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اللجنة الدولية الحكومية لعلوم المحيطات
政府间海洋学委员会

UNESCO

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IOC Circular Letter Nº 2921
(Available in English only)

IOC/VR/BA/ah
29 December 2022

To: Tsunami National Contacts (TNCs),
Tsunami Warning Focal Points (TWFP),
National Tsunami Warning Centres (NTWCs) of the Tsunami Early Warning and Mitigation Systems of the Intergovernmental Coordination Groups: ICG/CARIBE-EWS, ICG/IOTWMS, ICG/NEAMTWS, ICG/PTWS

Cc: Official National Coordinating Bodies for liaison with the IOC
Permanent Delegates/Observer Missions to UNESCO of IOC Member States
National Commissions for UNESCO of IOC Member States
Chairs of IOCAFRICA, IOCARIBE, IOCINDIO, and WESTPAC
IOC Officers

Subject: Review of the Ocean Decade Tsunami Programme Research and Development Plan

The United Nations Decade of Ocean Science for Sustainable Development provides a once-in-a-generation opportunity to leverage novel sensing platforms, techniques and/or infrastructures and to more quickly detect, measure, forecast and warn for tsunamis, potentially even for the “near-instant” types of tsunami, and to enhance the preparedness of coastal communities for tsunamis through the UNESCO/IOC Tsunami Ready Programme.

In June 2021, the IOC Assembly approved, through IOC Decision A-31/3.4.1(III) (Warning Mitigation Systems for Ocean Hazards), the development of an IOC Ocean Decade Tsunami Programme (ODTP). ODTP has now been formally registered as Decade Action UN31 – “The Ocean Decade Tsunami Programme”.

A Scientific Committee for ODTP (SC-ODTP) was established through Circular Letter 2876 in order to develop a draft 10-Year Research, Development and Implementation Plan for the ODTP for endorsement by the IOC Working Group on Tsunamis and Other Hazards related to Sea Level Warning and Mitigation Systems (TOWS-WG) at its 16th meeting in February 2023. SC-ODTP consists of 11 experts as follows: Mr Srinivasa Kumar Tummala (Chairperson), Mr Michael Angove, Mr Sergio Barrientos, Ms Silvia Chacon, Mr David Coetzee, Mr Yutaka Hayashi, Ms Christa Von Hillebrandt-Andrade, Mr Alexander Rabinovich, Ms Harkunti Pertiwi Rahayu, Mr François Schindelé and Mr Amir Yahav.

With this Circular Letter, I am pleased to submit the first draft of the Ocean Decade Tsunami Programme Research and Development Plan (ODTP R&D Plan) for your review and comments before its presentation to the TOWS-WG end of February 2023. In this view, I would very much appreciate receiving your initial feedback by 25 January 2023.

Moreover, I would like to refer to the recent Call for Decade Actions No. 04/2022 open until the 31 January 2023 (cf IOC Circular Letter 2913) as an additional source of contribution to the proposed ODTP R&D Plan. The 04/2022 Call focuses primarily on programmes that contribute to the Ocean Decade Challenge 6 – Coastal Resilience and Ocean Decade and Challenge 8 – Digital Representation of the Ocean. This includes regional programmes that potentially can be part of one of the 25 endorsed Decade Programmes, one of which is the Ocean Decade Tsunami Programme (ODTP). Contributions to this call aligning with one or more of the objectives described in the draft ODTP R&D Plan are most welcome and will be referenced in later versions of the ODTP R&D Plan.

Please send all feedbacks/suggestions/comments to Mr Angelos Haidar (a.haidar@unesco.org) with copy to Mr Bernardo Aliaga (b.aliaga@unesco.org) by 25 January 2023 at the latest.

A second draft of the ODTP R&D Plan will be produced building on your comments and suggestions. It will be available for further inputs/comments in early February 2023 at the following website: https://oceanexpert.org/event/3694#overview.

With the assurances of my highest consideration, I remain,

Yours sincerely,

[signed]

Vladimir Ryabinin
Executive Secretary

Enclosures & references (3):

Ocean Decade Tsunami Programme Research, Development and Implementation Plan (1st draft, 19 December 2022) – English only

IOC Decision A-31/3.4.1(III), Warning Mitigation Systems for Ocean Hazards in Summary Report of the 31st Session of the IOC Assembly, 14-25 June 2021 (online): IOC/A-31/SR

IOC Circular letter 2825 (Annex 1: Protecting Communities from the World's Most Dangerous Waves A Framework for Action under the UN Decade of Ocean Science for Sustainable Development)

Ocean Decade Tsunami Programme

Research & Development Plan

1st Draft December 2022

22 December 2022

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List of Acronyms (1st *pass. To be updated)*

BMKG	Badan Meteorologi, Klimatologi dan Geofisika. (Meteorological, Climatological and Geophysical Agency, Indonesia)
CARIBE-EWS	Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions
CPA	Civil Protection Agency
CTIC	Caribbean Tsunami Information Centre
DG-ECHO	Directorate General–Humanitarian Aid and Civil Protection of the European Commission
DIPECHO	Disaster Preparedness ECHO programme of the European Commission
GOOS	Global Ocean Observing System
ICG	Intergovernmental Coordination Group
IOC	Intergovernmental Oceanographic Commission
IOTIC	Indian Ocean Tsunami Information Centre
IOTWMS	Indian Ocean Tsunami Warning and Mitigation System
ITIC	International Tsunami Information Center
NEAMTIC	North East Atlantic, Mediterranean and connected seas Tsunami Information Centre
NEAMTWS	North East Atlantic, Mediterranean and connected seas Tsunami Warning and Mitigation System
NOAA	National Oceanic and Atmospheric Administration
NTWC	National Tsunami Warning Centre
PTWS	Pacific Tsunami Warning and Mitigation System
TEMPP	Tsunami Evacuation Maps, Plans and Procedures
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
TSP	Tsunami Service Provider
TT-DMP	Task Team on Disaster Management and Preparedness
TWFP	Tsunami Warning Focal Point
UNESCO	United Nations Educational, Scientific and Cultural Organisation

1 Introduction

1.1 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% of all trade is carried out by about 50,000 ships worldwide (Schnurr and Walker, 2019). Approximately 40% of the world's population live within 100km of the coast with approximately 680 million people living in low-lying areas (less than 10m above sea level) that are exposed to varying degrees of oceanic hazards (Ocean Conference Factsheet, 2017).

Though infrequent, one of the deadliest oceanic hazards, tsunami, is caused by the displacement of large volumes of water due to an undersea earthquake, a submarine landslide, volcanic eruption, meteorological disturbances or meteorite impact. Between 1992 and 2019, 295 confirmed tsunamis were observed worldwide. Thirty-five of these resulted in loss of life. We do not know when and where the next tsunami will hit, but we know the impacts can be devastating. The catastrophic potential of tsunamis is exemplified by some devastating events that occurred in the historical past but also in the last 20 years.

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 very large earthquake ruptured offshore NE Japan in the Pacific Ocean and generated 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 90% of them due to the tsunami. A nuclear accident took place in direct connection with this event. Within hours the tsunami propagated to all directions of the Pacific Ocean affecting as far as California, where damage was noted in Crescent City.

The 2018 Palu and Anak Krakatoa, and 2022 Hunga Tonga - Hunga Ha'apai events further illustrated the challenges of current Tsunami Warning Systems locally and globally. These three events are cataloged as "non-seismic tsunamis" as they were not caused by subduction earthquakes, and thus posed a challenge on 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 tsunamis and to prepare people to respond to all tsunamis.

1.2 Ocean Decade Tsunami Programme

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), the Caribbean and Adjacent Regions Early Warning System (CARIBE-EWS), each coordinated by a regional Intergovernmental Coordination Group (ICG). The regional warning systems are the building blocks of the end-to-end tsunami warning and mitigation system, coordinated by the Intergovernmental Oceanographic Commission (IOC) of UNESCO as a global “system of systems”. One of the primary goals of all ICGs is to improve earthquake and tsunami monitoring and early warning.

In 2016, UNESCO IOC initiated the concept, the “Ocean we have” to the “Ocean we want” and in December 2017, this concept culminated in the proclamation of the U.N. 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 achieve a well-functioning ocean in support of all Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development. In June 2021, UNESCO IOC 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 increase the readiness of coastal communities.

The **first objective of the ODTP** is to develop the warning systems’ capacity to send out actionable notifications within 10 minutes for tsunamis from all sources with the least amount of uncertainty (see Chapter 3). This is challenging, as current warning systems depend upon quick detection of tsunamigenic earthquakes, estimating location and the initial magnitude using only seismic sensors. Also, the earliest estimation of the faulting mechanism takes around 20-30 minutes with large uncertainties. To achieve this 10-minute target requires expanding existing monitoring systems and further technology advancements (Sumy et al., 2022).

The second ODTP objective is that 100% of communities at risk to be prepared and resilient to tsunamis by 2030 through programmes like the UNESCO IOC Tsunami Ready Recognition Programme (TRRP), which was approved by the UNESCO IOC 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. To date, there are over 30 communities in more than 20 countries currently recognized as Tsunami Ready.

The ODTP Research and Development Plan therefore proposes to expand observational systems and enhance forecasting techniques. This will ensure that all National Tsunami Warning Centres (NTWCs) and regional Tsunami Service Providers (TSPs) have the tools they need to effectively warn coastal and maritime communities irrespective of source. Also, the ODTP Research and Development Plan will support the communities at risk to enhance tsunami preparedness and make them tsunami resilient. This will be a decisive contribution to the implementation of the Sustainable Development Goals (SDGs), not only SDG 14 (the "Ocean" SDG), but many other goals as well. The means of implementing targets under each SDG is a global partnership supported by concrete policies and planning. National policies and local implementation strategies should support global planning. The ODTP Research and Development Plan adopts the SDGs strategies in global planning, pursuing them through national policies and local implementation at the community level.

Implementation of the Research and Development Plan will also need to ensure special consideration and priority is given to addressing and supporting the needs of Small Island Developing States (SIDS) and Least Developed Countries (LDCs).

1.3 Elements of Early Tsunami Warning and Challenges

Early Warning Systems include four pillars (UNDRR, 2009): (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 and Governance.

1.3.1 Tsunami Risk Assessment (Chapter 2)

Understanding the risk and developing a plan to mitigate the risk is what saves lives. While tsunamis are infrequent and catastrophic ones rare, the historical record shows that tsunamis have the potential to hit every coast around the world – we don't know when, where, or how big. Also, it is important to evaluate the geological history of tsunami-prone areas to identify the probable communities at risk. This evidence will be useful to tsunami risk communities to mitigate the loss during the next.

The 2011 Japan tsunami exceeded the threshold of risk that had previously been recognised. The tsunami protective measures (such as barriers and evacuation plans) were insufficient despite the region's high degree of tsunami preparedness (Mori et al., 2011; Suppasri et al., 2012). This event amply demonstrates the substantial level of unpredictability still present in tsunami hazard and risk assessments employed for pre-event decision-making. Therefore, when preparing their tsunami response, emergency management and monitoring, authorities must recognise and account for uncertainty (Angove et al., 2019).

Until recently only seismic sources were considered in Tsunami Hazard Assessment studies and operational warning procedures. This has been the case because seismic-originated tsunamis are the vast majority impacting near and far-field coasts. On the other hand, most non-seismic tsunamis have limited and localized areas of high impact. However, impacts related to recent events have highlighted the importance of non-seismic tsunamis, like Adriatic and Balearic "rissagas", Papua New Guinea, 1998; Greenland, 2017; Palu and Anak Krakatoa, 2018; and the Hunga Tonga - Hunga Ha'apai 2022 events. Hazard assessments should also include all possible tsunami sources affecting the interest areas, and not only seismic sources.

1.3.2 Detection and Warning (Chapter 3)

A dense observation network plays a crucial role in the quick detection of the earthquake and its potential to generate a tsunami. Based on observations, the warning system determines whether communities are to be evacuated from the tsunami-prone areas, and if so, when they should be allowed to return. However, in the case of a local tsunami where the estimated tsunami arrival time to the nearest coast is less than 15 min, it is important to educate the community about physical signs of the tsunami such as long ground shaking, approaching roaring sound, rapid withdrawal of the water etc. It is challenging to generate an accurate tsunami forecast in a short amount of time in the case of major earthquakes with ruptures that reach hundreds of kilometres. In contrast to the complicated slip distribution that occurs in real situations, the majority of models start off with a homogeneous slip distribution.

To improve the tsunami detection and more accurate tsunami threat assessment and impact forecast, Member States identified the requirement for denser real-time, multi-faceted sensor networks and faster, integrated algorithms to quickly characterize the tsunami source (seismic and atypical sources) and compute tsunami inundation forecasts for their coasts. Sensors include singly or array-deployed high-quality seismometers and accelerometers, coastal sea level gauges and deep-ocean pressure systems such as Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, dedicated seafloor observatories and trans-basin undersea cables such as Science Monitoring and Reliable Telecommunications (SMART) cables, and Global Navigation Satellite System (GNSS) land and sea elevation buoys. High-resolution coastal bathymetry and topography or Digital Elevation Model (DEM) contributions are also highly significant, e.g., the Nippon Foundation-GEBCO SEABED 2030 project. New data and methods, for both seismic and non-seismic sources, are needed to more precisely characterize rupture complexities of very large earthquakes within a few minutes to produce more accurate tsunami forecasts from numerical models. In summary, the warning system must identify, monitor, and forecast the risk at the earliest possible time, and it can be achieved when the system is built based on risk awareness, emergency preparedness, and early warnings. Then the warning must be generated, delivered, received, and utilized in a timely, complete, and accurate manner.

1.3.3 Warning Dissemination (Chapter 4)

Tsunami warnings and evacuation advice are only effective when it reaches a person on the coast in time before a destructive wave hits. Both the dissemination (its timeliness and reliability) and the communication of the advice (what the message says) must be successful and actionable, or lives may be unnecessarily lost. The warning dissemination includes organizational and decision-making processes, redundant communication systems in place and operational. Additionally, incorporating tsunami warning dissemination (which may be infrequent) into multi-hazard communication systems will help to ensure sustainability and readiness.

Clear messages conveying basic, practical, and usable information are essential to ensure the proper readiness of communities. For quicker forecast results, we need to deal with larger uncertainties; with this complexity, building community trust takes longer. Also, it is a basic and practical requirement to establish communication platforms in pre-identified regional, national, and local channels by authorities. To ensure that as many people as possible are alerted, to prevent the failure of any one channel, and to reinforce the warning message, numerous communication channels must be used. To convey warnings, alerting authorities employ a variety of standards and protocols. The recent development, Common Alerting

Protocol (CAP), is an international format for public warning and emergency alerting created by the International Telecommunication Union and supported by several organizations.

1.3.4 Preparedness and Response Capabilities (Chapter 5)

As disasters are foremost local, coastal communities will suffer the brunt of the impact from the next tsunamis. Adding to the challenge, ocean-wide tsunamis are infrequent; before memories of the great tsunamis 2004 and 2011 fade away, we must put more effort into creating awareness and preparedness. In order to be successful, we will need continuing and enhanced engagement from governments, research institutes and universities, industry, communities, the media, and other interested parties. In an end-to-end warning system, the communities at risk must be aware of how to respond quickly after receiving warnings; it is equally important as detection and warning.

The UNESCO IOC Tsunami Ready Recognition Programme motivates communities to take common-sense preparedness actions, which include hazard assessment, inundation and evacuation mapping, awareness and education and exercises. It includes preparedness measures, including response plans developed and operational, public awareness and education campaigns conducted, and public awareness and response tested and evaluated. Tsunami Ready is identified by most Member States as a priority activity. Novel initiatives like the Blue-Line project around New Zealand coastlines may also be disseminated in the context of Tsunami Ready. Finally, World Tsunami Awareness Day (WTAD) on November 5 is also mentioned by Member States as a means of increasing awareness and preparedness. WTAD may have been particularly beneficial to reducing casualties during the January 15th 2022 event in Tonga. In Tonga, WTAD was commemorated through a series of educational and outreach initiatives just 2.5 months before the Hunga-Tonga event. (Borrero et al, 2022)

1.4 Tsunami Warning in a Multi-Hazard Framework

Tsunami waves frequently originate from cascading effects, such as earthquake-landslide-tsunami, volcanic eruption-earthquake-tsunami, and others. Even when the fault displacement connected to the earthquake does not produce a tsunami, a powerful coastal or undersea earthquake may trigger a landslide that acts as a generator of tsunami. The 2011 Tohoku earthquake and tsunami in Japan is a striking example of the cascading effects of tsunami due to which nuclear power plants meltdown happened. The other examples of cascading effects are, storm surge during tsunami, coastal erosion which may impact tsunami wave approach after reaching the coast, increase in rainfall rate in coastal areas can directly influence landslides, triggering tsunami. Also, recently, studies have been conducted on possible effects that climate change may have on the long-term assessment of the tsunami hazard and, consequently, of the tsunami risk. Therefore, it is important to consider the potential for cascading impacts in locations that are vulnerable to these kinds of processes in pertinent investigations.

After the 2004 Indian Ocean Tsunami, most of the Member States have developed their national tsunami warning systems. However, these warning systems are designed for single hazards and rarely integrated as a multi-hazard system. For example, in the case of oceanic hazards, after the 2004 tsunami, many Member States established tsunami early warning centres, but early warning systems for storm-surges are not an integral part of tsunami warning systems and are still under development by many countries. Also, the warning system for harmful algal blooms, coral reef bleach and oil spills etc. are still at very early stages in many Member States and mostly operated under different operational agencies which are not interconnected. The need to improve and harmonize the warning systems including and beyond hydrometeorological hazards is widely acknowledged and is reflected in the Sendai Framework for Disaster Risk Reduction.

To support redundancy, consistency, and accessibility, the focus must be on multi-hazard early warning alignment by linking hazard-specific systems together. It is especially necessary in Least Developed Countries (LDCs) and Small Island Developing States (SIDS), where there still remain significant gaps in application of advances in scientific knowledge and reach to local endangered populations. This applies to resources, capacity, information, Standard Operating Procedures (SOPs), etc. When an individual hazard warning system is brought under the multi-hazard framework, the coordination becomes much easier, the resources can be utilized optimally and the information can be effectively used for hazard mitigation. The resulting societal benefits of early warning systems can thus be spread evenly across regions, countries and communities.

1.5 Summary

The main objective of this Ocean Decade Tsunami Programme Research, Development and Implementation plan is to guide the development of tsunami warning capabilities and prepare 100% of at-risk communities to be tsunami resilient by 2030. The programme includes the following focus areas related to tsunami warning capabilities and capacity building:

(i) Expansion of existing detection and monitoring systems, including seismometers, 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.

(ii) Ensure all National Tsunami Warning Centres 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

(iii) Emphasize the importance of building tsunami resilient communities through the UNESCO IOC Tsunami Ready Recognition Programme, which is achieved through involvement of stakeholders at all levels.

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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 1970's as a function of three main elements: hazard, vulnerability, and value exposed to hazard (see for example UNESCO, 1978). This definition was later generalized 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 organizations such as UNDRR, EU and UNESCO IOC. According to the IOC Tsunami Glossary (2019), 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.

However, the definition of risk is not standardized. The reason is that it depends on the type of risk under consideration, on the availability of relevant data sets and on the types of assets which are exposed to the hazard. Consequently, the initial concept of risk has been transformed to a more generalized scheme:

$$\text{Risk} = f\,\{\text{Hazard} * \text{Vulnerability} * \text{Exposure} * \text{Value}\} \quad (1)$$

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. Formula (1) implies that the risk assessment is a complicated issue that requires the assessment of each one of the various components involved.

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 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.

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.

2.2.1.1 Deterministic THA

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.

2.2.1.2 Probabilistic THA

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 1960's. PTHA focuses on the investigation of seismic (or 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 each seismic source, with feasible earthquake magnitudes in a given time frame. The tsunamis generated by those sources are numerically simulated to define the maximum expected heights in those time frames.

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.

2.2.2.1 Fixed Height

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.

Estimated arrival times can be estimated from tsunami propagation modelling or obtained from historical events if inundation numerical modelling is not available. Flow depths cannot be estimated from tsunami propagation modelling but may be available in the case of historical events.

2.2.2.2 Numerical Modelling

Either deterministic or probabilistic approaches for THA can use numerical modelling 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 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, flow velocities and sediment transport. However, some of them might not be adequate or accurate. In 2007 the US adopted mandatory benchmarks for tsunami numerical model validation and verification that are available for other countries to use (Synolakis et al., 2008). According to Synolakis and Tadepalli (2008), 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 in 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 characterized 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 systematization and availability of 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). **The goal 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 Tsunami Hazard Assessment as well as for tsunami forecasting. For tsunami forecasting during an event, rapid characterization 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 less frequent but also threatening, thus should be considered in THA when applicable.

Since 2013, UNESCO-IOC has organized 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 (UNESCO IOC 2013, UNESCO IOC 2016, UNESCO IOC 2018a, UNESCO IOC 2018b, UNESCO IOC 2019, UNESCO IOC 2020, UNESCO IOC 2021). 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 characterization 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. **The goal 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 Warning Systems (TWS) 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 characterization, 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. Landslides can be triggered by earthquakes and volcanic eruptions, but also can be spontaneously generated, such as at Nice, France in 1979 (Assier-Rzadkieaicz , 2000). 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. Such landslides 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 characterize 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 Tsunami Hazard Assessments. Unfortunately, there is a generalized 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. Many non-developed countries lack staff and/or their staff are not trained to perform these studies. Training will be required to strengthen capacity, not only to develop skills but also to increase the number of staff dedicated to these tasks. 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 (Working Document). 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

In human communities the 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 function as generalized by formula (1). In this sense, vulnerability is closely associated to damage or fragility functions. 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 characterized 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, the goal of 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 Tsunami Hazard Assessments (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 tsunami risk assessment 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, such as earthquake-landslide-tsunami, volcanic eruption-earthquake-tsunami and others. 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 100m 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.

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

3.1 Introduction

Tsunamis are caused by the displacement of large volumes of water and the response to that displacement. Around 80% of all tsunamis or 70% of deadly tsunamis result from large undersea earthquakes. The identification of such hazards as potential tsunami sources is relatively well known and understood, particularly after the destructive tsunamis of the last two decades. It became clear following the 2004 Indian Ocean Tsunami, the 2010 Chile and the 2011 Tohoku (East Japan) tsunamis that the potential of subduction zones to produce massive ocean-wide tsunamis had been underestimated. This led to a re-evaluation of the maximum potential earthquake size 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 how we treat the threat of non-earthquake source tsunami. 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) are recent examples.

For both seismic and non-seismic generated tsunamis, the accuracy of tsunami warnings at the times required to more effectively warn at-risk communities remains a challenge. Seismic and non-seismic generated tsunamis have a range of devastating impacts, from damage to critical infrastructure and livelihoods derived from marine industries at the marine threat level of warnings, to inundation and extreme casualties along entire coastlines across an ocean basin at the land threat level. All levels of warnings require active responses of at-risk communities based on the threat level. False alarms from inaccurate warnings can also lead to mass panic, including 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 better methods to monitor and detect tsunamis. To do this we need to understand the process of tsunami generation from both seismic and non-seismic sources and the best techniques to employ, given 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 an indication of some of the new and innovative data sources and analysis techniques being developed, and the challenges not only for the development of the science, but the implementation of new science and techniques into operational tsunami monitoring, detection, and warning systems. This will necessarily require robust communications be associated with any new data streams or techniques, as well as strong international cooperation.

The key to improved tsunami warning, particularly for nearby, known source locations is to greatly reduce the time it takes to characterize the tsunami source, as this can serve as the initial condition for the resultant wavefield in most circumstances. 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 maximum uncertainty of 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 at which the uncertainty has reduced has improved markedly between 2004 and 2019, but that much more improvement is possible and needed, and suggests a **target of close to zero uncertainty after 10 minutes by 2030**.

3.2 The Tsunami Threat Lifecycle

It is illustrative to consider the life cycle of a tsunami threat, from initial detection of a potential event, through characterization 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** and **mitigation measures** 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, as listed below, but in all cases the tsunami threat lifecycle has the follow phases:

1. **Initial Indicators:** The tsunami life cycle typically begins with the identification of a disturbance which may potentially lead to a tsunami threat. This is often a large undersea earthquake, but may be a volcanic eruption, landslide, abrupt atmospheric disturbance or any other event with the potential to displace enough water to generate a tsunami. In the case of seismically generated tsunamis, once the basic earthquake parameters are identified (location, depth, magnitude), an initial estimate of the tsunami potential is derived. This relationship between earthquake parameters and resultant tsunami is highly uncertain however, requiring strong consideration of "worst case" impacts especially in the near field.

   <u>Key Decisions</u>: Initial alert levels and inundation extent (worst case).
   <u>Mitigation measures</u>: initiate essential evacuations, secure critical infrastructure operations, sirens, Wireless Emergency Alerts (WEA), natural warnings, automatic procedures.

2. **Characterization:** This phase involves characterizing the tsunami source to the point where there is enough certainty to forecast the potential threat following detection. This characterisation can come from direct observations of the tsunami generation but is often initially estimated (with uncertainty) from the event characteristics. For the classic subduction zone earthquake this is a well-known process, but for non-earthquake sources the science is still developing. For the case of known sources (earthquake or non-earthquake) monitoring solutions can be deployed and the timescales and uncertainty can be reduced more quickly. Unknown sources present a major challenge, and uncertainties are likely to remain high for longer.

   <u>Key Decisions</u>: Refine alert levels and potential inundation extent,
   <u>Mitigation measures</u>: revised general evacuations, WEA, etc.

3. **Evaluation, forecasting and warning:** once a reasonable estimate of a tsunami source is available, 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. The evaluation part of this phase involves attempts to quantify the level of the potential impacts, including durations as much as possible. This phase often involves expert advice, but for near-source coastlines there is usually not enough time to wait for detailed expert advice. For non-earthquake sources, particularly if the source was unexpected, a high level of uncertainty is often unavoidable.

   Key Decisions: Targeted alert levels and inundation extent,
   Mitigation measures: Prescribed evacuations,

4. **Monitoring:** as the tsunami threat progresses, monitoring using all available data continues. At a particular location the threat can be evaluated and may be very different to other locations. Near the source, the impacts may be large and damaging, but may pass relatively quickly, but for more distant locations the threat may be less damaging but continue for many hours.

   Key Decisions: Refine alerted areas based on observations
   Mitigation measures: finalize evacuation plans; drop alert orders for "safe" zones, restore critical infrastructure as practicable

5. **Threat has passed:** at any particular location there will be a time when the threat has passed, although some impacts (sea-level fluctuations and currents) can 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 a "Final Warning". Although the decision is aided by data, information and expert advice, it is the local civil protection organizations who are eventually responsible for determining the "All Clear" for when it is safe for communities to return to potentially impacted and dangerous locations.

   Key Decisions: NTWCs issue "Final Warning". Emergency authorities issue "All clear"
   Mitigation measures: Enable first emergency response access; Restore normal activities outside of impact zone; preserve critical data

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. The important philosophical and indeed practical issue is to decide at what point in the initial phase of the life cycle there is enough certainty of a potential threat to provide warning. Science and technology can and do contribute strongly to all phases of the threat life cycle, and that contribution will continue over the Ocean Decade.

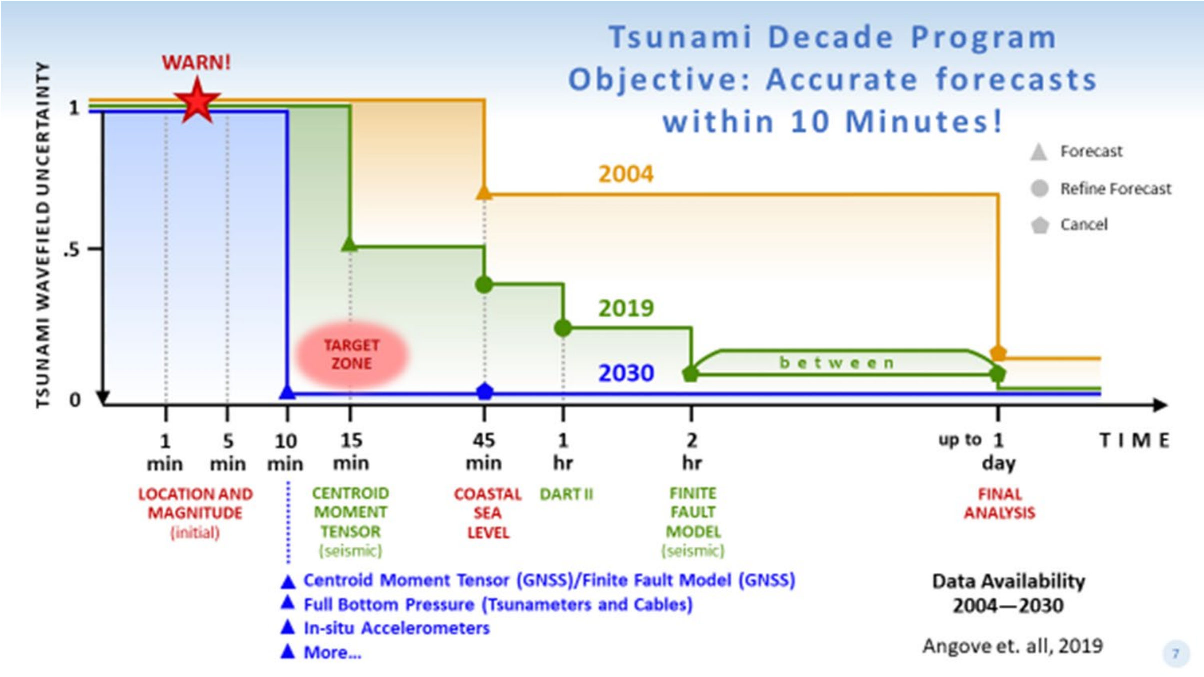

Figure 1: Diagram showing the generalized relationship between tsunami source uncertainty and time after earthquake origin for three different time frames. The orange line represents tsunami source uncertainty levels prior to 2004, the green line represents tsunami source uncertainty levels in 2019, 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 Ocean Decade Tsunami Programme (ODTP) is to greatly expand 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 plans can be 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 to more quickly provide direct 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 only 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 and on the Atlantic coasts of North and South America. As part of the ODTP new approaches are planned to be elaborated 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)	**Source partially constrained** (time after origin)	**Source fully constrained** (time after origin)
Earthquake	3min	10min	45 mins
Non-earthquake (known)	10mins	45mins	1hr
Non-earthquake (unknown)	45 mins	1hr	90mins

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 characterization 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 organizations such as the Comprehensive Nuclear Test-ban Treaty Organization (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 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 characterize an earthquake, among others, are location, 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 forecasts (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 characterize earthquakes. For example, the Pacific Tsunami Warning Center (PTWC) takes about 10 minutes to characterize significant earthquakes in the region providing epicenter, magnitude, and an evaluation of its tsunamigenic potential.

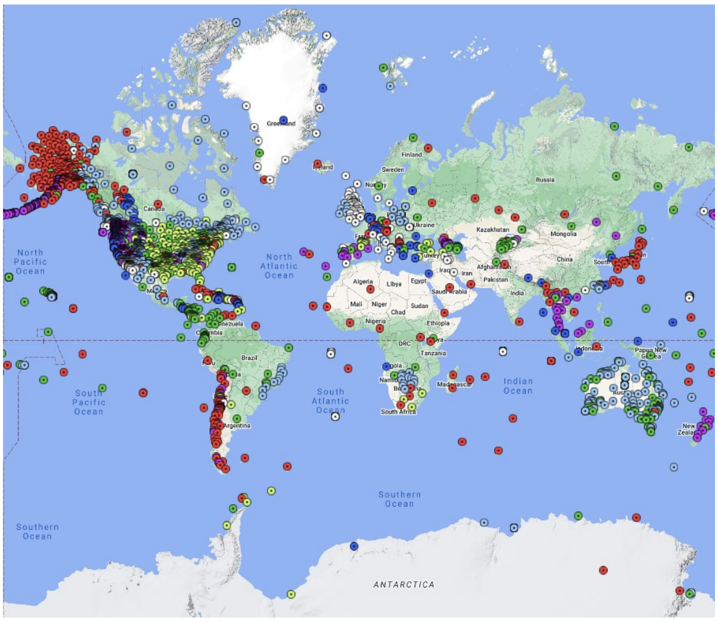

Figure 2 Distribution of broad-band seismic stations sending real-time data to IRIS DMC

Figure 2 shows the uneven distribution of land-based seismic stations contributing open data to the global system. In addition, the monitoring system of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), composed of 170 primary and auxiliary seismic stations, as well as 11 hydroacoustic stations, can provide data to the UNESCO IOC-recognized tsunami warning organizations.

The use of the available seismic data to assist in characterizing 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 Tsunami Service Providers (TSPs) and National Tsunami Warning Centres (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 is being shared in real time. The identification of network gaps and where existing stations need enhancement is therefore required and international organizations 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 in that they are the only means currently available to directly detect tsunami waves in the open ocean in near real-time. Tsunameters are primarily used to establish a most probable fit between deep ocean pressure readings and a presumed tsunami source. This requires sufficient time after origin, however, as at least half of the tsunami wave form must be measured at preferably at least two different locations.

The term tsunameter refers to all bottom pressure recorder installations, including SMART (Science Monitoring And Reliable Telecommunications) cables and cable observatories. SMART cables and cable observatories have the advantage of allowing continuous recording of bottom pressure, whereas standalone tsunameters such as Deep-ocean Assessment and Reporting of Tsunamis buoys (DARTs) developed and first deployed by the US NOAA in the late 1990s (Gonzales et al 1998) rely on the detection of a disturbance to trigger recording but can more easily be deployed where required. In general, the tsunameter networks target sources caused by subduction zone megathrust earthquakes, although there are examples where they are targeted at giving specific warning times to Member States.

The first permanent deep-ocean observational cabled network using seismographs and pressure gauges for the purpose of monitoring seismic and tsunami activity in offshore areas was installed off the coast of Tokai in 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 seismograph and pressure gauge observation networks have not yet been realized.

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 tsunameter buoys have enabled a global offshore tsunami observation network with a coarse observation network.

The maintenance of current tsunameter capabilities is important. Regular maintenance is required 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 placement closer to potential tsunami sources, reducing detection times, 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. Most countries that have deployed tsunameter networks have carried out studies to define the networks, but what is required is an overall design objective and coverage requirements. Several recent studies have also demonstrated the use of tsunameter data for a wider range of scientific applications to understand ocean circulation, Madden-Julian Oscillation, climate, etc. This offers a great opportunity to promote the use of tsunameter data by a larger scientific community and promote technologies for possible integration and co-deployment of 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 deployed in the right location in order to achieve the Table 1 aspirational goals.

3.3.1.3 Coastal Sea Level Gauges

Coastal sea level gauges (e.g., tide gauges used for port operations, tidal and coastal flood measurements, and monitoring sea level variations due to climate variability and climate change) are used to confirm tsunami impacts and height variations along coastlines. They can be used to confirm or alert tsunami generation and specify tsunami warnings for particular coastlines not yet reached by the still travelling deep ocean tsunami waves. Island-located tide gauges are especially important for these purposes. Coastal sea level gauges also provide confirmation data for comparing to open ocean forecast models and for archiving all tsunami events, even small ones that do not cause injury or damage.

Deploying additional coastal sea-level gauges can improve tsunami forecast and warning effectiveness if located in known coverage gaps and if the data is made available in real-time at appropriate frequency to support tsunami warning operations.

3.3.1.4 Global Navigation Satellite System

Rapid assessment of the source characteristics of large earthquakes in the near field is not easy to achieve using only seismometers and accelerometers. One possibility is to include low-gain broad-band sensors in the observation system so seismic signals close to the epicenter can be recorded on scale. The development of real-time precise positioning by means of the Global Navigation Satellite System (GNSS) has provided a complementary method to estimate ground displacement. Not only can it evidence the static component of earthquake-induced displacement, but seismic oscillations as well, within a few cm 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 centimetres 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.

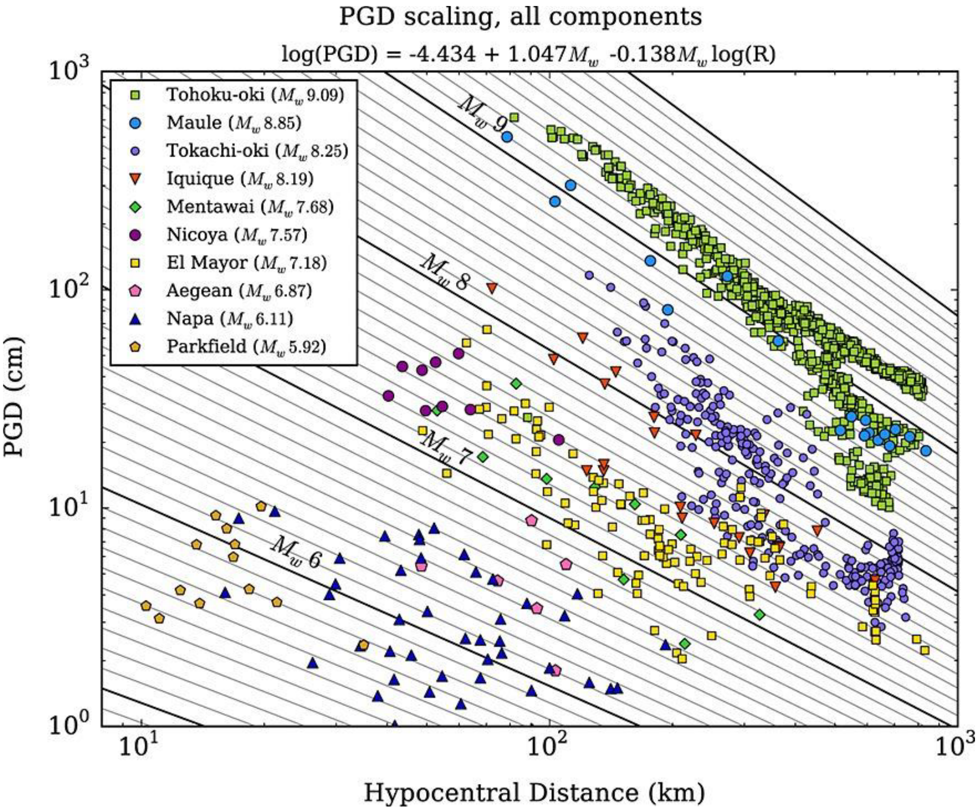

Figure 3 Scaling of peak ground displacement measurements (PGD) (Melgar et al, 2015)

Deploying additional GNSS ground stations can improve tsunami forecast and warning effectiveness if located in known coverage gaps and if the data are made available in real-time. This presents challenges 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 for realizing an observation network to monitor and detect tsunamis by installing cable seismometers and water pressure gauges on the deep-sea floor is fast developing . In some observation networks, the problem of low observation quality, such as unexplained noise and frequent sensor failures, has been identified after the installation of the sensors. 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 as the problem becomes apparent. However, it is believed that this can be technically solved in advance by conducting sufficient testing on land or in inland waters and appropriate design before the observation network is installed in the ocean area.

On the other hand, although a global observation network has been realized with tsunameter buoys, the increase in observation density required to detect tsunamis sufficiently early requires significant maintenance and replacement costs. This is a problem common to buoy systems, and GNSS buoys have a similar problem of low economies of scale relative to the number of observation points (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 and is technically feasible as a current technology to augment or in some cases replace buoy systems to develop a global ocean observation network for earthquakes and tsunamis with the cooperation of UNESCO IOC Member States. Realizing this sort of integrated, high-density detection and measurement network is one of the great opportunities 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 sea-level gauges as well as provide high accuracy tsunami impact forecasts. This is a clear example of a requirement where if the data were collected, it could be used for many purposes.

ii. **Sensor siting analysis.** A full analysis of all sensors that contribute to tsunami detection, characterization, forecasting and warning is required to identify gaps.

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

iv. **Comparison of modelling codes.** Globally, there are many modelling codes in use by scientists and Tsunami Service Provider (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 speed, to more analytical codes running on very fast computers to overcome speed issues. 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.

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.

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 intention is to identify possible lines of development the R&D community might pursue in order to include these types of capabilities into tsunami warning operations. 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.

3.3.2.1 Coastal Radar

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 several a few tens 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 tendency for high false-alarm rates that must be addressed before this capability is suitable for operational implementation.

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 and others. Four satellites happened to pass over the propagating 2004 Indian Ocean Tsunami and showed promise in representing the propagating tsunami retrospectively. 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 and processing time, which may not meet requirements for tsunami warning requirements. 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 sea surface that can be observed by passive sensing and change with a tsunami.

3.3.2.3 Infrasound

Acoustic waves and gravity waves generated by tsunamis propagate in the atmosphere and ionosphere faster than tsunamis. These waves propagating in the atmosphere and ionosphere have been reported as detection of changes in atmospheric pressure by microbarometers (e.g. Le Pichon et al., 2005) and radio wave delay time detected and GNSS (e.g. Heki et al., 2006), respectively.

Applying infrasound information to tsunami warning requires that we first have a mechanism to observe acoustic waves or gravity waves induced by the tsunami prior to the arrival of the tsunami itself. This must then be coupled with an unambiguous way to rapidly interpret the data in sufficient time to impact the tsunami warning process.

3.3.2.4 Identify other existing capabilities that can be potentially developed for tsunami warning

The general research and development community is encouraged to explore and catalog other capabilities that currently exist that could be shown to impact the UNTODP aspirational goals.

3.3.3 Identification of new candidate capabilities

Capabilities that are either unproven or undeveloped that if proven or developed could impact tsunami warning operations or mitigation could also 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. Basic scientific mis welcomed inquiry in this regard and seek to identify and endorse creative, novel approaches for advancing tsunami warning and mitigation capabilities according to the aspirational goals of the UNODTP. A substantial list of potential capabilities is expected that research activities on these topics will be actively supported and promoted by scientific research and development funds.

3.3.3.1 Ionospheric tomography

i. Potential capability: Ionospheric tomography applications have the potential to inform Tsunami Warning Operations of a propagating tsunami by detecting anomalies in Total Electron Content.
ii. Scientific challenges: It is unknown what direct contribution to the UNTODP aspirational goals could be achieved, or how this information would be successfully incorporated into operations
iii. Science and technology needs:
   a) Determine achievable operational capability gains
   b) Evaluate methods of incorporation into Tsunami Warning Operations

3.3.3.2 Identify other new capabilities that can be potentially deployed and/or developed for Tsunami Warning

The general scientific community is encouraged to explore and catalog other potentially new capabilities that could be identified, developed and applied to tsunami warning in ways that show progress toward the UNTODP aspirational goals.

3.4 Characterisation and Forecasting

Section 3.3 in this plan has focused on either optimizing, expanding, or in some cases developing new observational capabilities that can contribute to achieving the ODTP aspirational goals as applied to tsunami warning capabilities. Of equal importance is the ability to use this information in a way that will ultimately deliver improved capability across the tsunami lifecycle.

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 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 increase reliability of existing global historical tsunami catalogues, and to identify and quantify parts of subduction systems with the potential to generate large earthquakes or landslides should also continue. 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 AI Applications to relate discrete or combined observations to potential outcomes and probabilistic tsunami forecasting

Work is needed to develop tsunami forecasting methods using 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 CNN inference 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 “characterization” 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 pre-defined thresholds.

3.4.2 Dynamic Characterisation

3.4.2.1 Rapid Update Cycle Model

As real-time tsunami observations first become 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 anticipate coastal impacts. This is seen as a "bridge" capability between the CNN approach and full dynamic characterization of the wavefield. Such a model would feature sophisticated all-source data assimilation schemes that would provide a steadily improving (i.e., reduced uncertainty) dynamic characterization of the tsunami wave in near-real-time and make this information available to operation tsunami warning systems in order to inform alerting decisions. Such a capability would be used to rapidly update tsunami wavefield propagation characteristic independent of the tsunami source thereby giving operational tsunami warning centres the capability to issue dynamically based forecasts and alerts for all detected tsunamis regardless of source.

3.5 Implementation

Scientific objectives and tsunami warning quantitative enhancements associated maximizing and expanding current capabilities and instrumentation, identifying capabilities that exist but are not currently applied to tsunami, and identifying new capabilities that require development are listed in Table 2. The Research & Development Plan to reach the ODTP aspirational goals for detection, monitoring and forecasting through improved observational and analytic capabilities and techniques as described in this chapter are listed in Appendix 2. Figure 4 illustrates the ODTP vision for rethinking ocean observations to reduce uncertainty in tsunami forecasts.

3.5.1 Instrument Identification and Density

The first step in the implementation plan is to define an optimal notional global network design consisting of a mix of observation platforms including seismic instruments, tide gauges, tsunameters, GNSS, SMART, research cables, etc. that will ensure 100 percent detection and measurement of all significant tsunamis within an actionable timeframe from 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.

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

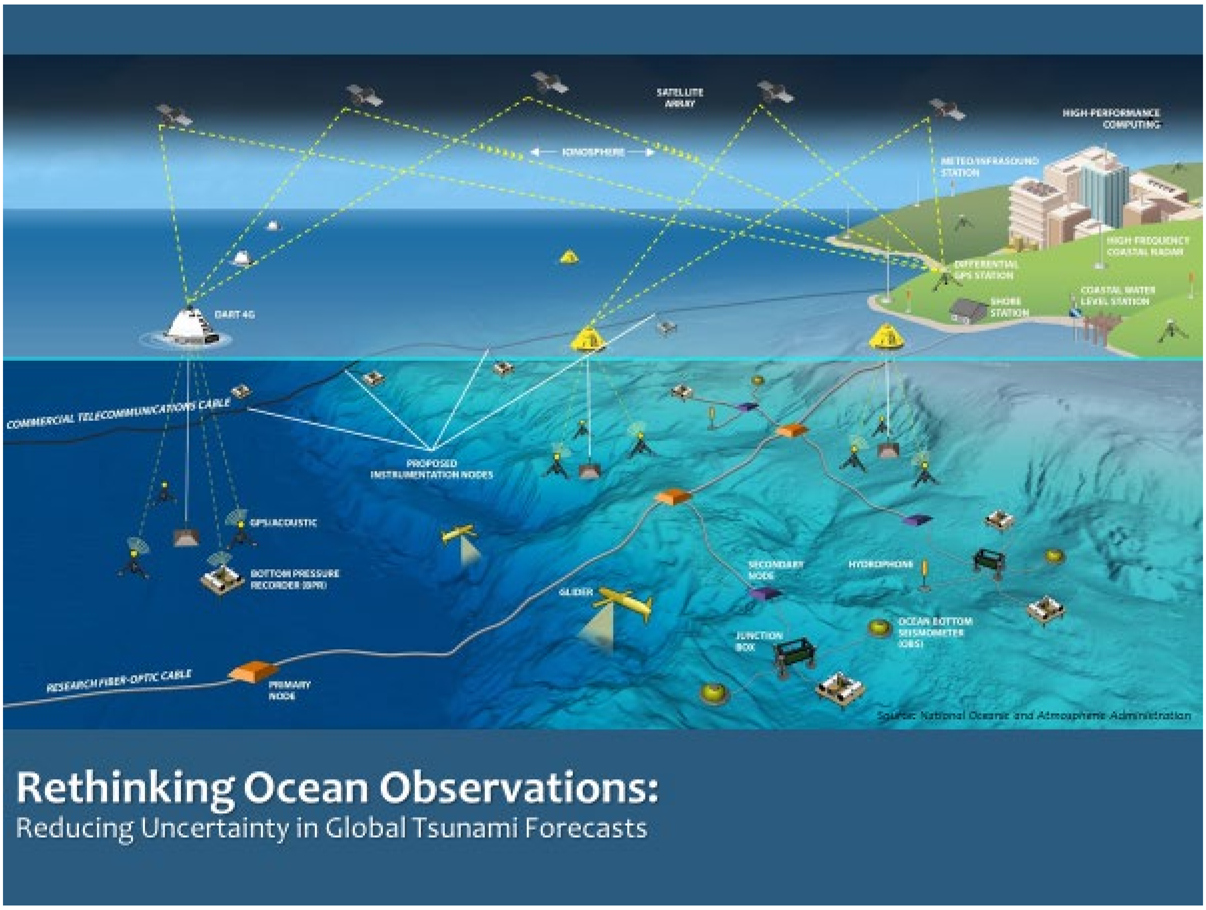

Figure 4. The Vision of the Ocean Decade Tsunami Programme is to move beyond the seismic proxy relationship and detect and measure the tsunami source or resultant wavefield *directly* in order for reliable forecasts to be produced. Many sensors will need to contribute (GNSS ground stations, in-situ seismometers,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

existing stations, upgrading existing stations to meet the requirements of tsunami warning, installing new 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. 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.

3.5.1.2 Identify range of opportunities for R&D community (or MS if development issues addressed) to invest in operational systems not yet incorporated in tsunami operations

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 nature of tsunamis, source mechanisms, source inversion and characterisation from heterogeneous observational data, uncertainty reduction, probabilistic tsunami forecasting techniques and development of new forecast methods for impact forecasting of 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.

3.5.1.3 Identify range of opportunities for Scientific Community (SC) to explore novel capabilities necessary to close remaining gaps

The scientific community can contribute to development of potential future observing technologies and testing of new instruments for Ionospheric tomography, earthquake / tsunami precursors, traditional knowledge etc. for enhancement of tsunami warning.

3.5.2 Characterisation and Forecasting

The second step in this implementation plan will be to develop data assimilation and computational techniques to effectively use (if determined usable) the array of new data sources identified in step 1.

3.5.2.1 Construct Global Database of potential tsunami sources

This database is necessary to facilitate determining which data can be viewed as reliable initial indicators in terms of assigning probabilities to potential tsunami impacts. This database will also help show which data cannot be reliably correlated with tsunami impacts.

3.5.2.2 Develop AI assisted probabilistic tsunami assessment and forecasting techniques

These capabilities will need to be developed in order to determine which real-time data sets are most important for supporting Convolutional Neural Network (CNN) techniques.

3.5.2.3 Develop Rapid Update Cycle tsunami forecast model

This capability will be necessary to incorporate real-time observational data into a dynamic representation of the tsunami wavefield.

Table 2 Scientific objectives and tsunami warning quantitative enhancements associated maximizing and expanding current capabilities and instrumentation, identifying capabilities that exist but are not currently applied to tsunami, and 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 characterize potential tsunamigenic earthquakes faster, including bringing all available techniques into operational use. 4. Identify additional ways in which the current distribution of seismometers and other seismic instruments can be more fully used to support tsunami warning	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.
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 source characterization to less than 45 minutes (Table 1) 2. Decrease time between event origin and partial tsunami source characterization 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) 4. Ensure that coastal tide gauges in tsunami prone regions have spatial resolution of ~100 km	1. Show decrease in time between event origin and aspirational goals in Table 1.

	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 characterization 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 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.
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 characterization times.	1. Deploy additional instruments in locations that contribute to deceased time between event origin and initial tsunami indicators. 2. Show decrease in time between event origin and aspirational 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 active 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 6. Take a global approach on where Member States can provide most value to Tsunami Warning Systems by investing in/deploying new tsunameters.	1. Show decrease in time between event origin and aspirational goals in Table 1

	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 aspirational 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 aspirational 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 aspirational 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 catalog of all known or suspected tsunami sources. 2. Determine and catalog 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 characterize 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. 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.	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.

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4 Warning, Dissemination and Communication

4.1 Introduction

Once a tsunami has been detected, analysed, characterized 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 stronger focus on stakeholder engagement and responsibility sharing, enhanced communication supported by technological innovations, and institutional capacity building, including strong inter-agency collaboration. This means that a good understanding of the community requirements is essential for the design of efficient warning systems.

With a view on people centred warning systems, the following key issues need to be addressed in the Ocean Decade Tsunami Programme (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: The implementation of effective warning services requires 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 Standard Operating Procedure (SOP) requirements among the Tsunami Service Providers (TSPs), National Tsunami Warning Centres (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.

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

4.3 Construction of Warnings

Warnings are produced for use by a variety of receivers in different situations. Challenges with the constriction of warnings include time constraints, being inclusive (fit for all audiences), and 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 may arrive in three to twelve 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, sexual orientation and gender identity. These groups require special consideration, 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 (disabled).

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 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. Further, 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 the international Common Alerting Protocol (CAP) as a tool for minimizing the overheads of using multiple channels. As an internationally supported standard, training, support and implementation guidelines are available to facilitate the use of CAP in new and existing warning systems. Provision must be made for capacity building of NTWC staff to apply and use the CAP.

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. Different 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.

By 2030 the goal is that there will be significant improvements in the national decision making to warn and mechanism in place for the effective 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.

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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, non-official communications 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 and elders. 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 UNESCO-IOC 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 marked the early era of national and basin-wide tsunami warning system development. Decades later, significant events such as the Indian Ocean 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. Significant events such as the Indian Ocean Tsunami and the Great Japan Tsunami in 2011 and the more recent 2018 Palu and Anak Krakatau events and the Hunga Tonga-Hunga Ha'apai volcanic eruption in 2022 have resulted in greater global attention and awareness on tsunamis and sources. 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 LCD where warning capacity and infrastructure are more 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 higher frequency of events compared with lower frequency of events. As society continuously changes, long-term strategies in tsunami awareness and response should also adapt and evolve. The institutionalization of tsunami and awareness and response is also very important for the sustainability of programmes such as Tsunami Ready.

Data, research and publications on tsunami risk perception is very limited. Given its importance, **risk perception studies need to be encouraged across all regions and targeted for the Ocean Decade Tsunami Programme.**

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 childrens which are most affected by tsunami events according to statistics (Pino et al, 2015). Comprehensive understanding of the importance of preparedness requires multi-transdisciplinary endeavors 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 in at 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 should be based on tsunami hazard zone mapping (see Chapter 2) and in accordance with the community's tsunami response plans. Maps also need to be made available via appropriate print and/or digital media. UNESCO-IOC has several Manuals and Guides that support planning including Tsunami Evacuation Mapping, Planning and Procedures, (TEMPP, UNESCO/IOC, 2020). Member States with communities at risk from tsunamis have indicated that there are many communities that 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. **The goal is that by 2030 all at risk communities have a tsunami evacuation map**

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 in the community in the event of a tsunami. 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). **The goal 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 may include tsunami evacuation maps, evacuation 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 of 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 UNESCO/IOC Tsunami Information Centres, these materials can be used and adapted to meet the needs of the local communities. **The goal 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. More disabled people need to be included in preparedness and response actions as well as integration of tsunami information in school curricula. Approaches to increased awareness, especially in schools, can include institutionalizing tsunami education and awareness into school curricula, sharing best practices and lessons learnt on tsunami education and awareness in school curricula and engagement with other global frameworks on School Disaster Risk Reduction, e.g., the Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector (GADRRRES). Another important strategy for enhancing awareness will be to **fully promote participation down to the community level on World Tsunami Awareness Day (November 5)**.

5.3.5 Tsunami Exercises

In most communities around the world, while the impact of tsunamis can be very significant, these events are infrequent. Through regularly conducted exercises, awareness can be increased, and response capacity can be enhanced and validated. The exercises can have different formats and focus solely on the tsunami hazard or can be a multi-hazard exercise that also addresses the tsunami hazard combined with a fire, tropical or sub-tropical cyclones and volcano exercise. The exercises should include a communications test between the components of the Tsunami Warning System. Each of the ICG's conduct regular tsunami exercises: CARIBE WAVE, IOWAVE, NEAMWAVE and PACWAVE. These exercises have helped validate Standard Operating Procedures for tsunami warning and emergency response as well as promote tsunami awareness in the communities (Chacón, 2021 and Kong, 2021).

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 (UNESCO/IOC, 2021). This guide provides guidance on how to plan, conduct, and evaluate a multiannual local tsunami exercise programme. These resources need to be more widely distributed in support of the UNESCO IOC regional exercises (CARIBE WAVE, IOWAVE, NEAMWAVE and PACWAVE) as well as nationally and locally organized 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 in real events. In the aftermath of tsunami events, countries affected 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.

The ODTP goal 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 (UNESCO/IOC, 2020) and other 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 in the absence of guidance from National Tsunami Warning Centres (NTWCs) can save lives. Individuals, including emergency personnel, 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, and considering non-tectonic destructive tsunamis associated with earthquake generated landslides, volcano collapse and the lessons from the Hunga Tonga Hunga Ha'apai volcanic eruption (Borrero et al, 2022), plans need to consider these types of events for which there are limited official warning protocols in place and where situational awareness is key. During the Decade, global and regional guidelines for local tsunamis should be developed that include these points and all at-risk communities with local tsunami risk should have integrated procedures for local events in their tsunami response plans.

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 Capacity

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 optimize 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 and guide evacuations and other response measures during a tsunami event.

The effectiveness of response is also dependent on the quality and accessibility of official warning information. The systems for the communication of official alerts to the communities and among the community have to be functional at all times. There needs to be redundancy in the case that one of the methods fails. The UNESCO-IOC Tsunami Ready Recognition Programme recommends that there be at least three ways for a community to receive and disseminate the alerts. It is important that systems be effective and sustainable, and that potential inequities associated with technologies, language comprehension and access and functional needs are addressed (Sumy et al, 2021). There is no one size fits all communication system.

According to Rahayu et al (2022), it is important to also 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. Furthermore, the use of existing and developing methods for other hazards and traditional means of communication for receiving and disseminating warnings should be considered. **The ODTP goal is that 100% of at-risk communities have multiple effective and sustainable communication methods in place**.

5.5 Mitigation

While planning and 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 are especially needed in areas where there is no higher land or the distance from the shore is too great to get people out of harm's way or to locate sensitive and critical infrastructure. Around the world there is a lack of availability of safe areas in tsunami at-risk communities considering the short lead time of tsunami arrival. The lack of availability of coastal protection infrastructures and plans to minimize impacts to critical infrastructure and marine assets are also noted in many communities. To address the gap efforts should be made 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 and fostering and facilitating mitigation measures is critical, 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 7). The integration of resources, services and systems from other coastal hazards will also be key for effectiveness and sustainability.

The ODTP goal is that by 2030 communities have access to an inventory of best practices of plans and structural and nature-based mitigation interventions and that more communities have implemented plans and measures to minimize impacts to critical infrastructure and marine assets from tsunamis and other coastal hazards.

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

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6 Governance

6.1 Introduction

In December 2004, nearly 230,000 people lost their lives and around US$10 billion were estimated as overall economic losses in the 14 countries affected by the 9.1-magnitude Indian Ocean Earthquake and Tsunami. Following the disaster, UNESCO-IOC received a mandate from its Member States to coordinate the establishment of a tsunami warning system for the Indian Ocean through several international and regional meetings, including the World Conference on Disaster Reduction (Kobe, Japan, 18 – 22 January 2005), and the Phuket Ministerial Meeting on Regional Cooperation on Tsunami Early Warning Arrangements (Phuket, Thailand, 28 - 29 January 2005).

To fulfil this mandate UNESCO-IOC could build on the collective experience of Member States of the Pacific Tsunami Warning and Mitigation System (ICG/PTWS), formerly known as the ICG/ITSU that was established in 1965. Intergovernmental Coordination Groups (ICG) for the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS), the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic NEAMTWS), and the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE-EWS) were established as subsidiary bodies of the IOC by resolution of the 23rd Session of the IOC Assembly in 2005. This mandate was backed up by United Nations General Assembly Resolution 61/132 in 2007 that recognised UNESCO IOC's role in leading the coordination effort of establishing regional tsunami warning systems based on its more than 40 years' experience of coordinating the Pacific Tsunami Warning System.

In 2007, the IOC established the Working Group on Tsunamis and Other Hazards Related to Sea Level Warning and Mitigation Systems (TOWS-WG) to advise the IOC Governing Bodies on coordinated development and implementation activities on warning and mitigation systems for tsunamis and other hazards related to sea level as a common priority of all ICG Tsunami Warning and Mitigation Systems. Through this structure, the individual ICGs are self-governing and report directly to the IOC Governing Bodies as subsidiary bodies, and they are coordinated and advised by the TOWS-WG (of which the ICG chairs are members), which also reports to the IOC Governing Bodies. In this way, the IOC maintains overall governance of the global tsunami warning system.

The core governance principles that apply to all 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.

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

6.2.1 The Sendai Framework for Disaster Risk Reduction

The Sendai Framework for Disaster Risk Reduction 2015-2030 recognises that early warning systems play an important role in reducing the risk of death, injury, disease, loss of livelihood and damage to property from disasters. It urges a paradigm shift towards an impact-based, multi-hazard risk-informed integrated approach for multi-hazard early warning systems (MHEWS, Target G), national and local disaster risk reduction strategies (Target E) and risk-informed government policies.

A report from the United Nations Office for Disaster Risk Reduction (UNDRR) and the World Meteorological Organization (WMO) in 2022 warns that half of countries globally are not protected by multi-hazard early warning systems and the situation is even worse for developing countries on the front lines of climate change. Less than half of the Least Developed Countries and only one-third of Small Island Developing States have a multi-hazard early warning system. The UN Secretary General has called on all countries to invest to ensure every person on earth is protected by Early Warning Systems within five years and has asked WMO to lead this effort and present the Early Warnings for All Initiative Executive Action Plan 2023-2027..

6.2.2 The UN Sustainable Development Goals

The 17 Sustainable Development Goals (SDG) were adopted by all UN Member States in 2015 as part of the 2030 Agenda for Sustainable Development. The SDGs address early warning, particularly those related to food security (SDG 2), healthy lives (SDG 3), resilient cities (SDG 11) and climate change adaptation (SDG 13). Of particular relevance to Tsunami Early Warning and Mitigation Systems and the UNESCO IOC Tsunami Ready Recognition Programme is SDG 11: Make Cities Inclusive, Safe, Resilient and Sustainable. The world is becoming increasingly urbanized. Since 2007, more than half the world's population has been living in cities, and that share is projected to rise to 60 per cent by 2030.

6.2.3 The Paris Agreement on Climate Change

Early Warning Systems are crucial components of climate change adaptation strategies and disaster risk management actions. They support processes to avoid or reduce the damages caused from different kind of hazards, exacerbated by climate change. Early Warning Systems are recognized as a key adaptation strategy in light of multiple stresses, including sea level rise, storm surges as well as the devastating impact of tsunamis. It is important to explore the interactions between climate change and relatively rare geophysical hazards and how they impact society.

6.3 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, UNESCO IOC along with many partners, strengthened its support and catalyzed 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, 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.

6.3.1 Hazard and Risk Assessments, Information and Communication

Over the past two decades, important tools ranging from tsunami databases, tsunami hazard assessments and modelling have been developed. In 2005, in response to the recommendation of the IOTWMS, the NOAA Center for Tsunami Research (NCTR) developed ComMIT, an internet-enabled interface for tsunami modelling which has been used around the world to generate tsunami inundation maps. Through a collaborative effort led by International Tsunami Information Center (ITIC), the USA (NOAA, USAID/OFDA), IOC, and New Zealand developed a standardized process, training course and Manual and Guide focusing on Tsunami Evacuation Maps, Plans, and Procedures (TEMPP). Another notable achievement demonstrating cooperation between partners, project countries and scientific organisations is the development of a first homogeneous long-term Probabilistic Tsunami Hazard Assessment (PTHA) for earthquake-induced tsunamis for the entire coastlines of the NEAM region which works in tandem with operational Tsunami Early Warning Systems (TSUMAP-NEAM Project). For the dissemination of sea level data and tsunami messages the WMO Global Telecommunications System (GTS), the US GOES, EMWIN and GEONETCAST systems have played a key role for reliable and redundant communications.

6.3.2 Monitoring and Tsunami Early Warning Services

Through cooperation arrangements facilitated by the UNESCO-IOC Intergovernmental Coordination Group (ICG) mechanism, there are now in total 11 Tsunami Service Provides (TSPs) established globally providing 24/7 tsunami warning services for all participating Member States. These are the Pacific Tsunami Warning Center (PTWC) based in Hawaii, USA; the North West Pacific Tsunami Advisory Center (NWPTAC) operated by Japan Meteorological Agency (JMA), the Joint Australian Tsunami Warning Centre operated by Geoscience Australia (GA) and the Bureau of Meteorology (BOM); the South China Sea Tsunami Advisory Center (SCSTAC), China, the Agency for Meteorology Climatology and Geophysics (BMKG), Indonesia; the Indian Tsunami Early Warning Centre (ITEWC) operated by the Indian National Centre for Ocean Information Services (INCOIS), India; the Centre d'Alerte aux Tsunamis (CENALT), France; the National Observatory of Athens (NOA), Greece; the Istituto Nazionale Geofisica e Vulcanologia (INGV), Italy; the Instituto Portugues do Mar e Atmosfera (IPMA), Portugal; and the Kandilli Observatory and Earthquake Research Institute (KOERI), Turkey.

The UNESCO IOC Sea Level Station Monitoring Facility (SLSMF) currently provides real time access to a network of over 900 sea-level stations operated by 170 data providers globally. This data is crucial for the provision of early warning of rapid onset sea-level hazards.

The CARIBE EWS is the only regional tsunami early warning system which encompasses other coastal hazards. International cooperation has been fundamental for advancing the system. With funding from Monaco, Saint Vincent and the Grenadines, Brazil, the UK and the USA for new equipment and capacity development, the sensing network grew from a dozen seismic stations and a handful of sea level stations to an integrated network of over 100 seismic stations and 80 sea level stations at its peak. Data portals like IRIS (supported by the US National Science Foundation, NSF)) and the SLSMF are key for access to these data. More recently, the US National Science Foundation has supported the integration of GNSS, with 85 stations across the Caribbean through COCONet (Continuously Operating Caribbean GPS Observational Network) and 40 stations as part of TLALOCNet (Trans-boundary, Land and Atmosphere Long-term Observational and Collaborative Network), in Mexico; now integrated into the Network of the Americas (NOTA).

6.3.3 Preparedness and Response Capacity

Tsunami warning systems must also go hand in hand with awareness and preparedness of the general public. Tsunami Information Centres (TIC) in each ocean basin were established under the coordination of UNESCO IOC to provide information on warning systems, risks and good practices in respect of tsunamis and other sea-level related hazards for civil protection agencies, disaster management organizations, decision makers, schools, industries in the coastal zone and the general public.

Governments, for example Italy and the Netherlands, have exercised a high level of cooperation and provided crucial seed funding to support the formal establishment and running of the Caribbean Tsunami Information Centre (CTIC) which is hosted by the Government of Barbados while project-based funding from the United States Agency for International Development (USAID), the European Commission Humanitarian Aid Department's Disaster Preparedness Programme(DIPECHO), the Norwegian Agency for Development Cooperation (NORAD), and the Australian Government together with pilot state contributions have significantly advanced the work of the CTIC focused on the recognition of national and local communities under the Tsunami Ready Recognition Programme. Similar support was provided towards the development of NEAMTIC, with support from the Directorate-General for European Civil Protection and Humanitarian Aid Operations. The IOTIC also operates as a partnership between Indonesia and UNESCO IOC, with an initial contribution from Canada, while ITIC is hosted by the USA in partnership with UNESCO IOC.

To reach the "last mile", an integrated approach built on multi-level cooperation to early warning must be based on and include the needs, priorities, capacities, and cultures of those people at risk. Best practices and experiences in multi-level cooperation are provided in the context of hazard and risk assessments, information, and communication, monitoring and warning, and preparedness and response capacity. The UNESCO IOC Tsunami Ready Recognition Programme is an international performance-based community recognition programme. The initiative is modelled on the US NOAA National Weather Service's TsunamiReady® Program. Implementation began in the Caribbean in 2011 and has since then extended into the Pacific, Indian Ocean and Northeast Atlantic and Mediterranean. To date, 33 communities in the Pacific, the Caribbean and the Indian Ocean have received Tsunami Ready recognition (www.tsunamiready.org) and the programme is now firmly established as a globally popular and recognized tsunami preparedness tool.

The Joint Research Centre (JRC) of the European Commission has also recently implemented "Tsunami Last Mile" TLM systems in Greece Turkey, and Malta. The TLM project objectives were to install technological tools to provide early warning to the populations in pilot cities; to build links between the relevant stakeholders that are involved in the tsunami warning system at regional, national and local levels; to build capacity in local communities and raise their awareness to tsunamis, and to conduct exercises that integrated the technological tools, involved the main stakeholders including the local population and demonstrated the benefit of awareness-raising. In the Caribbean, efforts towards the formal integration of other coastal hazards within the regional early warning system as well as the comprehensive integration of typical and atypical tsunami sources have been supported by USAID (2008-2010) and DIPECHO (2018 - 2020).

Regional tsunami exercises are regularly conducted in each region (up to 2022: 7 in the Pacific, 10 in the Caribbean, 6 in the Indian Ocean, and 4 in the North-east Atlantic and Mediterranean region) to test the readiness of early warning systems and prepare coastal communities for tsunami risks, underlining the level and scale of cooperation, coordination and efforts exercised among Member States and relevant partners. Due to relatively rare tsunami events (but high coastal exposure and risk) in the NEAM region there is a need to further strengthen cooperation and networks in particular with the Civil Protection Agencies/Organizations through the European Response and Coordination Centre (ERCC).

6.3.4 New Cooperation Opportunities

Recently, through ongoing and renewed cooperation between UNESCO IOC and partners including EU ECHO, UNESCAP, NORAD, etc.), new regional projects (e.g., the CoastWAVE project in the NEAM region) are underway to build coastal resilience to tsunami and other sea level related hazards through science and regional cooperation.

The goal of ODTP is to further develop Tsunami Early Warning Systems through technological and scientific advancements and make 100% of communities at risk of tsunami prepared and resilient to tsunamis by 2030, contributing to the societal outcome of a Safe Ocean through the implementation of the ODTP and other initiatives. To deliver such an ambitious goal, the ODTP is laying out the building blocks, through an international Science Committee and International Tsunami Ready Coalition consisting of broader stakeholders to drive and enhance international, regional to local cooperation mechanisms for support and guidance to dealing with such complex (e.g., triggering sources from volcanic eruptions, underwater landslides and meteorological phenomena), transboundary, sudden and high impact hazard, not only from seismic, but also other triggering mechanisms.

6.4 Accountability

The Words into Action (WiA) Guide on Multi-hazard Early Warning System (MHEWS) (UNDRR, in press) recognizes accountability as a guiding principle of MHEWS policy. It defines accountability as the responsibility for the decisions and/or actions and the expectation to provide an explanation for them when required. The Guide underlines that one 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. The accountability framework associated with these requirements can be addressed at four levels, namely at the institutional, governmental, intergovernmental level and at a user community level.

At institutional level, accountability requires definition of Standard Operating Procedures (SOPs) based on sound science supported by state-of-art technology and that the credibility of the scientific methods utilized is closely associated with the transparency of data and methods, In the case of governmental accountability this includes clearly defining roles and responsibilities through appropriate legislative and administrative frameworks while ensuring effective collaboration between all stakeholders and adequate financing. In the case of intergovernmental accountability, there should be instruments and opportunities to synergize actions, rules and procedures among practitioners and policy makers within an overall science and disaster diplomacy framework. As such it should promote sustainable accreditation mechanisms through independent bodies and further promote interoperability concepts through collaboration and partnerships among various stakeholders. From a user's and community level perspective, accountability is often viewed in terms of warning effectiveness, i.e., if alerts were timely and accurate and if it saved lives and reduced property damage. User level/public accountability is probably the most visible and important element of accountability, especially if there are fatalities.

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 Perform paleotsunami studies (funding)	Catalogue	Each Member State has a catalogue on tsunami records	2025
		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 seismometers, tide gauges, tsunameters, GNSS, SMART, research cables, interferometers, etc.	Design Document that incorporates global design, regional implementation, and national commitments	In all ICGs	2024
			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 centers 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 Measurements (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 characterizing 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 organizations 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 characterization 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, characterization 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 disabilities	National standard format and mechanism for warning and communication for people with disabilities	Warning and communication for people with disabilities 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 optimizes 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 disabilities are included in preparedness and response actions	Development of specialized tsunami awareness education resources for people with disabilities	At risk communities have engagement and inclusion of people with disabilities	100%	by 2030
			Engagement and inclusion with People with disabilities (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	Optimizing 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