastal erosion. However, these parameters usually require more and higher resolution input data.

In most places tsunamis and tides interact linearly and thus tsunami heights can be simply added to the tide level at any given moment. However, in some specific cases, tsunamis interact with the tide non-linearly. Hazard assessments should explore and account for this possibility.

2.2.1 Tsunami Hazard Assessment

Tsunami Hazard Assessment (THA) studies provide the necessary parameters for tsunami preparedness. The approaches developed for THA are classified in two main classes, deterministic and probabilistic, but some studies have a hybrid approach. THA studies, disregarding the approach, should consider all possible sources of tsunamis affecting the study area, not only seismic sources.

Deterministic hazard assessments employ the largest tsunami causative source or ensemble of sources for the study area, so-called worst-case credible tsunami scenario or scenarios. Characteristic historical events, e.g., large earthquakes, are usually taken as a guide, although hypothetical events could also be considered, particularly where historic information is scarce and/or where non-seismic events could cause tsunamis.

Probabilistic Tsunami Hazard Assessments (PTHA), which in recent years have gained ground, follow in many ways the experience obtained from the Probabilistic Seismic Hazard Assessment (PSHA) since the 1960s. PTHA focuses on the investigation of seismic and other sources that are potentially capable of producing tsunamis threatening a particular coastal segment. The probabilities of exceedance of certain run-up values in the coast are calculated taking into account the probabilities of activation of any tsunami source in a given timeframe. The tsunamis generated by those sources are numerically simulated to define the maximum expected heights in those time frames. Another approach is based on analysis of tsunami statistics itself and forecasting probability of expected tsunami runups based on these statistics (Kulikov et al., 2005).

2.2.2 Methodologies to Define Tsunami Parameters

Both approaches for THA can employ two methodologies to define the maximum tsunami heights caused by the selected scenarios: fixed-height or numerical modelling of tsunami inundation. Numerical modelling of tsunami inundation is the preferred method to calculate tsunami inundation areas, wave heights and flow depths. However, if the required data for tsunami numerical modelling is not available, a fixed-height approach can be employed to estimate the extent of the inundation areas. This method defines all land below a fixed height as the inundation area. It is also called the "bath-tub approach". The height can be defined based on maximum runup caused by historical tsunami events in the study area or based on results of numerical models of tsunami propagation up to a certain depth applying Green's Law to estimate the wave height at the coast. The latter can be calculated through deterministic, probabilistic or hybrid approaches.

Sometimes, the extent of the inundation area may need to be adjusted considering distance from the shore and the presence of rivers, particularly at very flat coastal areas and/or large river mouths. Also, a buffer may need to be defined to account for unknown factors and the increased uncertainties associated with this methodology.

If inundation numerical modelling is not available, arrival times can be estimated from tsunami propagation modelling or obtained from historical events. However, flow depths cannot be estimated from propagation modelling but may be available in the case of historical events.

Tsunami numerical modelling can be done by either deterministic or probabilistic approaches for THA to define tsunami parameters. For each tsunami source scenario, the tsunami wave is numerically simulated in three stages: generation at the source, propagation in the open ocean, and inundation and recession at the coastal zone in the coastal segment of interest. The outputs of the last stage are mainly tsunami arrival time, inundation area, wave heights, and flow depths, although depending on the data and resources available might also include tsunami flow velocity and coastal erosion.

For deterministic studies, if several source scenarios are employed, a flooding envelope is used to define the hazard zone or inundation area. The different characteristics of the scenarios employed are used to guide evacuation planning, particularly if there are differences in arrival time or impact of the sources employed.

There are many numerical models used for tsunami propagation, inundation, and simulation of flow velocities and sediment transport. However, some of them might not be adequate or accurate. In 2007, the United States (US) adopted mandatory benchmarks for tsunami numerical model validation and verification that are available for other countries to use (Synolakis et al., 2008a). According to Synolakis et al. (2008b), validation is "the process of ensuring that the model accurately solves the parent equations of motion" and verification is "the process of ensuring that the model represents geophysical reality".

The choice of numerical model depends on the purpose of the modelling, the type of tsunami source, the spatial resolution and the computing capacity available. Most tsunami numerical models are freely available, but some are not. Some of the freely available models are only shared with trained staff. **This is an issue that should be addressed internationally by the ODTP.**

2.2.3 Input Data Needed for THA

Any tsunami numerical model requires mainly two inputs: the forcing or scenario definition and the bathymetric and topographic elevation data. They also require records of past tsunamis for in-site verification and calibration. However, at the present stage of research both the probabilistic and deterministic methods suffer from a variety of uncertainties related to data, technical and scientific aspects.

The effort required for tsunami hazard determination is characterised by significant gaps in the availability of the data sets needed. Here the required inputs to perform THAs are detailed.

2.2.3.1 Tsunami Historical Records

The setup of a tsunami numerical model for a specific location should be verified against historical events in order to assure that the model is reproducing the interaction of nearshore and coastal morphology with tsunamis correctly.

However, the relative sparsity of quantifiable tsunami records, both instrumental (sea level gauges along the coasts or by tsunameters at the sea bottom) and runup, creates an important research gap, not only for model verification but also for the definition of worst- case scenarios and PTHA studies. Historical tsunami data sets are not equally available in all the parts of the global ocean, due to limited human settlements in the coastal zone and limited timespan of documented history in different parts of the world.

Catalogues that list paleoearthquake and paleotsunami events, which are identified by geological methods, e.g., by the recognition of tsunami sediment deposits, may provide further enrichment of the tsunami catalogues and useful input for the calculation of recurrence intervals of large events. However, possible under or overweighting of past tsunamis should be treated with caution, noting possible misidentification of storm surge deposits (Dewey et al, 2021). Of special interest are approaches developed initially for the PSHA with the utilization of incomplete and uncertain earthquake catalogues containing instrumental, historical and paleoearthquake data (Benito et al. 2012; Alvarado et al. 2017). Such approaches are suitable for hazard assessment associated with rare events and, therefore, recently were tested for the PTHA too with promising results, e.g., the Global Tsunami Model (https://edanya.uma.es/gtm/).

The systematisation and availability of reliable historical and paleotsunami datasets should be encouraged. For this geological and historical studies are required. But also, sea level monitoring networks must be expanded in order to register future tsunamis, even small ones, also ensuring that International Tsunami Survey Teams (ITST) are deployed immediately after a tsunami event occurs, given its proven value for more reliable historical tsunami dataset to test tsunami models against (Arcos et al, 2019). **A goal of the ODTP is for each country to have their catalogue of tsunami records by 2030**.

2.2.3.2 Tsunami Source Scenarios

Tsunami numerical modelling can be used for THAs as well as for tsunami forecasting. For tsunami forecasting during an event, rapid characterisation of the triggering event is required, while for hazard assessment, the definition of the scenarios will depend on whether it is a probabilistic, deterministic or hybrid approach.

One of the significant difficulties for THA is the complexity of the triggering sources, both seismic and non-seismic. The forcing of numerical models requires geophysical parameters in order to compute sea floor or sea surface deformation. In some cases, this deformation is instantaneous but in other cases it is not, such as for landslide-generated tsunamis and meteotsunamis for which the forcing can last for several minutes or hours. Even for the modelling of seismic sources there are many uncertainties; in their dimensions, the faulting styles and the rates of activation with larger magnitude earthquakes, as they are mostly located undersea. Non-seismic tsunami sources are also threatening and thus should be considered in THA when applicable. Meteotsunamis are very frequent especially near the Balearic Islands and in the Adriatic Sea; landslides and associated tsunamis are common in Norway, Greenland, Alaska and British Columbia. Tsunamis generated by volcanoes are common in some areas. Globally, about 50 volcanoes located inland close to coastlines or undersea are prone to induce various sources of tsunami waves.

Since 2013, IOC-UNESCO has organised Experts Meetings to define tsunami worst-case scenarios using a deterministic approach in several high-risk subregions of the Pacific and Caribbean basins prioritized by the respective ICGs (IOC 2013, IOC 2016b, IOC 2018a, IOC 2018b, IOC 2019b, IOC 2020a, IOC 2021a). The definition of those scenarios was based on seismic, geodetic and historical data. The scenarios and their modelled propagation for the Caribbean and for the Pacific coast of Central America are available at the Caribbean and Adjacent Regions Tsunami Sources and Models at https://www.ncei.noaa.gov/maps/CATSAM/.

For a better characterisation of potential tsunami sources, it is required to have better seismic, GNSS, and geophysical volcanic monitoring, and more scientific research. Also, the Experts Meetings to define tsunami sources provide a more accessible resource for countries performing THA, thus it is desirable to enhance them and broaden their scope also to non-seismic sources. **A goal of the ODTP is for each ICG to have a database of tsunami source scenarios available for tsunami modelling by 2030.**

2.2.3.3 Non-Seismic Sources

Volcanic-generated tsunamis represent a big challenge for Tsunami Early Warning Systems (TEWS) due to difficulties in monitoring and combined mechanisms. TWS are currently activated by earthquakes while non-seismic sources would require other activation mechanisms, such as sea level variations and source characterisation, in particular for regional and far-field warning. For this, wider monitoring networks such as sea level, GNSS, seismic, geodetic, etc. are required. However, such monitoring poses several challenges. Sea level monitoring faces relatively low coverage, maintenance costs, and noise. Seismic and geodetic networks over submarine volcanoes are not feasible and should be located in the periphery of the volcano edifice. Also, there is still debate on the type of geological and geographic characteristics of volcano edifices that are more prone to generate tsunamis, to define which volcanoes should be monitored and included in tsunami hazard assessment studies. Historical information is required for including volcanic tsunamis in THA studies. Even when recent events provided an important amount of data, paleotsunami data on volcanic tsunamis are more complex to obtain.

Atmospherically induced destructive ocean waves can also generate locally devastating impact. Called meteotsunamis, these sea level oscillations reach the coast with the same frequencies as typical tsunami waves. These oscillations are similar to ordinary tsunami waves and can affect coasts in a similar damaging way, although the catastrophic effects related to this type of waves are normally observed only in specific bays and inlets. These destructive waves are not related to any seismic activity, volcanic explosions, submarine landslides or meteorite impacts but to atmospheric forcing (atmospheric gravity waves, pressure jumps, frontal passages, squalls, etc.) (Monserrat et al., 2006).

Tsunamis can also be generated by sub-aerial and submarine landslides (Fine et al., 2003). Landslides can be triggered by earthquakes and volcanic eruptions, but also can be tectonically generated, such as at Nice, France, in 1979 (Assier-Rzadkieaicz, 2000) and in Skagway, 1994. Therefore, anomalous variations in sea level measurements should be included in tsunami warning activation protocols in addition to seismic and volcanic activity, also considering earthquake and volcanic triggered landslides. Landslides generated by seismic and volcanic activity can increase tsunami waves by more than an order of magnitude in height in the near field, as happened in Papua New Guinea in 1998 (Tappin et al, 2008). Including landslide generated tsunamis in THA is very difficult as it is almost impossible to anticipate the characteristics of future landslides. Even when bathymetric surveys can assist in some cases to identify and characterise the potential for possible future landslides, they are driven by complex processes and therefore there are many associated uncertainties.

As a result of climate change, it is anticipated that landslides may become more common in the future, due to thawing processes near the poles, saturated soils due to increased rain rates, and increased coastal erosion.

2.2.3.4 High-Resolution and Updated Digital Elevation Data

High-resolution and updated elevation data is required for THAs. Unfortunately, there is a generalised limited availability of digital elevation data, particularly bathymetric data, which is scarce in the near-shore domain. Additionally, many coastal areas lack topography at an appropriate resolution for numerical modelling of the inundation area. Furthermore, elevation data require regular updating due to tectonic and other inland and nearshore processes such as coastal erosion. This is a major challenge due to the economic and manpower costs of conducting surveys to obtain this data.

Globally, more qualified staff are required for survey data collection. Some countries lack staff and/or their staff are not trained to perform these studies. Additionally, funding is required to buy or rent the required equipment to survey elevation data. The collection of elevation data should follow quality and resolution standards. The ICG/CARIBE-EWS developed minimal requirements of elevation data for tsunami modelling (ICG/CARIBE-EWS WG2, 2019). It would be desirable that each ICG has a database of the extent of the existing elevation data and its metadata, including the conditions under which they might be shared. The ICG/CARIBE-EWS is currently exploring the possibility to create such a database under the Caribbean Marine Atlas initiative.

2.3 Exposure and Vulnerability

Tsunami impact may include fatalities and injuries as well as damage or even destruction of a variety of assets, such as buildings, critical or essential infrastructures, vessels and coastal cultivated areas. The tsunami impact may also include social disruption and direct or indirect losses in financial terms. In the natural environment there are several effects caused by tsunamis, such damage or destruction of flora and fauna, ground erosion, transport of sediments and deposition of medium-fine grained material, boulders and megaclasts.

Financial values exposed to tsunami hazards have been considered in a few studies. Relevant losses have been expressed using as metrics either the probable maximum loss for a given return period of the extreme tsunami event or the probabilistic average annual loss and the loss exceedance curve. An interesting approach is the one developed for the scenario-based method (Triantafyllou et al., 2019). In this approach, absolute monetary cost is calculated for building reconstruction and replacement after an extreme tsunami inundation.

The estimation of tsunami losses is closely connected to damage to buildings and infrastructure. Therefore, physical vulnerability and exposure constitute important components of the tsunami risk assessment. In this sense, vulnerability is closely associated to damage or fragility. This issue has been examined mainly on the basis of data collected either after the Indian Ocean 2004 and Japan 2011 mega tsunamis or from local building statistics and field inspections without a reference to the impact of particular tsunami events. However, a lack of consensus has been noted as regards the various aspects related to the fragility vulnerability modelling. Important research gaps include the data limitation about asset types. On the other hand, the effect of multiple hazards on the empirical tsunami fragility mode is also important. For example, the building damage caused by the earthquake occurrence before the tsunami attack may increase building vulnerability. An important gap refers to the difficulty of quantifying social vulnerability, either of populations or individuals. Some researchers recently highlighted that despite increased focus on vulnerability, the measurement of progress towards disaster risk reduction in the Sendai Framework for Disaster Risk Reduction (2015−2030) remains event/hazard-centric (Chmutina et al, 2021).

Exposure data provide information about the characteristics and the location of people and of various assets at risk. Several techniques for the acquisition of exposure data exist, although with different degrees of resolution and precision. Exposure modelling, however, is also characterised by several gaps, including lack of data or lack of data detail and lack of tsunami exposure model and taxonomy. For populations residing in, or visiting, coastal zones, particular attention should be given to the time-dependency of exposure. Seasonal and daily patterns of people gathering at the seashore is of crucial importance for the assessment of population exposure. Exposure could change due to environmental, socioeconomic and political migration.

To address the above indicated gaps, a goal of the ODTP is for each country to identify vulnerable groups and identify total and disaggregated numbers for population at risk within tsunami inundation areas by 2026 and identify and prioritize critical infrastructure by 2030.

Traditionally, tsunami risk assessment includes qualitative or quantitative scenario-based methods. Probabilistic and Deterministic Tsunami Risk Assessment (TRA) methods have been developed more recently with a variety of approaches. However, less progress has been noted in TRA with respect to THA. This is due to the fact that for hazard assessment, only data on the physical parameters of the events are needed, while for risk assessment, vulnerability, exposure and value data are also required. Datasets of these types are limited or even lacking in many coastal areas of the world. As a consequence, the several methods tested so far are quite variable and closely dependent not only on the kind of datasets available but also on the data quality and reliability. For these reasons the several components involved in the TRA are susceptible to a large variety of uncertainties making risk assessment a highly complex procedure. Therefore, no standard methods for TRA have been defined so far, and the chosen method should consider the context and data available, in a case-by-case approach.

By 2026 ODTP will seek to develop methodologies for tsunami risk assessments including multi-scenario, location-based risk assessment of tsunami hazard characteristics, vulnerability, exposure, likelihood and consequences.

2.4 Cascading Risk

Tsunami waves are often produced as the result of cascading effects, which may involve combinations of several physical processes. For example, a strong coastal or submarine earthquake may cause a landslide that becomes a tsunami generation agent although the fault displacement, which is associated with the earthquake, does not produce a tsunami. This possibility is of importance for the assessment of the tsunami hazard and risk. Therefore, relevant studies should not neglect the possibility of cascading effects in areas which are susceptible to processes of this type.

In recent years, particular attention has been attracted by the possible effects that climate change may have on the long-term assessment of tsunami hazard and, consequently, of tsunami risk. For example, in November 2020 a tsunami with 100 m runup was generated at a glacier lake in British Columbia, Canada, due to a landslide originated by rapid deglaciation and increased rain rates (Geertsema et al., 2022).

The acceleration of landslide processes may happen not only along coastal zones but also in the submarine environment where increase of the sedimentation rate is expected.

The long-term but gradual Sea Level Rise (SLR) is a crucial parameter that should be taken into account when considering the possible effect of climate change on tsunami hazard assessment. In very recent studies new PTHA approaches have been tested to meet such challenges in time frames of a century or so. However, SLR is very likely a non-stationary process and, therefore, probabilistic models incorporating Poissonian but non-stationary rates of SLR variations have been tried. Such models have been applied successfully to the PSHA in the past and, therefore, are promising for the PTHA as well.

The research and implementation plans for achieving the ODTP Risk Knowledge aspirational goals are provided in Appendix 1.

3 Detection, Analysis and Forecasting of Tsunamis and Associated Hazardous Consequences

3.1 Introduction

Tsunamis are the sea level response to the displacement of large volumes of water. Around 80 percent of all tsunamis or 70 percent of deadly tsunamis result from large undersea earthquakes. The role of such hazards as potential tsunami sources is relatively well known and understood, particularly after the destructive tsunamis of the last two decades. Following the 2004 Indian Ocean, the 2010 Chile and the 2011 Tohoku (East Japan) tsunamis it became clear that the highest potential of subduction zones to produce major trans-oceanic tsunamis had been underestimated. This led to a reevaluation of the maximum expected earthquake magnitude for many of the world's subduction zones. Similarly, several recent destructive tsunami events, generated by volcanic eruptions, landslides, and atmospheric disturbances (so called "non-seismic events") have caused a re-evaluation of the threat of such tsunamis. The March 2017 meteotsunami in the Persian Gulf (Heidarzadeh et al., 2020), the September 2018 Palu tsunami in Sulawesi, Indonesia, the December 2018 tsunami triggered by flank collapse due to the eruption of the Anak Krakatau volcano in the Sunda Strait, Indonesia (Kumar and Manneela, 2021), and the Hunga Tonga – Hunga Ha'apai volcanic eruption induced tsunami of January 2022 (Manneela and Kumar, 2022) clearly demonstrated the serious threat of such tsunamis for coastal communities.

For both seismic and non-seismic tsunamis, the accuracy of tsunami warnings and the required alarm times to effectively warn at-risk communities remains a challenge. Seismic and non-seismic generated tsunamis have a broad range of devastating impacts, from damage to coastal infrastructure and livelihoods, to significant inland inundation and numerous casualties along entire coastlines along the ocean basin. Tsunami warnings require active responses of at-risk communities based on the threat level. False alarms from inaccurate warnings can lead to mass panic, accidental deaths, disruptions to economies and inappropriate community responses to real tsunami threats in the future.

In order to enhance the accuracy and timeliness of tsunami warnings, we need to identify reliable methods to monitor and detect tsunamis. To do this we need to understand the processes of tsunami generation from both seismic and non-seismic sources and the best techniques to employ, taking into account that they require fundamentally different approaches. In all cases, there is a principal trade-off between accuracy (minimum uncertainty) and timeliness required for warnings which is inherent in the process. In this chapter we present the current status of our understanding of tsunami detection and monitoring, provide an analysis of the gaps in our knowledge and capability, and suggest how these gaps can be addressed. The overall tsunami monitoring and detection systems employed should be improved to quantitatively enhance tsunami warnings. This will include new and innovative data sources and analysis techniques that enables us not only to develop new science, but to implement this science and techniques into operational tsunami monitoring, detection, and warning systems. This will necessarily require robust data communication techniques, as well as strong international cooperation. To improve tsunami warning, especially for near-field known source locations we should greatly reduce the time it takes to estimate the tsunami source parameters needed to evaluate tsunami risk and to construct effective tsunami numerical models. This is illustrated in Figure 1 (after Angove et al., 2019) which shows the reduction in uncertainty with time. Immediately after a tsunamigenic event occurs, there is the maximum uncertainty in the likely impacts, and this uncertainty reduces as we learn more about the tsunami source. This is largely a function of data availability. Figure 1 shows that the rate of uncertainty has reduced markedly between 2004 and 2019. However, additional improvement is possible and needed.

3.2 The Tsunami Threat Lifecycle

It is illustrative to consider the life cycle of a tsunami threat, from the initial identification of a potential event, through confirmation of the threat and characterisation of the tsunami source or resultant wavefield, to forecasting of potential impacts, to the response of civil society, and finally to when the threat has passed. The full tsunami threat life cycle includes **key decisions** taken by civil society to respond to the event, including the issuance of warning and other advice and evacuations when necessary. The techniques employed and the timescales involved will depend on the tsunami source, but in all cases the tsunami threat lifecycle has the follow phases:

1. **Initial Indicators:** The identification of a geophysical event that has potential to create a tsunami. This is often a large undersea earthquake, but may also be a volcanic eruption, landslide, abrupt atmospheric disturbance or any other event with the potential to displace enough water to generate a tsunami. In this lifecycle phase it is normally unknown whether the event created a tsunami or not.

   Key Decisions: Initial alerts issued based on established standard operating procedures, including attention to natural warning signs.

2. **Confirmation:** The positive identification that a significant threatening tsunami was or was not created by a potentially tsunamigenic event. This phase focuses on positive detection of the tsunami itself via sea level observations but will usually not allow effective forecasting. The tsunami impact is still uncertain, but the potential threat is confirmed**.**

   Key Decisions: If tsunami is confirmed, continue with established standard operating procedures. If a tsunami is confirmed not to exist, alerts can be stood down.

3. **Forecasting:** Enough observations have been collected to support initial hydrodynamic tsunami forecasts. Once a reasonable estimate of a tsunami source is available, and tsunami generation is confirmed, forecast modelling is used to estimate the potential impacts on coastlines, with nearby impacts taking priority. Over time the potential impacts to all coastlines within an ocean basin can be estimated, along with the impact timelines, although these will usually be very uncertain, particularly for unexpected sources.

   Key Decisions: Targeted alert levels and inundation extent.

4. **Validation:** Enough sea level observations are available to verify or scale the initial tsunami forecasts. As the tsunami threat progresses, monitoring using all available data continues. At a particular location the threat can be evaluated and can be very different to other locations. Near the source, the impacts can be large and damaging, but pass relatively quickly, but for more distant locations the threat can be less damaging but continue for

many hours. At specific sites ("hot spots") local topographic amplification of arriving tsunami waves can take place.

Key Decisions: Refine alerted areas based on observations.

5. **Cancellation:** Enough verifying data is available to determine when the threat has passed at particular locations. At any particular location there will be a time when the threat has passed, although some impacts (sea-level fluctuations and currents) may continue for hours to days. The time at which a tsunami threat can be considered as passed relies on observations of sea-level, modelling and expert advice and can be a very difficult decision. NTWCs may then decide to issue an end of threat message. Although the decision is aided by data, information and expert advice, it is the emergency management organisations who are eventually responsible for determining when it is safe for communities to return to potentially impacted and dangerous locations and coastal and harbour infrastructure and coastal and harbour infrastructure can return to normal work level.

   Key Decisions: Issue end of threat message as per established standard operating procedures

Throughout the full tsunami threat life cycle, it is possible to provide information on the potential threat, but initially the uncertainties are very large and in fact no tsunami may have been generated at all. What is important is the ability to decide when to issue warnings with limited information.

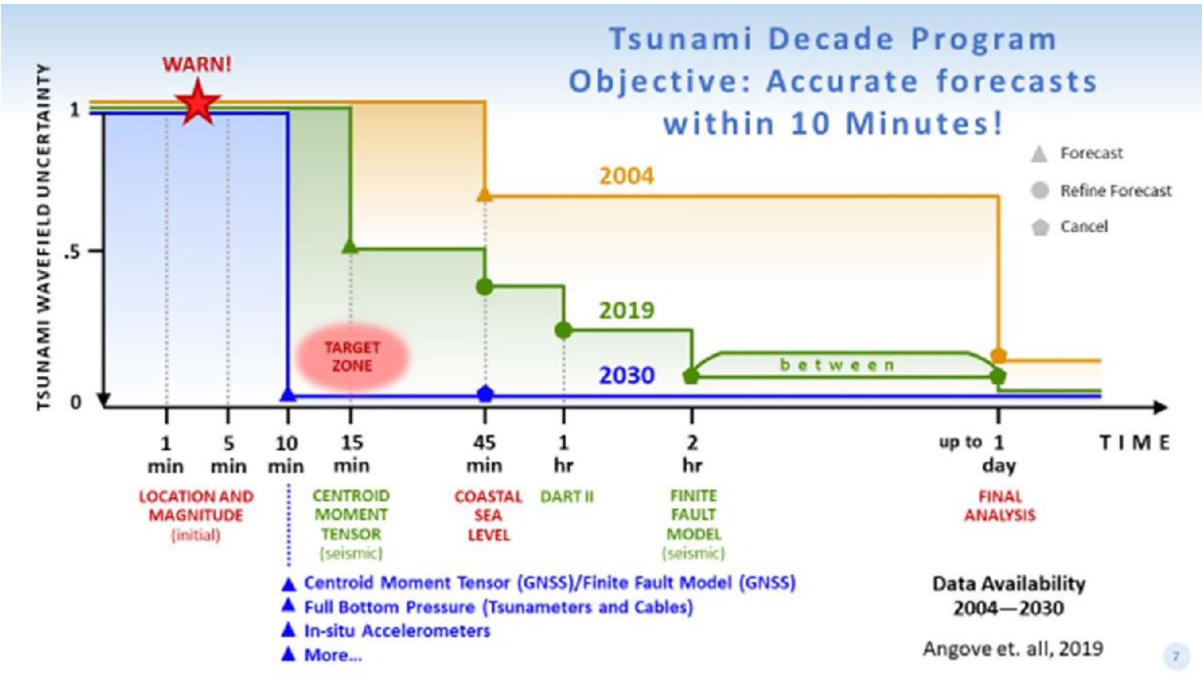

Figure 1: Diagram showing the generalised relationship between tsunami source uncertainty and time after earthquake origin for three different time frames. The orange line represents tsunami source uncertainty levels prior to 2004, the green line represents tsunami source uncertainty levels in 2019, and the blue line represents tsunami source uncertainty levels achievable with the ocean sensing and analysis techniques described in this paper. Initial earthquake location and magnitude is considered "fully uncertain" in terms of solving tsunami source parameters for the purposes of this depiction.

3.3 Detection and Measurement

A goal of the ODTP is to greatly expand international cooperation in tsunami warning and mitigation, to improve capability to directly detect and measure tsunamis and reduce reliance on seismic proxy relationships in terms of projecting impacts. As shown in Angove et al (2019), Emergency Managers require information that is relevant, accurate and timely to ensure appropriate response can be operatively developed and executed. The seismic proxy provides the necessary timeliness but can be inaccurate and even irrelevant due to the imperfect nature of the relationship between initial earthquake parameters and a potential tsunami. By identifying and supporting development of capabilities for faster tsunami detection, the ODTP can help ensure that regional and national Tsunami Warning Systems deliver relevance and accuracy as well as timelines.

An additional and very important issue is non-seismic tsunamis (volcanic, landslide and meteorological). These events are still a serious challenge for the existing Tsunami Warning Systems. There are certain regions around the world where specifically non-seismic tsunamis are the major threat for coastal communities. For example, it appears that volcanic tsunamis are especially dangerous for the Tonga-Kermadec zone, Indonesia and the Lesser Antilles Islands, landslides and associated tsunamis are common for the areas of British Columbia, Alaska, Norway and Greenland, while destructive meteotsunamis are typical for the Mediterranean, Gulf of Mexico, Great Lakes, the western coasts of Korean Peninsula and on the Atlantic coasts of North and South America. As part of the ODTP, new approaches are planned for the warning and mitigation of these events.

Table 1 Specific aspirational targets of the ODTP related to tsunami detection, analysis and forecasting

Tsunami Source	Initial indicators (time after origin)	Tsunami detected (time after origin)	Tsunami constrained (time after origin)
Earthquake	3 min	10 min	45 mins
Non-earthquake (known)	10 mins	45 mins	60 mins
Non-earthquake (unknown)	60 mins	90 mins	120 mins

Achieving the aspirational goals in Table 1 will require investigation of four focus areas including (1) maximizing current capabilities and instrumentation; (2) expanding current instrumentation network; (3) identifying capabilities that exist but are not currently applied to tsunami, and (4) identifying new capabilities that require development. For each focus area it will be necessary to estimate the quantitative improved accuracy and timeliness in relation to the aspirational targets to justify implementation.

3.3.1 Maximise and expand current capability to meet ODTP goals

3.3.1.1 Seismic Networks

Real-time, low latency, on-scale data from seismic stations at close epicentral distances are essential to facilitate prompt characterisation of earthquakes. Seismic networks are fundamental to the early detection of earthquakes with tsunamigenic potential. Many thousands of seismic stations world-wide are used to identify earthquakes. Most of these stations are run by global, regional or national agencies to locate earthquakes for purposes other than tsunami detection, and many are for longer term research purposes. Additionally, international organisations such as the Comprehensive Nuclear Test-ban Treaty Organisation (CTBTO) operate seismograph networks; in the CTBTO case to monitor the nuclear test-ban treaty, but all data is available to hazard monitoring agencies including Tsunami Service Providers (TSPs). The maintenance of these networks needs encouragement, and the sharing of data in real-time must be made universal.

Seismologists have long agreed on standards under the Federation of Digital Seismographic Networks (FDSN) for data acquisition, transmission, distribution, and archiving which has facilitated data sharing among different institutions worldwide. Thanks to these efforts, data can be automatically centralized and distributed to be used by interested parties with almost no delay.

The basic parameters to characterise an earthquake, among others, are location, depth, fault orientation, source time function, and magnitude (moment tensor includes source geometry and size); all these elements determine the earthquake´s tsunamigenic potential. For larger earthquakes, i.e., extended rupture zones, a full description includes other properties of the source such as fault slip distribution.

The location and size of an earthquake provide a reasonable estimate of its tsunamigenic potential. Because appropriate regional and global models of velocity structure have been developed at almost all scales, it is easier to estimate the earthquake initiation location (epicentral geographical coordinates and hypocentral depth) from seismic waves. More difficult is the prompt estimation of earthquake magnitude because, at short distances, high gain broad-band sensors reach clip levels (when the wave amplitude exceeds the upper limit of their dynamic range) and, on the other hand, it is not simple to extract the long period information from the strong motion instruments in real time. This issue often causes serious underestimation of tsunami impact (Ozaki, 2011). This is where the Global Navigation Satellite System (GNSS) plays a major role, which will be discussed below.

More than 6,000 stations affiliated with FDSN provide data to the three main centres of the Federation: the Data Management Center of the Incorporated Research Institutions for Seismology (IRIS/DMC) U.S.A; the Observatory and Research Facility for European Seismology (ORFEUS), Netherlands; and the Institute for Frontier Research on Earth Evolution (IFREE, JAMSTEC), Japan (Suarez et al., 2008)

As of September 2022, the IRIS/DMC receives and distributes continuous low-latency data from nearly 4,000 broad-band seismic stations (Figure 2). These data are available to interested users to characterise earthquakes. For example, the Pacific Tsunami Warning Center (PTWC) takes about 10 minutes to characterise significant earthquakes in the region, estimating their epicentre, magnitude, and tsunamigenic potential.

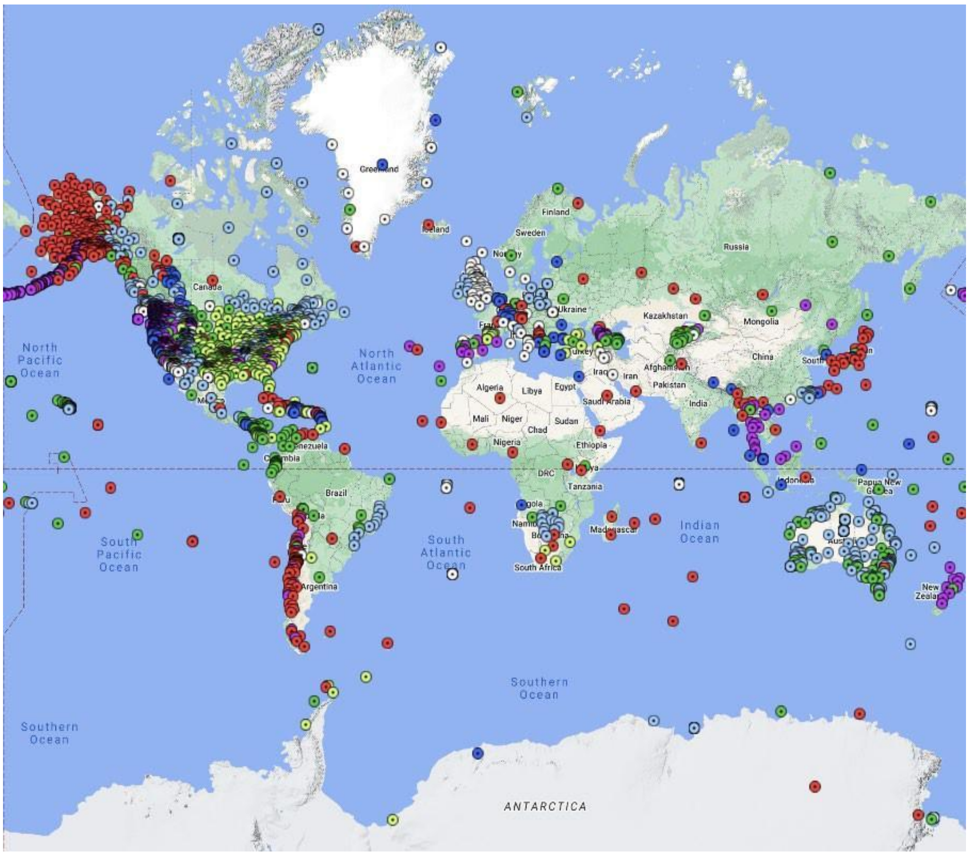

Figure 2 Distribution of broadband seismic stations sending real-time data to IRIS DMC

Figure 2 shows the uneven distribution of land-based seismic stations contributing open data to the global system. In addition, the CTBO monitoring system, composed of 170 primary and auxiliary seismic stations, as well as 11 hydroacoustic stations, can provide data to UNESCO IOC-recognized tsunami warning organisations.

The use of the available seismic data to assist in characterising earthquake sources can still be greatly improved. Examples include regionalised W-Phase determination to reduce source characterisation times, back-projection and strong-motion centroid approaches to quickly estimate source dimensions. Moving these capabilities into operational use by TSPs and NTWCs is key to taking full advantage of the global network of seismograph stations.

In general, seismic network coverage on land is adequate to allow the detection of all tsunamigenic earthquakes, but there are some regions where this is not the case, and not all data are being shared in real time. The identification of network gaps and where existing stations need enhancement is therefore required and international organisations and Member States are encouraged to fill gaps. An example of where this is starting to improve is the South-west Pacific where extra stations are being planned and installed following the Hunga Tonga – Hunga Ha'apai eruption and tsunami.

3.3.1.2 Tsunameters

Deep ocean pressure gauges (tsunameters) provide a critical underpinning for the Tsunami Warning Systems because they are the only means currently available to directly detect tsunami waves in the open ocean close to the source region in near real-time. Tsunameters can be effectively used for real time tsunami modelling and for the initial tsunami source reconstruction.

The term "tsunameter" in this document refers to all bottom pressure recorder installations, including SMART (Science Monitoring And Reliable Telecommunications) cables and cable observatories. SMART cables and S-Net, DONET and NEPTUNE cable observatories have the advantage of allowing continuous recording of bottom pressure, whereas standalone automatic tsunameters such as Deep-ocean Assessment and Reporting of Tsunamis buoys (DARTs) afford high resolution tsunami detection only during relatively short period of time of the "Event Mode" (2-24 hours) (Rabinovich and Eblé, 2015). In general, the tsunameter networks target tsunamis caused by subduction zone megathrust earthquakes, although there are DART buoys targeted to provide essential tsunami information to specific Member States.

The first permanent deep-ocean observational cabled network using seismometers and pressure gauges for the purpose of monitoring seismic and tsunami activity in offshore areas was installed in 1978 off the coast of Tokai at Japan (Meteorological Research Institute, 1980). This method uses a deep-sea cable connecting land stations and ocean-bottom sensors. Additional cabled deep-ocean instruments have since been deployed including the North-East Pacific Time-series Undersea Networked Experiments (NEPTUNE) in Canada (Thomson et al., 2011; Barnes et al., 2013), the Dense Ocean Floor Network system for Earthquakes and Tsunamis (DONET) in Japan (Kaneda et al., 2015); and Seafloor Observation Network for Earthquakes and Tsunamis (S-net) along the Japan Trench (Aoi et al., 2020) are also in operation (see overview of deep-ocean tsunami monitoring system by Rabinovich and Eblé, 2015). However, all these observation networks are targeting earthquakes and tsunamis in specific areas, and ocean-wide cable-based seismometer and pressure gauge observation networks have not yet been developed.

GNSS buoys (Kato et al., 2000) and tsunameter buoys (Gonzalez et al., 1998) have been put into practical use for offshore tsunami observation. GNSS buoys are moored on the seafloor and measure changes in buoy position in real time, while tsunameter buoys have an acoustic communication function that transmits water pressure data observed with pressure gauges installed on the seafloor.

The maintenance of current tsunameter capabilities is important to keep networks effective, and this is a major contribution of Member States who are supporting currently deployed tsunameters.

Recent advances in the technology of standalone tsunameters (e.g., DART 4G) allow better separation of the seismic and tsunami signals by sampling at higher frequencies and applying filtering techniques. This allows to deploy instruments closer to potential tsunami sources, reducing detection times of generated tsunamis, but requires more sites to provide the same coverage. To take full advantage of the newer tsunameter technologies (including DART 4G, cable observatories and SMART cables) a detailed analysis of the current networks and planned future expansion is required. Several recent studies have demonstrated the high potential of tsunameter data for a wider range of scientific applications to understand ocean circulation, Madden-Julian Oscillation, climate, etc. This enables much wider use of tsunameter data and promote technologies to integrate and co-deploy tsunameters with other ocean observing networks.

The challenge will be both to identify resources and/or leveraging opportunities to densify the existing tsunameter networks as well as ensuring the right instrument is to be deployed in the right location in order to achieve the ODTP objectives.

3.3.1.3 Coastal Sea Level Gauges

Coastal sea level gauges (e.g., tide gauges used for port operations, tidal measurements, and monitoring sea level variations due to seasonal and climate variability) are used to estimate tsunami impacts and height variations along coastlines. They can be used to confirm or alert tsunami arrivals and to specify tsunami warnings for particular coastlines. Island-located tide gauges are especially important to estimate expected tsunami wave heights and upgrade/ cancel the warnings. Coastal tide gauges can also be effectively used to verify numerical forecast models and for cataloguing tsunami events, even small ones that do not cause injury or damage.

Deploying additional coastal tide gauges in known coverage gaps can improve the tsunami forecast and warning effectiveness and support tsunami warning operations [1 minute sampling interval, 1-15 minutes reporting interval, GLOSS Implementation Plan – Table 1, IOC, 2012].

3.3.1.4 Global Navigation Satellite System

Rapid assessment of the source characteristics of major earthquakes in the near field is not easy to be achieved using only seismographs and accelerometers. One possibility is to include low-gain broad-band sensors in the observation system so seismic signals close to the epicentre can be recorded on scale. The development of real-time precise positioning by means of GNSS has provided a complementary method to estimate actual ground displacement. Not only can it evidence the static component of earthquake-induced displacement, but seismic oscillations as well, within a few mm of error.

Figure 3 shows the observed peak ground displacement (PGD) for different earthquakes at different hypocentral distances (Melgar et al., 2015). Allowing a few millimetres of error, surface displacements generated by magnitude 7 or larger earthquakes can be detected at hypocentral distances of 100 km. The larger the earthquake, the more distant the effect. Observation of surface displacements close to the rupture zone allows a rapid (and better) estimation of the variability of the fault slip. In subduction zones, this slip variability is better inferred if geodetic devices are deployed as close as possible to the source and their spacing is of the same order as the distance to the plate contact.

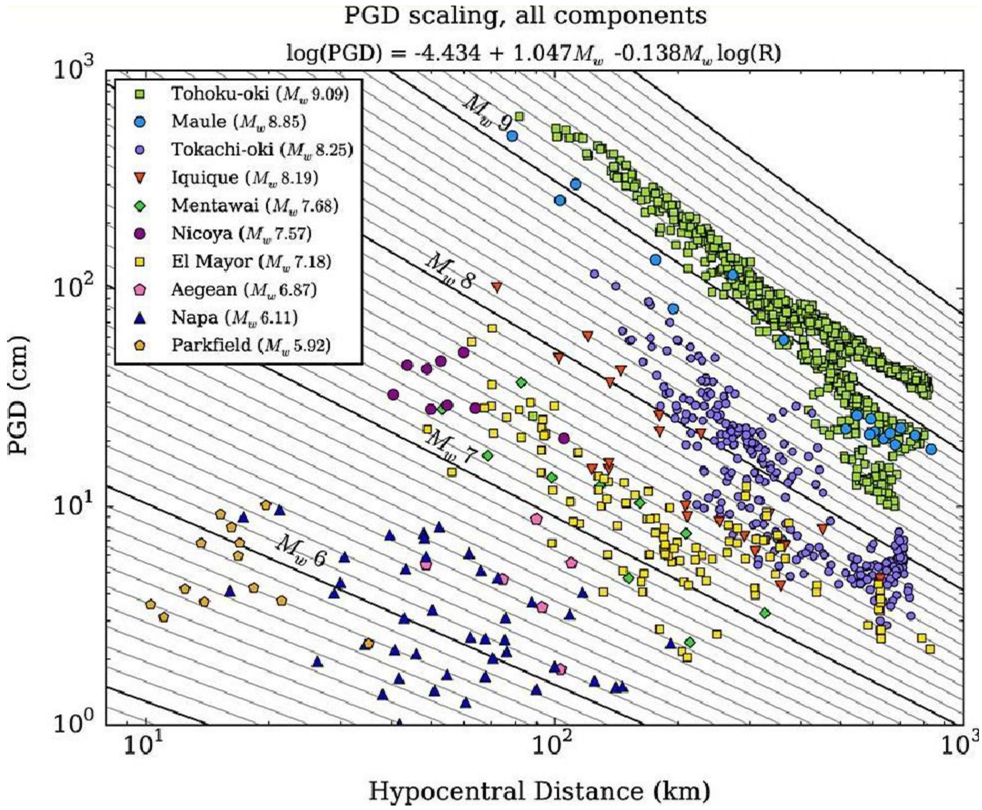

Figure 3 Scaling of peak ground displacement measurements (PGD) (Melgar et al, 2015)

Deploying additional GNSS ground stations in known coverage gaps can improve tsunami forecast and warning effectiveness, if the data are made available in real- time. This presents a challenge as some of the most dangerous tsunamigenic zones (e.g., Aleutian Trench, Kermadec trench) provide limited opportunities to deploy additional land- based instruments. This may require greater consideration of ocean based GNSS instruments and associated communications strategies.

3.3.1.5 Dedicated Observatories

The basic technology to establish an observation network to monitor and detect tsunamis by installing cable seismometers and water pressure gauges on the deep-sea floor is fast developing. Unfortunately, some observation networks, which have low observation quality, such as significant instrumental noise and frequent sensor failures, has been identified after the installation of the gauges. The problem is that it is very difficult for an ocean-bottom observation network to determine the cause of the failure and to repair it after installation. However, it is believed that this can be technically solved in advance by conducting sufficient testing on land or in inland waters and by appropriate design before the observation network is installed in the ocean area.

On the other hand, the increase in observation density needed for the early detection of tsunamis requires significant maintenance and replacement costs. This is a problem common to buoy systems, and GNSS buoys (albeit high economies in scale with regards to warning confirmation and lives saved).

Based on the above, the cable method has certain economic advantages over the buoy method. It is technically feasible as the current technology to augment or replace buoy systems became to be developed by the UNESCO IOC Member States. Realising this sort of integrated, high-density detection and measurement network is one of the great targets of the ODTP.

3.3.1.6 Expansion of Supporting Capabilities

i. **Coastal bathymetry.** The lack of accurate high-resolution coastal bathymetry in many regions inhibits the ability to fully utilize coastal tide gauges into the tsunami warning service as well as to provide precise real-time tsunami impact forecasts based on numerical modelling. This is a clear example of a requirement where if the data were collected, it could be used for many purposes, including detailed local tsunami zoning.

ii. **Sensor siting analysis.** A full comparative analysis of all gauges that contribute to tsunami detection, characterisation, forecasting and warning is required to identify gaps, standardization of the coastal measurements and elaboration of the exact requirements to height, space and time resolution of the sea-level data.

iii. **Global Digital Synthetic Database.** This capability is needed to provide a probabilistic relationship between initial indicators (e.g., earthquake location parameters) likelihood of tsunami generation and possible heights of the generated waves.

iv. **Comparison of modelling codes.** Globally, there are many modelling codes in use by scientists and TSP staff. These vary from pre-calculated databases of potential events (or methods of combining “unit sources” of pre-calculated tsunami source displacement), to “on-the-fly” modelling codes using approximations to improve the computation speed, to modern numerical codes running on very fast computers to provide real-time operative tsunami forecast. Many codes have now been modified for parallel processing and to use fast graphical processors (GPU) that are now available. A gap in our capability is currently any systematic method of comparing the different techniques.

v. **Identification of potential tsunami sources.** Ongoing work is required to identify potential tsunami sources. This is particularly important for “non-seismic sources” such as volcanic eruptions and landslides. This will require collaboration with volcanologists, and techniques such as space and ground-based Interferometric Synthetic Aperture Radar (Hébert et al., 2020). Efforts to identify and quantify parts of subduction systems with the potential to generate large earthquakes or landslides should also continue. New approaches should also be elaborated to identify the atmospheric sources responsible for meteotsunami generation.

vi. **The science to practice challenge.** There is a fundamental problem faced in all branches of science but particularly acute for tsunami monitoring and detection. The issue is how to ensure the exciting and effective advances in the science and technology of tsunami monitoring and detection are implemented by TSPs.

vii. **Training on tsunami warning operations.** Training for the operation of tsunami warning centres and TSPs in each country is essential to guarantee a system capable of issuing appropriate warnings, particularly as new observational strategies and techniques are deployed and implemented. In particular, it is important to maintain international training courses to continuously train experts in areas where tsunami warning systems do not yet exist, LDCs and SIDs.

3.3.2 Implementation of existing capabilities not being applied to tsunami operations

In this section we describe some capabilities that exist but have not been specifically adapted for the purpose of impacting tsunami warning. The general research and development community is encouraged to explore and catalogue other existing capabilities not specifically listed that currently exist that could be shown to impact the ODTP aspirational goals and incorporate the capabilities into tsunami warning operations. This list is not exhaustive, and we encourage the corresponding community to explore other developmental ideas that could be applied to tsunami warning and bring them forward for evaluation.

3.3.2.1 Coastal Radars

Coastal radars measure the distribution of sea surface current velocity in coastal areas. The 2011 tsunami off the Pacific coast of Tohoku was detected through post-tsunami analysis of current velocity distribution observed by HF radars (e.g., Lipa et al., 2011). Because the method can only detect tsunami velocity within tens of kilometres, there is a need to study its feasibility to cover larger areas or comparative advantage to monitor some specific types of tsunamis. There is also a high tendency for high false alarms that must be addressed before this capability is suitable for operational implementation. It appears that at the present time coastal radars cannot replace the existing sea-level and bottom pressure recorders, but they can be important source of additional information that can be effectively used in the tsunami research and warning.

3.3.2.2 Passive/active remote sensing

Altimeter-equipped satellites orbiting at low altitudes measure sea-surface height beneath and are used to monitor global oceanographical phenomena such as ocean currents, wind waves and others. Four satellites over the Indian Ocean clearly recorded the 2004 Sumatra Tsunami and showed promise in representing the propagating tsunami retrospectively (Hayashi, 2008). Tsunami components extracted from these observed sea-surface height data (e.g. Hayashi, 2008) were used for mechanism study of tsunami generation (e.g. Fujii et al., 2021). It remains to be seen whether active altimeter data can be collected, analyzed and made available to the Tsunami Warning Centre in near-real-time to support warning operations. Altimeter-equipped satellites are limited in real-time or near-real-time coverage due to orbital dynamics, non-tsunami sea-level changes, and transmission delays. Altimeter data requires significant processing time, which does not meet operative tsunami warning services. An additional challenge is represented by the fact that in order to achieve real-time tsunami detection from satellites, it is first necessary to discover the physical properties of the actual sea surface that can be observed by passive sensing and be changing with a propagating tsunami.

3.3.2.3 Infrasound

Acoustic and atmospheric gravity waves generated by tsunamis propagate in the atmosphere and ionosphere faster than tsunamis can be used for the tsunami warning purposes. They can be detected as changes in atmospheric pressure by microbarometers (e.g. Le Pichon et al., 2005) and radio wave delay times recorded by GNSS (e.g. Heki et al., 2006), respectively.

To apply infrasound information to tsunami warnings we must first develop the technology to observe atmospheric acoustic or gravity waves induced by the tsunami prior to the arrival of the tsunami itself. Another key problem is to rapidly process and interpret the data in a timely manner for tsunami warning purposes.

3.3.3 Identification of new candidate capabilities

Capabilities that are either unproven or undeveloped, but potentially could impact tsunami warning operations or mitigation have also to be considered. A particular area of interest is tsunami observations using remote sensing techniques. Remote observations of the various phenomena generated and accompanied by tsunamis not only provide opportunities for more multifaceted tsunami analysis, but also have the potential to become candidates for innovative methods of global tsunami monitoring in the next decade or later. The general scientific community is encouraged to explore and catalogue other potentially new capabilities that could be identified, developed and applied to tsunami warning in ways that show progress toward the ODTP aspirational goals. This list is not meant to be exhaustive, and we encourage the R&D community to explore other developmental ideas that could be applied to tsunami warning and bring them forward for evaluation.

3.3.3.1 Ionospheric tomography

Ionospheric tomography applications have the potential to inform tsunami warning operations of a propagating tsunami by detecting anomalies in Total Electron Content. It is unknown get what direct contribution to the ODTP aspirational goals could be achieved, or how this information would be successfully incorporated into operations. It will be necessary to determine the achievable operational capability gains and evaluate methods of incorporation into tsunami warning operations.

3.3.3.2 Fibre Optic Applications

Distributed acoustic sensing (DAS) systems use fibre optic cables to provide distributed strain sensing. In DAS, the optical fibre cable becomes the sensing element and measurements are made, and in part processed, using an attached optoelectronic device. Such a system allows acoustic frequency strain signals to be detected over large distances and in harsh environments. There may be potential applications for seismic and direct tsunami measurement applying this technique using fibre-optic cables.

3.4 Characterisation and Forecasting

Section 3.3 of this plan has focused on either optimising, expanding, or in some cases developing new observational capabilities that can contribute to achieving the ODTP aspirational goals and be applied to tsunami warning. Of equal importance is the ability to use this information in a way that will ultimately deliver improved capability across the tsunami lifecycle. Tsunami prediction methods that are less affected by tsunameter noise are required.

3.4.1 Database Applications and Matching Schema

3.4.1.1 Global Threat Database

Ongoing work is required to identify potential tsunami sources. This is particularly important for "non-seismic sources" such as volcanic eruptions, landslides and atmospheric disturbances. This will require collaboration with volcanologists, meteorologists, and techniques such as space and ground-based Interferometric Synthetic Aperture Radar (Hébert et al., 2020). Efforts to increase reliability of existing global historical tsunami catalogues, and to identify and quantify parts of subduction systems with the potential to generate major earthquakes or landslides, should be activated. This capability is primarily applicable to the "initial indicators" phase of the tsunami warning lifecycle but can also be used to develop pre-planned responses and evaluate emergency plans.

3.4.1.2 Artificial Intelligence applications to relate discrete or combined observations to potential outcomes and probabilistic tsunami forecasting

Work is needed to develop tsunami forecasting methods using Artificial Intelligence (AI) assisted techniques. An example would be a Convolutional Neural Network (CNN) capable of directly forecasting tsunami inundation based solely on up-to-date observation data from tsunami and geodetic observation networks and does not require extensive computational resources. The computational cost of this technique is much lower than that of nonlinear tsunami propagation simulations. Additionally, such an approach does not require a tsunami source estimation process. The basic premise of the proposed method is the efficient transformation of a low-resolution maximum tsunami elevation resulting from a linear simulation into a nonlinear high-resolution inundation map. Therefore, in the real-time application, the time consuming nonlinear high-resolution simulation can be substituted by the simple linear low-resolution model, once the tsunami source is estimated with a rapid method. This approach is thought to be particularly applicable to the "initial indicators" and "characterisation" phases of the tsunami warning lifecycle. Further, probabilistic tsunami forecasting techniques based on tsunami model databases can assist with quantification of uncertainties and transform the information into warnings based on predefined thresholds.

3.4.2 Dynamic Characterisation

3.4.2.1 Rapid Update Cycle Model

Despite real-time tsunami observations becoming available, uncertainty in the source mechanism particulars and the wavefield itself remains high. A rapidly updating assimilation and simulation capability is needed to provide "most probable" estimation of the propagating tsunami that can be used to initialize forward models and estimate anticipated coastal impacts. This is seen as a "bridge" capability between the CNN approach and full dynamic characterisation of the wavefield. Such a model would feature sophisticated all-source data assimilation schemes and provide a steadily improving (i.e., reduced uncertainty) dynamic characterisation of the tsunami wave in the near-real-time. The corresponding information would become available to operation tsunami warning systems in order to inform alerting decisions. This enables rapidly update tsunami wavefield propagation characteristics independent of the tsunami source operational tsunami warning centres to issue dynamically based forecasts and alerts for all detected tsunamis regardless of source.

3.5 Implementation

The ODTP is designed to be implemented by contributing Member States, academic institutions, industry and philanthropic organisations. The purpose of the implementation plan is to describe the range of opportunities to advance the global tsunami warning system according to metrics identified in Tables 1 and 2 and according to the various lifecycle stages of the tsunami warning process, as well as contributions that support Member State capacity to establish robust readiness protocols.

3.5.1 Instrument Identification and Density

The first step in the implementation plan is to define an optimal tsunami global network aimed at meeting the aspirational goals outlined in Table 1. This will consist of a mix of observation platforms including seismic instruments, tide gauges, tsunameters, GNSS, SMART, research cable observatories, etc. that will ensure reliable detection and measurement of all significant tsunamis within an actionable timeframe after the generation. Considering the nature of tsunami hazard, the optimal network should have a global design, to address regional imperatives, implemented through contributions from Member States and all other stakeholders. The network design document would provide a framework for identifying gaps, prioritize resources, and deploying and maintaining the global tsunami detection and monitoring network through contributions by all relevant stakeholders. Tide gauges should meet the modern technology level, have at least 1 mm height resolution and 1-minute time sampling (resolution). The data should be intercomparable and available for Member States and tsunami specialists/researchers. Key attributes of the design document as described in Table 1 would include:

- Emphasis on sufficient instrument density to support early positive tsunami detection in the most at-risk near-source coastlines
- Emphasis on sufficient instrumentation density and technique development to provide accurate impact forecasts in the regional field
- Emphasis on fielding sufficient instrumentation density, techniques, and derived quantities to ensure detection of all tsunamis independent of source.

3.5.1.1 Identify range of opportunities for Member States to invest in system procurement/deployment

Member States should endeavour to dovetail their national observational plans/programmes with the optimal notional global network. Specific contributions might entail sustaining stations, real-time sharing of data from existing and new stations, sharing of ship-time / other resources for installation / maintenance of stations and enhancing advocacy amongst scientific community and policy makers to strengthen tsunami observations and data exchange. Expert groups and industry partners working on tsunameters, tide gauges, seismic instruments, GNSS stations, SMART cables and other observing platforms can assist with defining the sensor specifications, telemetry, data formats, etc. to meet the future requirements of tsunami and multi-hazard early warnings as well as other ocean and climate applications.

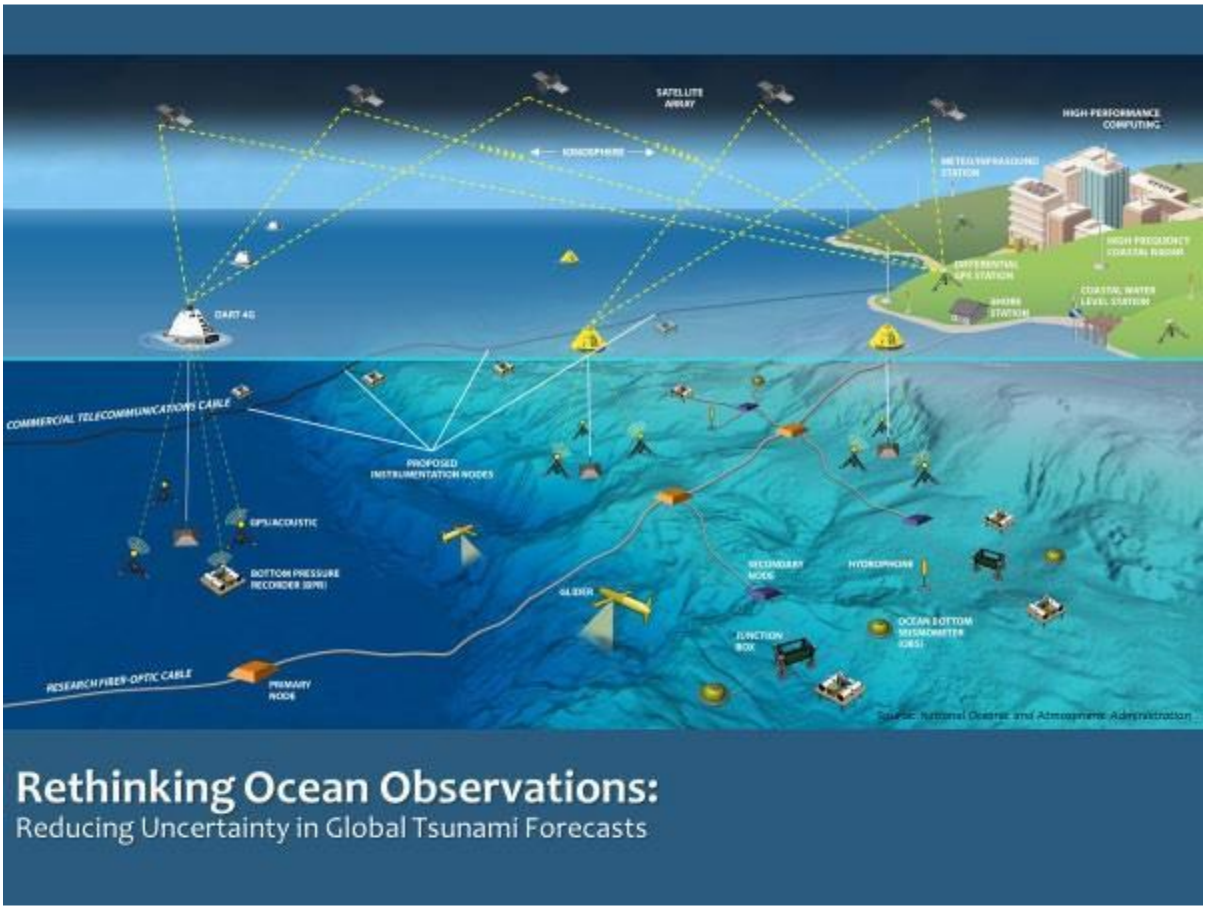

Figure 4. The Vision of the Ocean Decade Tsunami Programme is to move beyond the seismic proxy relationship and detect and measure the tsunami source or resultant wavefield *directly* in order for reliable forecasts to be produced. Many sensors will need to contribute (GNSS ground stations, in-situ seismographs, hydrophones, tsunameters, gliders, coastal radars and coastal sea level stations) and many are low-cost or no-cost. It is a goal of the ODTP to provide opportunities for all at-risk Member States to make meaningful contributions to this global detection and monitoring grid.

3.5.1.2 Identify range of opportunities for R&D community

Research and Development (R&D) community and Industry has the opportunity to develop technological solutions for production of Commercially-Off-The-Shelf (COTS) repeaters, sensors and allied components to be deployed on SMART cables that meet the purpose of tsunami warning and other ocean applications. It is important to develop analysis methodologies for incorporating data from existing GNSS, Strong Motion Accelerometer, Coastal Radar networks for operational tsunami warning. This would also include research on the tsunami nature, source mechanisms, source inversion and characterisation from heterogeneous observational data, uncertainty reduction, probabilistic tsunami forecasting techniques and development of new forecast methods for tsunamis from all potential sources. Multi-disciplinary research on the use of high-performance computing systems and deep learning techniques is another important area where the scientific community can contribute to enhance tsunami early warning systems. Development of more efficient communication systems to reduce data latency from observing systems and for dissemination of warning to end users could benefit the overall timelines and effectiveness of tsunami warning. The scientific community could also explore novel capabilities to close existing gaps such as development of potential future observing technologies and testing of new instruments for ionospheric tomography, earthquake / tsunami precursors, traditional knowledge for tsunami warnings, construction of global database of potential sources, develop procedures for AI assisted forecasting techniques, rapid update forecast models, etc.

The science and implementation plans for achieving the ODTP Detection, Analysis and Forecasting aspirational goals are provided in Appendix 2.

Table 2 Scientific objectives and tsunami warning quantitative enhancements associated with (i) maximizing and expanding current capabilities and instrumentation, (ii) identifying capabilities that exist but are not currently applied to tsunami, and (iii) identifying new capabilities that require development.

	Scientific Objectives	Tsunami Warning Quantitative Enhancements
MAXIMISE Current Capability		
Seismic	1. Ensure all available seismic data is shared in real-time. 2. Establish coverage gaps and determine if they can be addressed within current resources. 3. Fully utilize the available data to characterise potential tsunamigenic earthquakes faster, including bringing all available techniques into operational use. 4. Identify additional ways in which the current distribution of seismographs and other seismic instruments can be more fully used to support tsunami warning	1. Increase data availability and sharing to support initial ts indicators within 3 minutes of origin. 2. Apply advanced seismic techniques to reduce source uncertainty to less than 50% (ie "partially constrained" i 1) within 10 minutes of origin.
Tsunameter	1. Improve tsunameter data use to decrease time necessary to determine tsunami impact (seismic sources) 2. With potential deployment of other capabilities, such as sensors on undersea communication cables, look to repositioning of existing tsunameters in other priority areas not covered by the new systems or present tsunameter networks. 3. Develop direct assimilation schemes independent of source correlation (non-seismic sources). 4. Support and encourage Member States who are operating tsunameter networks to maintain the currently deployed systems and share all data. 5. Identify additional ways in which the current distribution of tsunameters be more fully used to support tsunami warning.	1. Decrease time between event origin and full tsunami tsu source characterisation to less than 45 minutes (Table 1 2. Decrease time between event origin and partial tsunam characterisation to less than 10 minutes (Table 1)
Coastal Sea Level Gauges	1. Ensure all coastal sea level gauges are available in real-time to NTWCs with data at required temporal and height resolutions 2. Ensure all coastal sea level gauges have automatic tsunami phase detection capabilities to alert NTWCs of potential tsunami waves 3. Ensure all coastal sea level gauges are equipped with real-time data transmitters to make the data also available for multi-hazard warning (tsunami and storm surge)	1. Show decrease in time between event origin and aspira goals in Table 1.

	4. Ensure that coastal tide gauges in tsunami prone regions have spatial resolution of ~100 km 5. Use shallow water models in ocean forecasts to be able to assimilate shallow water observations into tsunami forecasts 6. Identify additional ways in which the current distribution of coastal water-level instruments can be more fully used to support tsunami warning.	
GNSS	1. Ensure all land and ocean-based GNSS station data is shared in near-real-time 2. Ensure operational tsunami warning systems are configured to accept and process GNSS-derived deformation data 3. Ensure operational tsunami warning systems are equipped to analyze GNSS data-streams in order to support tsunami source characterisation and forecasts. 4. Identify additional ways in which the current distribution of GNSS instruments can be more fully used to support tsunami warning.	1. Increase data availability and sharing to support initial ts indicators within 3 minutes of origin. 2. Apply advanced seismic techniques to reduce source uncertainty to less than 50% (ie "partially constrained" i 1) within 10 minutes of origin.
EXPAND Current Capability		
Seismic	1. Describe optimal placement of additional instruments to support tsunami detection 2. Establish coverage gaps and develop a plan for addressing gaps. 3. Concentrate on regions with currently known issues with network coverage to address local and near-regional source tsunami detection and characterisation times.	1. Deploy additional instruments in locations that contribu deceased time between event origin and initial tsunami indicators. 2. Show decrease in time between event origin and aspirat goals in Table 1
Tsunameters	1. Describe optimal placement of additional or redistributed instruments to support tsunami detection. This requires a detailed study of current and planned future networks including all varieties of bottom pressure recorders (DART, SMART Cables, Cable observatories). 2. Ensure deep-ocean instruments are designed to be compatible with industry standards to enable SMART deployment. 3. Ensure adequate tsunameter coverage of the most productive subduction zones to meet detection times and thresholds. 4. Consider some deployments to give source agnostic coverage to meet defined detection times and thresholds. 5. Promote new use cases for the use of tsunameter data by the wider scientific community and explore opportunities for possible integration and co-deployment with ocean observing networks including met-ocean moorings	1. Show decrease in time between event origin and aspirat goals in Table 1

	6. Take a global approach on where Member States can provide most value to GTWS by investing in/deploying new tsunameters. 7. Encourage a federation approach to tsunameter deployment and maintenance to improve the cost effectiveness of networks.	
Coastal Sea Level Gauges	1. Describe optimal placement of additional instruments to support tsunami detection 2. Ensure all new coastal sea level gauges are equipped with real-time data transmitters to make the data also available for multi-hazard warning (tsunami and storm surge)	1. Show decrease in time between event origin and aspirat goals in Table 1
GNSS	1. Identify the most valuable locations to install additional land-based GNSS stations 2. Identify the most valuable location to deploy ocean-based GNSS stations including buoys and other direct measurement systems. 3. Ensure deployment of additional instruments addresses need for real-time communications to support tsunami warning operations.	1. Show decrease in time between event origin and aspirat goals in Table 1
Dedicated Observatories	1. Determine most valuable location for the installation of additional cable-based sensor networks to support tsunami detection both locally and basin-wide. 2. Support procurement or deployment of cabled observatories in locations best served by this technology. 3. Identify best practices and cost-control measures to enable more Member States to consider deployment of dedicated cabled observatories.	1. Show decrease in time between event origin and aspirat goals in Table 1 at multiple scales
Expansion of supporting capabilities		
Coastal bathymetry	1. Determine areas where bathymetry is of insufficient resolution to support tsunami warning operations 2. Support additional collection operations to fill known gaps	
Sensor siting analysis	1. Through quantitative analysis determine optimal instrumentation mix in major ocean basins to support tsunami warning operations. 2. Provide specific instrumentation recommendations for Member States and networks	
Global digital synthetic database	1. Using AI and "big data" methodology, develop global database to describe tsunami potential for all possible locations	

Comparison of modelling codes	1. Use dynamic weighting or ensembling techniques (similar to Numerical Weather Prediction) to provide probabilistic forecast output to tsunami warning operations.	
Identification of potential tsunami sources	1. Comprehensive catalogue of all known or suspected tsunami sources. 2. Determine and catalogue range of possible tsunami impacts from each known or suspected source	
The science to practice challenge	1. Encourage early involvement of TSP and NTWC in the development of new science ideas and practice. 2. Develop a framework to allow the effective introduction of new science into operational practice.	
Database applications and matching schema		
Global threat database	1. Establish a global Threat Database that provides the Tsunami Warning System with worst case and most probable impacts based on available real-time location information of potential sources. 2. Establish coverage gaps and determine if they can be addressed within current resources. 3. Fully utilize the available data to characterise potential tsunamigenic earthquakes faster, including bringing all available techniques into operational use.	1. Increase data availability and sharing to support initial tsunami indicators within 3 minutes of origin. 2. Apply advanced seismic techniques to reduce source uncertainty to less than 50% (ie “partially constrained” in Table 1) within 10 minutes of origin.
AI applications	1. Establish the relational databases and simulations required to support the CNN forecasting approach 2. Use Probabilistic tsunami forecasting techniques to quantify uncertainties and incorporate the information into decision making tools.	1. Application of AI assisted techniques and probabilistic tsunami forecasting methods can generate tsunami warnings and impact forecasts in a more timely and computationally efficient way.
Dynamic characterisation		
Rapid update cycle model	1. Develop assimilation schemes aimed at the statistical or dynamical incorporation of all relevant real-time tsunami observations into tsunami source or wavefield calculations. 2. Develop dynamic modeling schemes that can appropriately weight the various assimilated data streams in order to create “best fit” for the actual tsunami wave field at any given point in space and time. 3. Include system attributes that would identify when a particular tsunami was sufficiently constrained by observational data to allow tsunami warning centres to issue detailed, prescriptive impact forecasts.	1. More efficient dynamic tsunami modelling codes/techniques and all-data assimilation schemes together with high performance computing systems will make real-time tsunami inundation modelling and impact-based forecasting possible, paving the way for timely, effective and localised public response.

	4. Develop an easily deployable architectural and computation framework to allow deployment of rapid update cycle models across the spectrum of tsunami warning operational centres.	

4 Warning, Dissemination and Communication

4.1 Introduction

Once a tsunami has been detected, analysed, characterised and forecasted, the corresponding information must be converted into a warning, and communicated. The responsibility for warning lies within the sovereign responsibilities of countries.

Warning systems must be encouraged to be 'people-centred'. Some key characteristics of people-centred warning systems include a focus on stakeholder engagement and responsibility sharing, accessible communication supported by technological innovations, and institutional capacity building, including strong inter-agency collaboration. This means that a good understanding of all the stakeholders' requirements is essential for the design of efficient warning systems.

National warning services have also to be strongly encouraged to actively communicate and cooperate with each other and with the tsunami service providers as well as international centres.

With a view on people centred warning systems, the following key issues need to be addressed in the ODTP:

1. Effective decision making to warn
2. Effective construction of warnings
3. Effective dissemination and communication of warnings

4.2 Decision to Warn

National and local tsunami warning chains and procedures: Decisions and their downstream management require the collaboration of stakeholders from different sectors and levels along a warning chain. Mechanisms need to be established that facilitate the exchange between these stakeholders and the agreement of well-coordinated procedures to overcome the still existing divide between upstream and downstream actors and processes. In particular, the cooperation between warning providers and disaster risk management institutions could be significantly improved. A basic requirement for this is building a shared understanding of the system among all stakeholders, including the population at risk.

Decision support tools: Weighing up the costs and benefits of a decision, while also taking into account the level of uncertainty associated with the forecast, is often a difficult challenge. Parameters for risk thresholds are therefore needed by the National and Local Disaster Management Offices (DMO) to inform decisions and response. The parameters must be agreed at the national and local levels.

The Tsunami Watch Operation Global Service Document (Intergovernmental Oceanographic Commission, 2016) must be reviewed with a view to support the co-design of warning information and SOP requirements among the TSPs, NTWCs, National/Local DMO, and other relevant stakeholders – to be applied in all ICGs. The Tsunami Watch Operation Global Service

Document must support the development of a decision matrix for warnings in all countries at risk of tsunami.

Capacity building: Alongside investment in technical solutions for monitoring and dissemination, the focus should also be on people. The job of the NTWC is to interpret hazard information with a view on a decision to issue warnings, while the job of emergency management is to be aware of the potential impacts with a view on appropriate response to a warning. NTWC staff may be highly knowledgeable about relevant hazards and familiar with technical language, though perhaps less familiar with specific forecasting methods. Emergency managers will likely be experts of their profession but may be less familiar with the interpretation of warning content and the nature of tsunamis.

4.3 Construction of Warnings

Warnings are produced for use by a variety of recipients in different situations. Challenges with the construction of warnings include time constraints, being inclusive (fit for all audiences), and being actionable.

Time constraints: Warning for tsunamis is often more challenging than other hazards as lead times may be very short. Even for distant source tsunamis that can arrive in over three hours, emergency managers still consider this a short amount of time to respond effectively (i.e., successfully evacuate at-risk communities). A focus should therefore be on solutions to speed up the warning construction process. The next review of the Tsunami Watch Operation Global Service Document should consider options for the seamless integration of monitoring and warning tools and applying new and emerging technologies

Inclusive: Cultural diversity and marginalisation affect all elements of any early warning system. People may be marginalised on the basis of age, gender, disability, race, ethnicity, religion, migration status, socio-economic status, place of residence, etc. Some of these groups require focused attention, proactive engagement and sensitive or transformative approaches to ensure no one is left behind. The key consideration should be equity of outcome rather than equality of treatment.

With a view on inclusiveness, countries must analyse audiences (culture, education, capacity, abilities, etc.) and specify in the national and local tsunami response plans how inclusiveness will be achieved. In particular, there appears to be a general lack of standards for the format and mechanisms for warning (and communicating with) people with different functional abilities.

Actionable content: Dominance of warning content by science information at the expense of user-focused communication is common. Warning content must include the expected or potential impacts and consequences to support appropriate decision making and action. The more that the warning includes information about the hazard impact, the more actionable it is and the more effective the warnings become.

4.4 Warning Dissemination and Communication

Regardless of accurate and timely decisions to warn, and warning content complying with the requirements above, warnings will only achieve their objective if they reach their audiences timely and widely. The challenges in this regard to be focused on include institutional capacity, the integration of and use of appropriate dissemination and communication mechanisms; and managing the multiple sources of information available to communities.

Institutional capacity: 24/7 warning dissemination and communication must be embedded in a systematic architecture of stakeholder institutions to be able to quickly and reliably relay tsunami warnings from the NTWCs to interface agencies and the communities at risk. The challenges here are primarily of an institutional nature and may involve institutions from international to national, regional, and local levels.

The most common capacity need exists among local institutions, that often do not have the necessary resources to receive and disseminate warnings to communities and deciding on and managing evacuations on the ground. Supporting countries to review and further develop their national warning chains to reinforce effective understanding and efficient reactions at local level is a low hanging fruit to uplift tsunami warning effectiveness.

Communication mechanisms: Challenges are often experienced with robust mechanisms to receive and disseminate warnings, and communication in general. Countries at risk of tsunami must provide for at least three mechanisms for NTWCs to receive threat assessments from TSPs, as well as for NTWCs to disseminate warnings. These mechanisms must be integrated across hazards where possible and tested regularly.

Regarding the communication of warnings to agencies and communities, existing channels and technologies should be used as much as possible and integrated into a multi hazard early warning framework to create, where possible, a common portal for the community to access warnings and be informed of the hazard and actions to be taken. In any case, technology solutions must be adapted to local conditions, and they must also be tested regularly. As noted by Rahayu et al (2020), regulation is required that considers extension nodes to relay warnings to the populations at risk, often referred to as "the last mile", where both formal and informal warning channels are important. Standard methods for people with different functional abilities need to be addressed. To leave no one behind, a transectoral approach must be taken for the local warning chain.

Multi-hazard warning systems: Most countries maintain warning systems for single hazards and these systems are rarely integrated. To support redundancy, consistency, and accessibility, the focus must be on multi-hazard early warning alignment by linking hazard- specific systems together. This applies to resources, capacity, information, SOPs, etc. Further, to support standardization in communication across all hazards, NTWCs should apply machine readable XML formats such as the international Common Alerting Protocol (CAP), as a tool for minimizing the overheads of using multiple channels. Provision must be made for capacity building of NTWC staff to apply and use the machine-readable XML formats. Therefore, tis important that these formats have an internationally supported standard, training, support and implementation guidelines.

Multiple sources of information: Broadcasting media and social media play an important role in the warning chain and warning dissemination. Broadcasting media not only provide important warning channels (radio, TV, online) for warning dissemination but is also considered an important actor and link in the warning chain. Well-established partnerships with traditional broadcast media therefore play an important part. Communities are however exposed to, or have access to, numerous sources of information that can influence decisions. Some of these sources often present conflicting, misleading, or misinterpreted information that can undermine both decisions and responses with potentially fatal consequences. This problem can be countered by guidelines and procedures on the use of social and broadcast media by NTWCs and emergency management, supported by training in this regard.

The ODTP goal is that by 2030 there will be significant improvements in the national decision making to warn, and mechanisms in place for the effective and inclusive construction, dissemination and communication of warnings. Most importantly, 100% of the national authorities will be able to effectively warn the communities and population at risk. The communities at risk will be able to use these advances to improve local tsunami preparedness and response capabilities and become Tsunami Ready (for details about Tsunami Ready see chapter 5).

The science and implementation plans for achieving the ODTP Warning, Dissemination and Communication aspirational goals are provided in Appendix 3.

5 Preparedness and Response Capabilities

5.1 Introduction

Communities must be prepared and ready to respond for appropriate life-saving actions when a potential tsunami arises. A community may become aware of a tsunami threat through an official warning chain or natural warning signs.

The preparedness and response capabilities of a community will depend on the following main factors:

1. Risk perception and awareness
2. Community wide preparedness actions
3. Effective Response Planning and Capabilities
4. Implementation of Mitigation Measures

All these elements need to be approached through active engagement of stakeholders at the national and local level. At the local level it is critical to be inclusive of governmental, non-governmental, community leaders, scientists, businesses, education and cultural sectors, traditional/indigenous people and to consider the needs of women, youth, elders and people with different functional ability. It is important in the co-design and co-delivery of awareness, preparedness, response and mitigation actions that no one be left behind. If people are left behind in the design stage, they will most likely be left behind when the tsunami strikes.

The aspirational social outcome of the Ocean Decade Tsunami Programme is that 100% of communities at risk from tsunamis are prepared for and resilient to tsunamis by 2030 through efforts like the IOC-UNESCO Tsunami Ready Recognition Programme.

5.2 Risk Perception and Awareness

Risk perception will be an important driver for mobilizing people and resources for awareness and preparedness actions. The varied level of preparedness and responses are very much shaped by the diverse risk perceptions with different embedded factors. These factors include among others memory of past events, experiences, risk knowledge and information, media exposures, culture beliefs, socio-psychological factors and many more (Rafliana, 2022).

Historically, tsunamis in Japan and other regions in the Pacific, destructive 1946 Aleutian and 1960 Chile tsunamis, marked the early era of national and basin-wide tsunami warning system development. Decades later, catastrophic 2004 the Indian Ocean Sumatra Tsunami in 2004 raised awareness and triggered the development and strengthening of warning systems in the Indian Ocean, Caribbean and North Europe and Mediterranean regions. Highly devastating events such as 2004 the Indian Ocean Tsunami and the 2011 Tohoku tsunami and the more recent 2018 Palu and Anak Krakatau events and the Hunga Tonga-Hunga Ha'apai volcanic eruption and tsunami in 2022 have resulted in greater global attention and awareness on tsunamis and their sources/generation mechanisms. These events also provided lessons on the importance of awareness and response capabilities and how they become the core prerequisites for an effective warning system. The awareness of risk and self-evacuation capacities are particularly important where tsunami waves might arrive within minutes, and in SIDs and LDCs where warning capacity and infrastructure are limited.

Shaped by new knowledge and experiences and also interventions, awareness and response will change over time. Responses towards tsunamis, being shaped by different perceived risks, are often difficult to predict, for example in rural as compared to urban areas, mainlands and small islands, areas with high frequency of events compared with areas of infrequent events. As society continuously changes, long-term strategies in tsunami awareness and response should also adapt and evolve.

Data, research and publications on tsunami risk perception are very limited. Given their importance, **risk perception studies need to be encouraged across all regions and targeted for the ODTP.**

5.3 Preparedness

Tsunamis are rapid onset events with impacts reaching communities within minutes and hours after an onset. A multi-level whole community approach which is responsive to the local needs of the community at risk is needed, including all socio-economic groups, language diversity, migrants and tourists, as well as special groups and in particular elders and children which are most affected by tsunami events according to statistics (Gonzalez-Riancho et al, 2015). Comprehensive understanding of the importance of preparedness requires multi-transdisciplinary endeavours that engage all possible stakeholders, and all possible innovations in overcoming challenges towards effective tsunami risk reduction efforts.

Some of the key challenges for communities to get prepared for a tsunami and are addressed in the Tsunami Ready Recognition Programme include:

1. Availability of easily understood tsunami evacuation maps
2. Public display of tsunami information for risk areas
3. Inclusive educational and awareness resources
4. Effective outreach in tsunami at risk areas
5. Regular Tsunami Exercises

5.3.1 Evacuation Mapping

Every community at risk needs an easily understood tsunami evacuation map to plan for and to guide evacuations during tsunami events; people need to know where to go when a tsunami strikes. Tsunami evacuation maps should depict tsunami evacuation routes and assembly areas and be based on tsunami hazard zone mapping (see Chapter 2) in accordance with the community's tsunami response plans. Maps also need to be made available via appropriate print and/or digital media. IOC-UNESCO has several Manuals and Guides that support planning including Tsunami Evacuation Mapping, Planning and Procedures, (TEMPP, IOC, 2020b). Member States with communities at risk from tsunamis have indicated that there are many communities that still do not have evacuation maps. In order to increase the availability of local evacuation maps, training, tsunami hazard assessment, enhancement of GIS capacity within countries, evaluation on effectiveness of evacuation maps and implementation of community participatory approaches is necessary.

A goal of the ODTP is that by 2030 all at-risk communities have tsunami evacuation maps.

5.3.2 Public Display of Tsunami Information

Tsunami information including signage must be publicly displayed. The public displays may provide information on tsunami risks, as well as public education on how to respond to the tsunami event. Painting murals by local artists can create awareness and integrate stakeholders that otherwise might not be engaged. National standards for tsunami signage should be established; existing signage used can be inventoried and shared in this regard (this is already done by the CARIBE-EWS).

A goal of the ODTP is that by 2030 all at-risk communities have some type of public display of tsunami information.

5.3.3 Education and Awareness Resources

Outreach and public awareness and education resources need to be made available and distributed within all at risk communities. These materials can include tsunami evacuation maps, and routes, safety tips and information about when and how to respond to warnings. It is important that they be tailored to meet local information needs and be based on location-specific tsunami threats and also be inclusive for people with disabilities. Currently the IOC and the Tsunami Information Centres have available many educational resources; these can be more widely distributed, but also adapted to the local context (language, culture, local threat, risk, etc) and be inclusive (disabled, migrants, etc.) in addition to the development of new materials at the national and local level. Authoritative social media outlets and websites can also help increase public awareness and education. There are many resources that have been designed and distributed by the IOC-UNESCO Tsunami Information Center (Honolulu, Hawaii) these materials can be used and adapted to meet the needs of the local communities.

A goal of the ODTP is that by 2030 all at-risk communities have locally relevant education and awareness resources.

5.3.4 Outreach

Public outreach and educational activities should be conducted annually in the community. The aim is to educate community residents, businesses, and visitors, with an emphasis on those in the tsunami hazard zone, on tsunami hazards, evacuation routes, how warning information will be received (including natural warnings for regions with a local tsunami threat), safety, and response. These activities may be multi-hazard as long as they include tsunamis in the content. People with different functional abilities need to be included in preparedness and response actions, tsunami information should be integrated in school curricula, as well as general tsunami education and awareness. best practices and lessons learned should be shared with other global frameworks on School Disaster Risk Reduction, e.g., with the Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector (GADRRRES).

Another important strategy for enhancing awareness will be to **promote communities to actively participate in the World Tsunami Awareness Day (5 November)**.

5.3.5 Tsunami Exercises

In most communities around the world, even in those where the impact of tsunamis can be catastrophic or very significant, tsunami events are infrequent. Through regularly conducted exercises, awareness can be increased, and response capability can be enhanced and validated. The exercises can have different formats and focus solely on the tsunami hazard, or they can be multi-hazard exercises that also addresses the tsunami hazard combined with coastal floods caused by storm surges, fire, tropical or sub-tropical cyclones and volcano explosions. The exercises should include a communications test between the components of the Tsunami Warning System. Each of the ICG's must conduct regular tsunami exercises: CARIBE WAVE, IOWAVE, NEAMWAVE and PACWAVE. These exercises in the past helped validate Standard Operating Procedures for tsunami warning and emergency response, as well as promote tsunami awareness in the communities (Soto et al., 2022; Chacón-Barrantes et al., 2021; Kong et al., 2021), and offer on-going opportunities for Member States.

According to the Tsunami Ready guidelines, tsunami exercises should be conducted at least every two years in at-risk communities. Additional guidance is available from the Multi-Annual Community Tsunami Exercise Programme Guidelines for the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (IOC, 2021b). This manual provides guidance on how to plan, conduct, and evaluate a multiannual local tsunami exercise programme. These resources need to be widely distributed in support of the IOC-UNESCO regional exercises (CARIBE WAVE, IOWAVE, NEAMWAVE and PACWAVE), as well as nationally and locally organised events. All the WAVE exercises, and also smaller-scale exercises, need to be reflected and documented for education purposes and use.

In addition to regular exercising, effectiveness of awareness and response can be tested during real events. In the aftermath of tsunami events, affected countries need to collaborate in post-event surveys, like the UNESCO-ITST (International Tsunami Survey Team). Assessing real events should also address and document the response of NTWCs, local government and community responses at local level to a particular tsunami event or phenomena. These lessons should be integrated in disaster risk education at school curriculums and within development planning from village and community level, engaging all related key stakeholders.

A goal of the ODTP is that by 2030, 100% of communities at risk conduct a local tsunami exercise every two years. In addition, the timeline for warning and response should be tested and reported for events and exercises.

5.4 Response Capability

Communities need to be ready to respond 24 x 7 to tsunami events. Some of the main areas that have been identified for action and are indicators of the Tsunami Ready Recognition Programme are:

1. Comprehensive and tailored tsunami response plans
2. Capacity in place to manage tsunami events

5.4.1 Tsunami Response Plans

Communities must have a plan in place that addresses responding to a tsunami incident. While many countries have national response plans, the number of at-risk communities with local tsunami response plans is much lower. It is important that these plans be tailored to the potential tsunami scenarios and community assets and needs. TEMPP training (IOC, 2020b) and other multihazard planning and training resources can be used to advance capacity in this area.

For communities with local tsunami hazards, there will probably not be enough time for official alerts to be issued before tsunami arrival time. Preventive evacuation arrangements and response based on natural warning signs in the absence of warnings from NTWCs can save lives. Individuals, including emergency officers, will need to take personal responsibility to evacuate immediately after recognizing the natural tsunami warnings or environmental clues of a possible or imminent tsunami (e.g., strong or long ground shaking from an earthquake, unusual rapid rise or fall of the ocean, roaring sound). In a local tsunami scenario, official communications and warnings may also be difficult or limited due to damage of telecommunication infrastructure caused by the earthquake, and due to the short time between tsunami generation and arrival of the first wave. In addition to actions for rapid onset tsunamis from tectonic events, specific measures must be considered for non-tectonic events associated with earthquake generated landslides, abrupt atmospheric disturbances and volcanic eruptions like the recent the Hunga Tonga - Hunga Ha'apai volcanic event (Borrero et al, 2022). Plans need to be completed for all these types of events, including those for which there are limited official warning protocols. During the Decade, global and regional guidelines should be developed for all at-risk communities. The local tsunami risk should be evaluated and the integrated procedures and tsunami response plans have to be elaborated.

A goal of the ODTP is that by 2030 all countries with tsunami risk should have agreed parameters at the national and local level for warning and have approved response plans. Inclusiveness should be addressed in these plans.

5.4.2 Tsunami Emergency Management Capability

Communities should have the means to ensure that community officials can execute tsunami warning functions (public notifications) and response functions (evacuation) in a timely manner. Many at-risk communities need to enhance this type of capacity. Being aware of local resources and capacities that are available, be these tangible or intangible, is a good start. Data on the existing economic, infrastructural (e.g., Emergency Operations Centre), political, and social resources can form the baseline from which to expand. This inventory can be used for response planning and as a reference in case of a tsunami incident. If official data are not available, it is recommended to share, compare and discuss this information among the community stakeholders. Another strategy is to optimise and integrate resources available for other hazards. The plan is that over the Decade all at-risk communities are empowered and have the required capacity to provide public notifications, guide evacuations and other response measures during a tsunami event.

According to Sakalasuriya et al. (2022), it is important to consider formal and informal sources, like religious and disaster preparedness officials, to mobilize evacuation more effectively during an emergency. Care also must be taken that different dissemination methods do not alter the information content of the alerts.

A goal of the ODTP is that 100% of at-risk communities have multiple effective and sustainable communication methods in place.

5.5 Mitigation

While planning of timely and effective response can go a long way to save lives and some property, mitigation measures are required to ensure life safety, livelihoods and continuation of critical services. Mitigation measures like the design and construction of blue, green and grey infrastructure, standards for vertical evacuation facilities, and appropriate urban planning are especially needed in areas where there is no sufficiently high ground or the distance from the shore is too great to get people out from the at-risk coastal area or to locate sensitive and critical infrastructure. Around the world there is a lack of available safe areas or special safety constructions for at-tsunami-risk communities. in tsunami at-risk communities considering the short lead time of tsunami arrival. The lack of coastal protection infrastructures and marine assets are also a serious problem for in many communities. To address the gap, specific efforts should be taken to consult with engineers, scientists, and researchers and community stakeholders to share best practices of structural and nature-based interventions and mitigation plans.

Institutionalizing tsunami awareness and response fostering and facilitating mitigation measures are critical. It is important not only to meet the Decade goal of 100% of communities prepared for and resilient to tsunamis, but also to be able to sustain the capabilities through time. One of the challenges of tsunamis are their relative infrequency in most places in the world. Despite their potential catastrophic impact, they often become the forgotten hazard. Successful enhancement of preparedness and response capabilities will require efforts in terms of funding, time and successful multi-stakeholder partnerships (Thomalla et al., 2009), and good governance (see Chapter 10). The integration of resources, services and systems from other coastal hazards will also be the key for effectiveness and sustainability.

Spatial and Land Use Plan, Development Plan, and Coastal and Small Islands Zoning Plan are three important tools in urban planning for coastal cities. Spatial planning itself is a system of planning processes for space utilisation and spatial use control. The long-term and medium-term development plan is a tool in actualising the spatial plan into actions. However, for the built environment at coastal and small island areas, the existence of Coastal and Small Islands Zoning Plan is very critical to regulate the spatial and land use of both land and water areas. However, currently the issues of tsunami risk and its reduction have not been considered and properly mainstreamed in urban planning which can be achieved through strong legal and institutional frameworks.

A goal of the ODTP is that by 2030 communities have access to an inventory of best practices of plans and structural and nature-based solutions and that more communities have implemented plans and measures to minimize impacts to critical infrastructure and marine assets from tsunamis and other coastal hazards, and importantly mainstreaming disaster risk reduction into urban planning.

The science and implementation plans for achieving the ODTP Preparedness and Response aspirational goals are provided in Appendix 4.

6 Capacity Development

Within the context of the ODTP and this Research, Development and Implementation Plan, capacity development is the process by which individuals, organisations, institutions and communities develop abilities to perform functions, solve problems and set and achieve its objectives within its four components. Alongside the development of technical solutions, individual and institutional capacity is required. **A goal of the ODTP is therefore to ensure investment in capacity development for the different stakeholders including the generators and the users of the tsunami early warning system.** Capacity currently varies across regions, countries and communities, as well as across genders and generations. While capacity enhancement is required at the national and regional (multi-national) levels, focus on the local level will be especially important to reach the objective of 100% at-risk communities to be prepared and resilient to tsunamis by 2030. The aim is to have equitable access to data, information, knowledge, technology, and infrastructure, leaving no-one behind.

The ICG Tsunami Information Centres have been conducting training to enhance capacity of Member States. Additional tsunami training will need to be developed, delivered and scaled up to strengthen capacity, not only to develop knowledge and skills of existing stakeholders, but also the anticipated many new stakeholders that will be required to meet the ambitious objectives of the ODTP. Trainings should consider the recipients' abilities, priorities, and culture. It will also be more effective when delivered within an integrated multi-hazard framework.

There is a wide diversity of training needs across the tsunami warning chain. Some of these focus on data collection, sharing, and analysis, warning centre operations, bathymetry and digital elevation modelling, evacuation mapping and planning, GIS, warning dissemination infrastructure, and tsunami literacy. The recent approval of the IOC-UNESCO Tsunami Ready Programme as a mechanism to achieve the 100% objective brings a need for corresponding training. In addition, to support the objectives of ODTP our scientific knowledge of tsunamis and social behaviour must continue to develop. This will require enhanced research capacity and transfer of technology.

In 2020, IOC Ocean Teacher Global Academy Specialised Training Centres (OTGA-STC) were established for tsunami capacity development. Courses are to include: Tsunami Awareness, IOC-UNESCO Tsunami Ready Recognition Programme, Tsunami Early Warning Systems, Tsunami Warning Centre and Tsunami Emergency Response Standard Operating Procedures (SOPs), Tsunami Evacuation Maps, Plans, and Procedures and Tsunami Warning Centre Staff Basic Competencies. The OTGA-STCs for Tsunami will work with each other, other OTGA Regional and Specialized Training Centres and the Tsunami Information Centres. They will also seek to partner with academic institutions or other entities to develop accredited courses that satisfy advanced degree requirements. This effort will be a cornerstone of ODTP Capacity Development efforts. In the context of the ODTP new centres might be proposed to fill training gaps and needs.

Many SIDS and LDCs are more vulnerable and exposed to tsunami risk than other countries. Many of these countries also lack staff and/or their staff do not have the scientific and technical capacity to effectively support and enhance their tsunami warning system. Therefore, the implementation of the Research and Development Plan will need to ensure special consideration and priority is given to addressing and supporting the capacity needs of SIDS and LDCs. This will both ensure a high level of local preparedness, as well as address important gaps in the global tsunami warning system.

A goal of the ODTP is to ensure investment in capacity development for the different stakeholders involved in the tsunami warning and dissemination processes.

7 Governance

The 31st Session of the IOC Assembly (IOC Decision. A-31/3.4.1) established the Ocean Decade Tsunami Programme (ODTP) and the Scientific Committee to Develop Research, Development and Implementation Plan. The newly established Scientific Committee (SC) has the initial task to develop the Draft 10-Year Research, Development and Implementation Plan for the Ocean Decade Tsunami Programme (this document) for endorsement by the TOWS-WG. More broadly, the ODTP Scientific Committee has an advisory role to TOWS-WG which acts as the Steering Committee of the programme for the whole duration of the programme as indicated in Figure 5.

Services associated with the global tsunami warning system are governed by the four ICGs and advocated for by the Inter-ICG TOWS-WG. TOWS-WG is informed by two standing task teams made up of ICG representatives on Tsunami Warning Operation (TT-TWO) and Disaster Management and Preparedness (TT-DMP). The Chair of the TOWS-WG ensures development and delivery of recommendations to the IOC Executive Council and General Assembly.

TOWS-WG is composed of the Chairs of the four ICGs, GOOS, IODE and JCB, plus high-level representatives invited from the key TOWS-WG stakeholders (CTBTO, FSDN, UNDRR, WMO and IUGG Tsunami Commission).

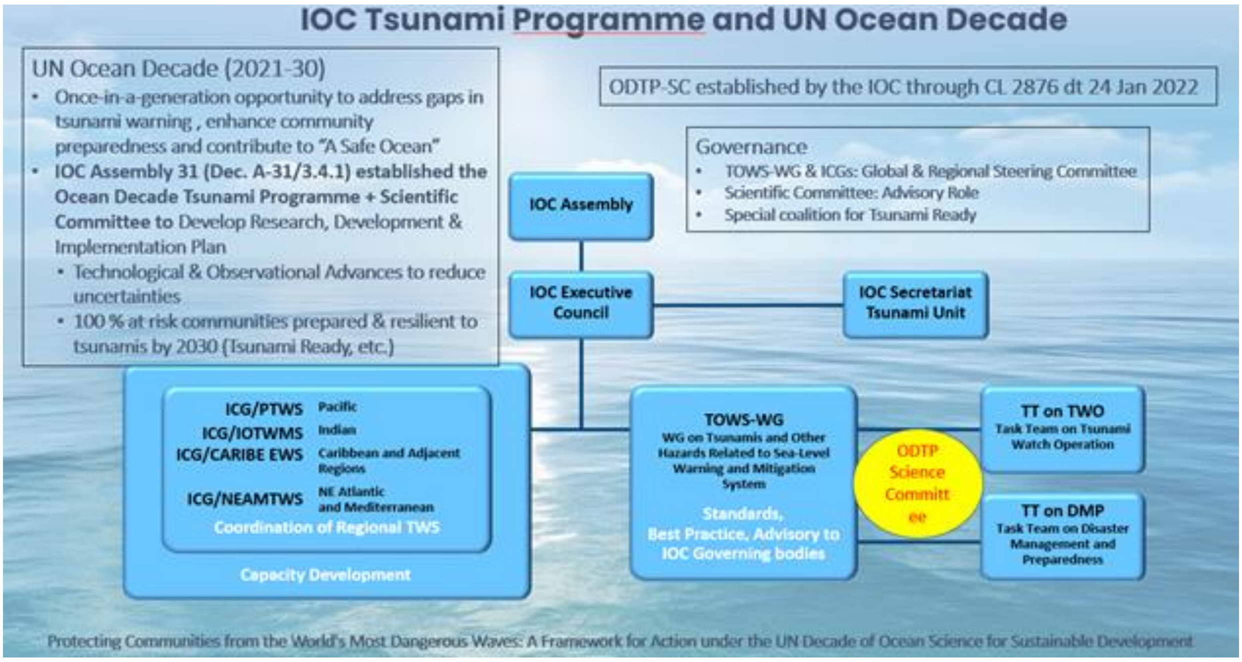

Figure 5 Relationship and interaction of the IOC Tsunami Programme with the UN Ocean Decade**.**

The IOC-UNESCO Tsunami Ready programme will form an integral part of the ODTP and will play an important role in Objective 2 that deals with making 100 percent of at-risk communities prepared and resilient to tsunamis by 2030. This programme is implemented through Member States and coordinated by the ICGs and their associated Tsunami Information Centres under the oversight of the IOC Tsunami Unit. In addition, the Tsunami Ready Coalition, established through IOC Decision A-31/3.4.1 - Warning Mitigation Systems for Ocean Hazards. The Coalition includes critical stakeholders across the UN structure as well as national civil protection agencies. The goal of the Coalition is to "contribute to increasing the number of Tsunami Ready communities as part of the Ocean Decade" through the following objectives of: 1) raising the profile of IOC-UNESCO Tsunami Ready in collaboration with critical stakeholders across the UN system, interested regional organisations, national disaster management agencies and the public; 2) increasing funding resources for the implementation of Tsunami Ready and; 3) advising the IOC TOWS-WG, TT-DMP, and TT-TWO on the implementation of the IOC-UNESCO Tsunami Ready programme.

The ODTP contributes to meeting several challenges of the Ocean Decade, in particular Challenge 6 on coastal resilience. The Decade calls for action provide opportunities for a wide range of stakeholders to propose programmes, projects and contributions that can help achieve the objectives of the ODTP. Within the framework of the Ocean Decade, Decade Collaborative Centres (DCC) as well as Communities of Practice (CoP) can facilitate the work being proposed to be undertaken as part of the ODTP Science Plan. The ODTP will also need to engage in the Ocean Decade Monitoring and Evaluation framework to ensure strong cross-linkages and reporting.

A goal of ODTP is to explore opportunities and establish connections with Decade programmes, projects, contributions, DCCs and CoPs.

7.1 Alignment with International Frameworks, Calls for Action and Multi-lateral Environmental Agreements

The ODTP is aligned and contributes to international frameworks, calls for action and multilateral environmental agreements including the Sendai Framework for Disaster Risk Reduction 2015-2030, the SDGs (e.g 3, 8, 10, 11 and 14), and the Paris Agreement on Climate Change. It also is aligned with the Executive Action Plan of the UN Global Early Warning Initiative for the implementation of climate adaptation, Early Warnings for All (2023-2027).

7.2 International Cooperation

International and regional cooperation underpins the development, coordination, support, guidance and sustainability of effective end to end Early Warning Systems. In the aftermath of the Indian Ocean Tsunami, IOC-UNESCO along with many partners, strengthened its support and catalysed international cooperation to enable all countries to assess their tsunami risk, implement Tsunami Early Warning Systems and educate communities at risk about preparedness measures. In the Indian Ocean region, China, Germany, France, Japan, Australia, Norway, the United States, and many other countries and agencies have worked through strategic collaboration and partnership within the international community, host country governments, private sector and NGO partners and at community levels to deliver operational 24/7 tsunami early warning systems to ensure a safe ocean and coast. The IOTWMS alone cost approximately USD450 million to establish and every year it requires between USD50-100 million for operation and maintenance (UNESCO, 2017). Similar investments, efforts and achievements founded on international, regional, and national cooperation have been realized in the Caribbean (CARIBE EWS), the North-eastern Atlantic and Mediterranean (NEAMTWS) and the Pacific (PTWS) regions. The development and coordination of the regional tsunami early warning and mitigation system in all ocean basins stands out as one of the greatest multi-level cooperation efforts for support and guidance of transboundary tsunami risk and disasters.

A goal of ODTP is to provide new cooperation opportunities by laying out the building blocks, through an international Science Committee and International Tsunami Ready Coalition while renewing and strengthen existing cooperation with partners.

7.3 Inclusiveness, gender diversity and youth involvement

The ODTP will apply an inclusive approach to governance, providing a balanced platform for gender and generational participation. People-centred Early Warning Systems require a gender-responsive approach that ensures women's meaningful participation and leadership as well as the participation of youth and elders.

In implementing actions, ODTP will give strong consideration to inclusiveness, gender considerations and youth participation and engagement. To be inclusive requires the needs, perspectives, priorities, and meaningful participation of the many different people in society, which vary according to their age, gender, people with different functional ability, gender roles, sexual orientation, literacy, language, cultural practices, race, geographic location, socio-economic position, among many others. Marginalised people are often those most overlooked by early warning systems and require special consideration and focused attention. Gender discrimination and lack of diversity limits the access of women and girls to information, resources, and opportunities, increasing their exposure to risk, and loss, and disruption of livelihoods during disasters. The youth, young professionals, and early career researcher should be fully engaged, the nearly 20 years of the development of the end-to-end tsunami early warning system required regeneration of experts in tsunami science, early warning system, and tsunami emergency response. Youth can bring new energy, initiatives and approaches that will contribute to the adoption and innovation for the early warning system. Furthermore, their early engagement will also help to reduce the inter-generational gap and ensure the continuity of the system.

A goal of ODTP is to encourage and promote inclusiveness and gender diversity, and that youth and early career professionals engage and involve in tsunami early warning systems and actions.

7.4 Accountability

The ODTP will follow the guiding principles of accountability as described in MHEWS Policy. Accountabilities are the decisions and/or actions and the expectation to provide an explanation when inquired. It is also understood as the obligation to sustain the capability of replying and responding to any queries related to the service being provided and therefore could provide an indirect measure of the vulnerability and fragility of the system itself.

One of the most important elements of the accountability framework is having a transparent performance monitoring system based on international norms, standards and agreements being respected without compromise. Accountabilities can be addressed at four levels, namely at the institutional, governmental, and intergovernmental level and also at a user community level. User level/public accountability is usually the most visible and important level/element of accountability, especially if there are fatalities.

A goal of the ODTP is to develop and operationalize a transparent performance monitoring system based on international norms, standards and agreements.

8 Pathways to Implementation

The IOC-UNESCO tsunami programme will oversee the overall implementation of the ODTP through contributions and engagement of Member States, in coordination with the ICGs, and with the collaboration of academic institutions, researchers, industry, philanthropic organisations and other stakeholders.

Considering the nature of tsunami hazard, the optimal solutions should have a global design, address regional imperatives, and be implemented through contributions and actions of Member States and other stakeholders. The ODTP will provide a framework for identifying gaps, suggesting solutions, prioritise resources, and implementing actions within the timeframe of the Ocean Decade.

Appendices 1 - 4 provide a pathway for achieving the overall objectives of the ODTP. They outline the challenges, solutions, performance indicators, milestones and target dates for the four main components of the tsunami early warning system. Scientific objectives of the tsunami warning enhancements will be achieved by maximizing and expanding current capabilities, identifying capabilities that exist but are not currently applied to tsunami, and developing new capabilities through innovation and research.

Member States should endeavour to dovetail their national tsunami warning system plans/programmes with the ODTP objectives. Member states, academic institutions and industries will seek, possibly through ICG consultation to identify candidate proposals aimed at addressing the solutions described in the Appendices.

It is recognized that not all Member States or national activities have resources to make substantial investments in risk assessments, observing and warning infrastructure, communications and preparedness and response. The R&D community and Industry has the opportunity to develop and contribute to scientific understanding, technological solutions, product development and capacity building. It is therefore the intent of the plan to offer contribution pathways that cover the full spectrum or financial commitment by targeting the objectives most important to advancing Member State capabilities.

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Appendices

Science and Implementation Plans for Achieving ODTP Goals

Appendix 1 Risk Knowledge science and implementation plans

Science Plan				Implementation Plan		
Chapter	**Section**	**Challenge / Issue**	**Solutions**	**How will it be measured**	**Milestone**	**Date**
2. Risk Knowledge	Definition of inundation areas, flow depths and arrival times through Tsunami Hazard Assessments	Historical tsunami records are scarce or absent	Densify sea level networks		See Chapter 3	
			Perform historical data research (staff, $)	Catalogue	Each Member State has a catalogue on tsunami records	2025
			Perform paleotsunami studies (staff, $)			
		Scenario definition (seismic and non-seismic) are required as input forcing for numerical models	Seismic and GNSS Monitoring		See Chapter 3.	
			Geophysical Volcanic Monitoring			
			Densify sea level networks			
			Scientific Research	Database	Each ICG has a database of tsunami source scenarios	2025
			Experts Meetings			
		High-resolution digital elevation data is required for numerical models but is lacking in many countries. Lack of qualified staff to conduct surveys	Increase staff	Extension of available DEMs	Each Member State has coastal digital elevation data in chosen communities	2026
			Capacity building			
		Lack of equipment including boats	Funding to buy/rent equipment			
			Densify sea level networks		See Chapter 3.	

		Lack of data to validates numerical models.	Perform historical data research	Catalogue	Each Member State has a catalogue on tsunami records	2025
			Perform paleotsunami studies (funding)			
		Lack of qualified staff to conduct numerical modelling	Funding to hire and train staff	Qualified staff	Each Member State has at least one person able to do the numerical modelling	2025
		Based on the above		**Inundation areas defined**	**Each Member State has defined the inundation area for the chosen communities**	**2026**
	Definition of vulnerability and exposure	Inventories of critical infrastructures inside the inundation area (accessibility e.g., airport, ports) (telecomms, energy, food, fresh water & medical supply)	Multistakeholder resources (trained staff and $)	Inventory	Each Member State has critical infrastructure identified and prioritized	2026
		Ability to identify the vulnerable groups within the inundation area	Multistakeholder resources (trained staff and $)	Inventory	Each Member State has identified vulnerable groups within the inundation area	2026
		Number of residents and visitors with their fluctuation (daily and seasonal) within the inundation area	Multistakeholder resources (trained staff and $)	Inventory	Each Member State has identified number of population at risk within the inundation area	2026
		Identifying and prioritizing economic assets	Multistakeholder resources (trained staff and $) and coordination	Inventory	Each Member State has identified and	2026

					prioritized economic asset at land and ocean	
		Identifying and prioritizing critical infrastructure for economic impact	Multistakeholder resources (trained staff and $) and coordination	Inventory	Each Member State has identified and prioritized critical infrastructure for economic impact at land and ocean	2026
		Identifying and prioritizing the built environment	Multistakeholder resources (trained staff and $) and coordination	Inventory	Each Member State has identified and prioritized the built environment at land and ocean	2026
		Identifying and prioritizing the natural environment	Multistakeholder resources (trained staff and $) and coordination	Inventory	Each Member State has identified and prioritized the natural environment at land and ocean	2026
	Definition of capacity to respond	Definition of legal framework existing and desirable. Identifying gaps and priorities.	Strategy and funding to bridge the gap	Functional and comprehensive legal framework considering tsunami response	Each Member State has bridged the gaps on legal framework	2026
		Definition of institutional framework existing and desirable. Identifying gaps and priorities.	Strategy and funding to bridge the gap	Functional and comprehensive institutional framework considering tsunami response	Each Member State has bridged the gaps on institutional framework	2026
		Definition of EWS elements available and desirable. Identifying gaps and priorities.	Strategy and funding to bridge the gap	Functional and comprehensive TEWS	Each Member State has bridged the gaps on EWS	2026

	Definition of methodology to calculate risk	Develop methodologies for tsunami risk assessments including multi-scenario, location-based risk assessment of tsunami hazard characteristics, vulnerability, exposure, likelihood and consequences Multistakeholder definition of methodologies for tsunami risk assessments	Document methodology (include multi-scenario, location-based hazard inundation mapping)	Methodology defined	Each Member State has defined their tsunami risk assessment methodology	2026
			Developing and publishing of Supporting guidance and templates	TRA methodologies published		2026
	Using results from Tsunami Risk Assessments	Conduct and periodically review tsunami hazard risk assessments, using agreed methodologies.	Resources (trained staff and $) and coordination	TRA studies conducted	Each Member State has performed TRA studies	2026
		Translate risk assessment findings to the appropriate stakeholders and sectors.	Coordination	Tsunami RR tools in place	Each Member State has developed tsunami risk reduction tools according with results from TRA studies	2028

Appendix 2 Detection, analysis and forecasting of tsunamis and associated hazardous consequences science and implementation plans

Science Plan				Implementation Plan		
Chapter	**Section**	**Challenge/ issue**	**Solutions**	**How will it be measured**	**Milestone**	**Date**
Monitoring and Detection	Overall	100 percent detection and measurement of all significant tsunamis within an actionable timeframe from generation (see aspirational goals in Table 1)	Optimal notional global network design consisting of a mix of observation platforms/types including seismographs, tide gauges, tsunameters, GNSS, SMART, research cables, interferometers, etc.	Design Document that incorporates global design, regional implementation, and national commitments	In all ICGs	2023
			Optimal observing network implementation	Member State Contributions as evidenced through ICG observation network monitoring	In all ICGs	2025 onwards
			Enhanced data Sharing	Progress in availability of observational data to TSPs and NTWCs for operational tsunami warning as evidenced through ICG observation network monitoring	In all ICGs	2024
			Coastal Bathymetry and Topography where necessary (GEBCO/2030)	Availability of Coastal Bathymetry and Topography data for modelling and forecasting systems	In all vulnerable coastal regions	2030
			High Performance Computing /	Availability of computing	In all Tsunami	2027

			modeling and impact forecasting / assimilation / analytics including AI-ML / uncertainty reduction	infrastructure and improved forecasting methods	Service Providers	
			Warning centres have access to the analysis (data, tools and communication platforms) for effective warning to impacted populations	Implemented in Operational Systems	In all Tsunami Warning Centres	2030
	Coastal Sea Level Measuremen ts (Tide Gauges)	Current network is not adequate from the perspective of: a) Not all gauges measure time (1 min) /height (1mm) /spatial resolution that is optimal for operational warning and better scientific understanding of the hazard b) Not all existing gauges transmit data in real-time	Review and update TOWS WG report on requirements - recommendations on optimal core network for tsunami operations from the perspective of locations, sensors, telemetry, standardized formats, reporting units, etc	ICG observation network monitoring	In all ICGs	2023
			Ensure groups working on other sea level applications such as GLOSS take onboard the requirements of tsunami so that the stations address multi-hazard requirements	Incorporated in the sea level network design	In all relevant groups	2025
			Identify hotspots from tsunami / climate perspective for prioritization and redundancy of installations	Supported design network implementation	In all ICGs	2025
			Advocacy and Awareness among Member States, Network Operators, International Organisations (IHO, etc) to install new or enhance existing tide gauge networks that comply with agreed standards recommendation; real-time data sharing and access	Supported design network implementation	In all ICGs	2025

			Multi-purpose instrumentation and platforms.	Supported design network implementation	In all ICGs	2030
	Open Ocean Sea Level Measurements (Tsunameters)	The current networks (e.g. NEPTUNE, DONET, S-net) of tsunameters are used primarily for tsunami warning validation and unit source inversion of seismic sources for limited range of locations and forecasting of tsunamis; The networks are not adequate for characterising tsunamis from all tsunamigenic zones and for all types of sources; Challenges with long-term maintenance;	Design a global optimal network of ocean bottom pressure sensors that can provide the capability for direct detection of tsunami wave fields from all sources in reasonable time for tsunami warning (not tied to unit sources)	Design document	In all ICGs	2023
			Technical solutions for better communication (acoustic modems, cable-connected, hybrid, etc.)	Reports on the status of communication tests	Pilot Implementation	2027
			Technological solutions to implement sensors (pressure gauges and seismometers, etc.) to deep sea floors for high S/N, high reliability, and high durability of observations.	Reports on the Status of sensor tests	Pilot Implementation	2027
			New use cases of Tsunameter Data for other applications such as ocean circulation, climate, MJO, etc. and promote technologies for possible co-deployment of sensors (pressure gauges and seismometers) with met-ocean moorings to enhance network coverage and maintenance.	Reports and Publications	Pilot Implementation	2025
			Big data Analytics, High Performance Computing and Processing techniques for real-time data analysis and forecasting	Reports on the status of research activities	Pilot Implementation	2024

			A workshop involving observing, data utilisation, analysis, modeling and data assimilation communities for tsunami and other ocean applications	Report of the Workshop		2025
	Seismic / GNSS	Lack of adequate offshore broadband seismic stations; Lack of adequate onshore GNSS stations for direct measurement of co-seismic displacement; Lack of adequate onshore low gain (strong-motion) broadband seismic stations as countermeasures for tsunami earthquakes and huge earthquakes;	Design a global optimal network of ground-based and offshore Broadband/Strong motion/GNSS stations with priority deployment areas identified that can provide the capability for detection of tsunamigenic earthquakes in all source zones within a reasonable time for tsunami warning	Design Document Progress in sharing tsunami observation data	In all ICGs	2023
			Instrument/communications design	Reports on the status of sensor and communications tests	Pilot Implementation	2025
			Keep track of the new technology developments in geodetic observing systems and include them in the update of the plan	Updated plan document		2027
	SMART	Current networks (S-net, DONET) are targeting very limited seismic source zones; Lack of adequate network for detecting large non-seismic tsunami before arrival to coastal area;	Design a global optimal network of SMART cables that can provide the capability for direct detection of tsunami wave fields from all sources in reasonable time for tsunami warning and other ocean applications	Design Document		2023
			Technical solutions for production of Commercially Off The Shelf (COTS)	Reports on Status of tests	Pilot implementation	2024

		Currently not used for operational tsunami warning; Industry dependencies related to deployment locations, repeater design, etc; Significant upfront cost;	repeaters, sensors and allied components to be deployed on SMART cables that meet the purpose of tsunami warning and other ocean applications			
			Advocacy with all stakeholders including Private Industry, Intergovernmental organisations and Scientific Expert Teams for rapid development and implementation of SMART cables	Reports on the status of implementation of SMART cables and utilisation of data for operational tsunami warning	In all ICGs	Ongoing
	Other future potential observing technologies (Coastal Radars, Altimeters, Infrasound & TEC Measurements, etc.)	Challenges with network coverage, data latency, accuracy, data analysis methodologies for implementation in operational tsunami warning	Promotion of Research & Development in potential future observing technologies and analysis methodologies that could enhance operational tsunami warning of tsunamis from all sources.	Reports on Status of research activities in this field		2027
			Development and testing of instruments and methodologies to detect tsunami waves	Reports on the Status of demonstration and testing	Pilot implementation	2028
	Characterisation and forecasting of all significant tsunamis within an actionable timeframe	Challenges with integration of data from enhanced observing networks and new methodologies for defining the tsunami wave fields for operational tsunami warning including	Research on the nature of tsunamis, source mechanisms and characterisation from various observation data.	Demonstrated uncertainty reduction	Contributing capabilities identified	2024
			Probabilistic Tsunami Forecasting Techniques - assign confidence level (0.0-1.0) to wavefield definition	Reports of testing/evaluation	Prototype wavefield predictor	2023

	from generation	detection, verification, characterisation and impact			developed	
			Development of new forecast methods for operational impact forecasting of all significant tsunamis within an actionable timeframe from tsunami generation	Reports on the development and evaluation of forecast methods	Improved forecasting methods deployed and operationalised at the TSPs and NTWCs	2030 ?

Appendix 3 Warning, dissemination and communication science and implementation plans

Science Plan				Implementation Plan		
Chapter	**Section**	**Challenge/Issue**	**Potential Solutions**	**How will it be measured**	**Milestone**	**Date**
4. Warning Dissemination and Communication	National and local tsunami warning chains and SOPs	Parameters needed by the National and Local DMO to advice response	Co-design of warning information and SOP requirements among the TSPs, NTWC, N/L DMO, and other relevant stakeholders	Review of Tsunami Watch Operation Global Service Document (IOC Technical Series 130)	in all of ICGs	By 2024
				Agreed parameters at the National - Local level for warning and response plan	100% Countries at Risk of Tsunami	By 2025
		Decision Matrix on Warning.	Competency training for NTWC and National and Local DMO staff	The existence of National Tsunami Warning Response Plan and SOP in countries at risk of tsunami	100% Countries at Risk of Tsunami	by 2027
	Construction of the warning	Time constrain	The use of IT	Time line for warning and response plan is included in the National Tsunami Warning Response plan and SOP	100% Countries at Risk of Tsunami	by 2027
				Time line for warning and response is tested and reported for events and exercises	100% Countries at Risk of Tsunami	by 2030
		Languages and fit for audience (not inclusive)	Understanding the target audience (culture, education, capacity,	Inclusiveness is addressed in the National Tsunami Warning and Response Plan	100% Countries at Risk of Tsunami	by 2027

			abilities, inclusiveness, etc.)	Inclusiveness is addressed in the Local Tsunami Warning and Response Plan	100% Countries at Risk of Tsunami	by 2030
		The lack of actionable content of warning.	Develop impact based warning content (concequences).	Agreed impact based warning content for the NTWC for warning and response plan	100% Countries at Risk of Tsunami	by 2025
	Warning Dissemination and Communication Options	The lack of redundant mechanism in receiving and disseminating warning and commmunication	Redundant mechanism in receiving and disseminating warning and communication	At least three mechanisms to receive threat assessment from TSP identified, agreed, and tested	100% Countries at Risk of Tsunami	by 2027
				At least three mechanisms to disseminate warning identified, agreed, and tested	100% Countries at Risk of Tsunami	by 2027
		The lack of standard format for warning and commmunication	Promote Common Alert Protocol (CAP)	CAP is implemented by the National Tsunami Warning Centres	100% Countries at Risk of Tsunami	by 2030
			Training of NTWC staff on CAP			
		The lack of national standard format and mechanism for warning and communication for people with Different Functional Abilities (Difable) - *check with SFDRR*	National standard format and mechanism for warning and communication for People with Difable	Warning and communication for People with Difable is addressed in the National Warning Response plan	100% Countries at Risk of Tsunami	by 2030
		Conflicting and multiple source of warning information	Effective use of Broadcast and Social Media	The use of Social Media and Broadcast Media is addressed in Tsunami	100% Countries at Risk of Tsunami	by 2030

			Media Training for NTWC staff and Training for Media Broadcaster and Social Media Influencers	Warning Response Plan and tested during events and exercises		
		Technology Gap and/or not fully utilized	New/emerging technologies (Digital and Communication)	Review of Tsunami Watch Operation Global Service Document (IOC Technical Series 130)	in all of ICGs	By 2024
		Lack - limited Interoperability	Multi-hazard Early Warning Alignment (resources, capacity, information, SOP, etc.)	National Warning Centre Response Plan is aligned with and optimises arrangements, resources, capacities, and information across hazards	100% Countries at Risk of Tsunami	by 2027

Appendix 4 Preparedness and Response science and implementation plans

Science Plan				Implementation Plan		
Chapter	**Section**	**Challenge/Issue**	**Potential Solutions**	**How will it be measured**	**Milestone**	**Date**
5. Preparedness and Response Capabilities	Preparedness	Limited availability of easily understood tsunami evacuation maps	Training on Tsunami Evacuation Maps, Plans and Procedures (TEMPP)	Number of easily understood community evacuation map	30%	By 2025
			Identification of Tsunami Hazard Zones and development of Tsunami Inundation Map			
			Enhancing GIS capacity within country		75%	by 2027
			Data and information for evacuation maps (sensitive and critical infrastructures)			
			Inclusion and guidance on effectiveness of tsunami evacuation map (social and culture)		100%	by 2030
			Community participatory approach in tsunami evacuation map			
		Limited public display of tsunami information in tsunami prone areas	Establish a national standard of Tsunami Signage (i.e. take ISO)	The availability of public display of Tsunami Information in the communities	100%	By 2030
			Inventory of the type of tsunami signages used by different countries			

			Engage local artist			
		Limited local context in tsunami awareness and education resources (language, culture, local threat, risk, etc.)	Adaptation of tsunami education resources to the local context (language, culture, local threat, risk, etc.)	At risk communities have local tsunami awareness and education resources in the community	100%	by 2030
			Use local authority social media and website for public awareness and education	Monitor the use of hashtags (#tsunamiready)	Increment of 10% annually	by 2030
		Limited people with difable are included in preparedness and response actions	Development of specialized tsunami awareness education resources for people with difable	At risk communities have engagement and inclusion of people with difable	100%	by 2030
			Engagement and inclusion with People with difable (association, communities, authorities, etc.)			
		Limited inclusion of tsunami in school curricula	Institutionalizing tsunami education and awareness into school curricula	Tsunami hazard and mitigation is included in the school curricula	100%	by 2030
			Share best practices and lessons learnt on tsunami education and awareness in school curricula	Schools in at risk communities are engaged in community tsunami preparedness activities		
			Engage with other global frameworks on School DRR, i.e. GADRRRESS			
		Limited effective outreach activities for people in tsunami prone area	Community at risk to conduct at least three outreach activities annually	Community at risk engagement in World Tsunami Awareness Day	100%	by 2030

		Lack of validation of tsunami response capacity due to infrequent Tsunami	Community at risk to conduct tsunami exercise	Community Tsunami Exercise at least once every two years	100%	by 2030
				Engagement of Community at risk in ICGs Wave exerices as well as other national tsunami exercises		
	Response capabilities	Lack of understanding of the Tsunami Ready Community, especially to scope and definition of community	Advocacy and promote of Manual and Guide 74 on Tsunami Ready	1. Number of at risk community in each country declared 2. Number of at risk communities prepared and resilient	100 % Number of at risk community in each country	By 2024
			Training of UNESCO-IOC Tsunami Ready Recognition Programme (i.e. OTGA)			
		Undetermined number and location of at risk communities	To identify the location and number of at risk communities		100% of at risk communities prepared and resilient	By 2030
			To include the location and number of at risk communities in the national tsunami response plan			
		Limited National support/structure/mechanis m to implement Tsunami Ready Recognition Programme	Establishment of the National Tsunami Ready Board	1. Number of National Tsunami Ready Board established in countries 2. Number of community implement Tsunami Ready Recognition Programme	1. Number countries that implement Tsunami Ready Recognition Programme established NTRB 2. Number of at risk communities that implement UNESCO-IOC	1. X% by 2025 X% by 2030 2. X% by 2025 X% by 2030
			Advocacy and campaign (Global, Regional, and National) of UNESCO-IOC Tsunami Ready Recognition Programme (i.e through the Tsunami Ready Coalition, ICGs, TICs, Permanent Delegation to UNESCO, UNESCO National			

			Commission, IOC National Contact)		Tsunami Ready Community are recognized	
			Training of UNESCO-IOC Tsunami Ready Recognition Programme (i.e. OTGA)			
			Share best practices and lessons learnt on the Implementation of Tsunami Ready Recognition Programme			
		In near field tsunami, the time to issue tsunami warning might exceed the time for effective response	Understanding of natural signs			
			Self-evacuation (escape / run) arrangement (evacuation decided by individuals)			
			Preventive evacuation arrangement (evacuation decided by authority)			
		Un-known resources and capacities within the community to support tsunami emergency response	Inventory of the available resource and capacity for tsunami emergency response within at risk community		100%	by2030
		Local tsunami response plan do not exist in all at risk communities	To use TEMPP training or other multihazard trainings		100%	by 2030

		Insufficient capacity to manage tsunami response activities in at risk communities	Optimising resources available for all Hazards		100%	by 2030
		Lack of redundant mechanism to receive tsunami warning at risk communities	To use existing methods of other hazards and traditional means of communication for receiving warnings	At least three communication mechanism to receive tsunami warning at risk communities	100%	by 2030
		Lack of redundant mechanism to disseminate tsunami warning at risk communities	To use existing methods of other hazards and traditional means of communication for disseminate warnings	At least three communication mechanism to disseminate tsunami warning at risk communities	100%	by 2030
	Mitigation	Lack of availability of safe area in tsunami at risk communities considering the lead time of tsunami arrival.	Best practices of structural mitigation intervention and consult with experts (engineers, scientist, and researchers)		100%	by 2030
		Availability of coastal protection infrastructures.	Best practices of structural and nature based mitigation intervention consult with experts (engineers, scientist, and researchers)		100%	by 2030
		Plans to minimize impacts to critical infrastructure and marine assets	Best practices of structural and nature-based mitigation intervention consult with experts (engineers, scientist, and researchers)		100%	by 2030