Intergovernmental Oceanographic Commission
Technical Series

200

Meteotsunamis: Definition, Detection and alerting services investigation

UNESCO

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UNESCO 2025

IOC Technical Series 200
Paris, February 2025
English only

Prepared by the *Ad hoc* Team on Meteotsunamis: definition, detection and alerting services of the Intergovernmental Oceanographic Commission of UNESCO

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For bibliographic purposes, this document should be cited as follows:

UNESCO-IOC *Meteotsunamis: definition, detection and alerting services investigation*. 2025. Paris, UNESCO. (*IOC Technical Series No. 200*).

Cover photograph: © the municipal photo archive of Vela Luka
(HR-DADU-SCKL-692, Vladimir Stanišić)

Printed in France

(IOC/2025/TS/200)

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ANNEXES

1. INTRODUCTION

A ‘meteotsunami’ (heretofore ‘MT’) is a technical term that is sometimes used to describe long ocean waves generated by weather disturbances. It differs from tsunamis generated by undersea earthquakes, volcanic eruptions, or landslides. ‘MTs’ can form when a transitory weather disturbance moves over a body of water at roughly the depth-dependent tsunami phase velocity, creating ocean resonance and shallow water gravity waves that can either travel with (“forced” wave) or become disconnected from the source disturbance (“free” wave). For the purposes of this report, such weather-driven long waves are differentiated from tsunami-like waves induced by atmospheric acoustic-gravity or by gravity waves generated by rare cataclysmic events such as volcanic eruptions or meteor impacts.

Although these weather-driven long ocean waves are commonly referred to as ‘meteotsunami’ in academic circles, ‘meteotsunami’ is not an official term recognized and/or used by the World Meteorological Organization (WMO). Some National Meteorological and Hydrological Services (NMHS) have traditionally treated these phenomena within the same class of weather-driven coastal inundation events such as storm surges, seiches and other secondary tidal motions. Concern exists in the meteorological community that the introduction of the term ‘meteotsunami’ in forecasts and early warnings has the potential to confuse the public with imminent and potentially devastating tsunami events.

This report was developed in response to a request from the Working Group on Tsunamis and Other Hazards related to Sea-Level Warning and Mitigation Systems (TOWS-WG) Task Team on Watch Operations to review the global capabilities specifically associated with tsunamis of non-seismic origin. An ad-hoc Task Team within the IOC/TOWS-WG was established and has produced this report with the intent to review:

a) Current global status of existing guidance for monitoring of and the development of early warnings for ‘MTs’, identifying gaps where noted.

b) Roles of Tsunami Service Providers/National Tsunami Warning Centres and Regional/National Meteorological and Hydrological Services (NMHS) to monitor and warn for ‘MTs’, considering future coordination among them as appropriate.

2. BACKGROUND

2.1 METEOTSUNAMI RISKS

MTs’ have been observed in various ocean regions, inland seas, and lakes. In general, however, certain locations are more prone to impacts from these long wave phenomena than others.

‘MT’ formation, propagation and impact have been catalogued with good background references found in Monserrat *et al.* (2006), Pattiaratchi and Wijeratne (2015) and Rabinovich (2020). The primary cause of these ‘MTs’ is transiting weather disturbances moving at the tsunami phase velocity as defined by depth. Since most weather phenomena have translational speeds less than 40 m/s (78 kt), this limits the amount of ocean area susceptible to 'MT' formation to shallower regions, such as coastal margins. An example of areas where ‘MTs’ have been documented are depicted in Figure 1.

The ‘MT’ phenomenon' is recognized in many areas around the world where the prerequisite atmospheric and water depth conditions occur. It should be noted that often these long wave events amplify already impactful weather phenomena, such as landfalling tropical cyclones. However, in some cases the ‘MT’ can become fully disconnected from the source disturbance and propagate as free long ocean waves reflected/refracted/tunnelled by the ocean bathymetry or can be associated with smaller scale weather phenomena, such as convective clouds lines, or a clear-sky atmospheric gravity wave. These cases could be dangerous since the impacts of these weather driven long waves are not always covered within broader meteorological alerts.

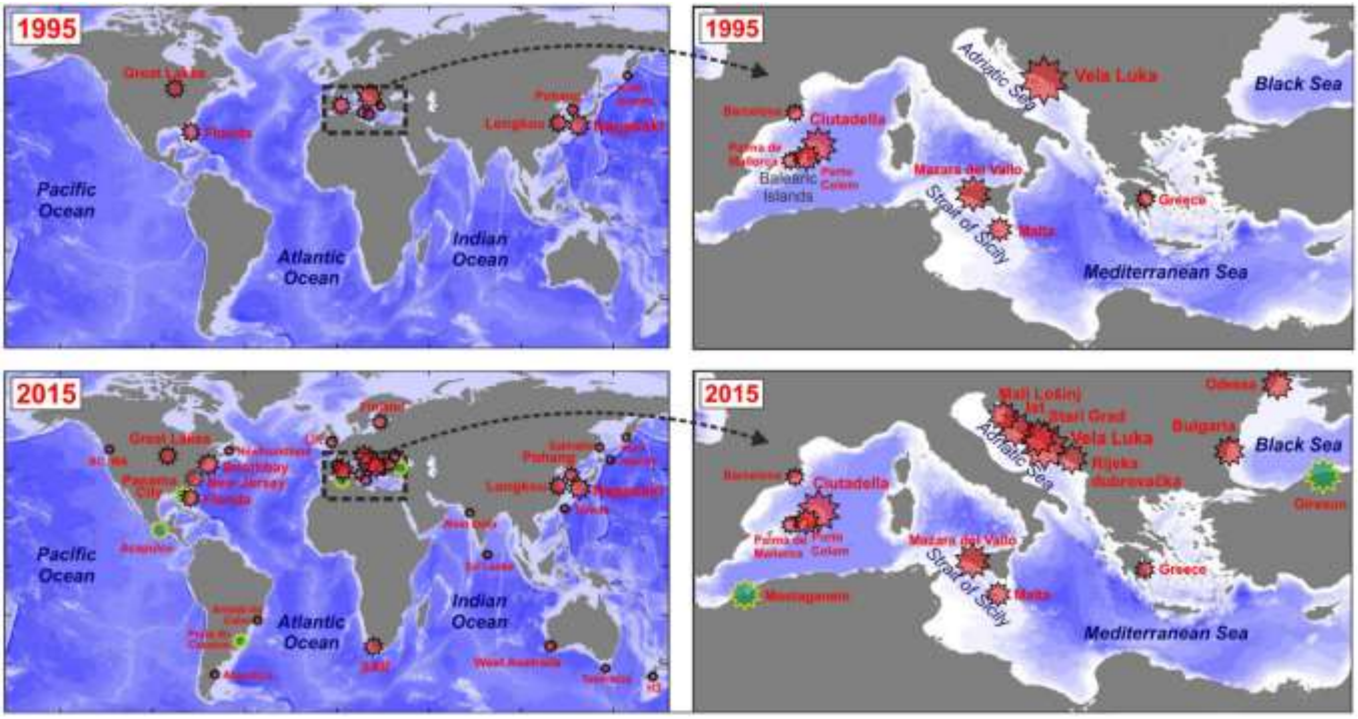


Figure 1. Locations where ’MTs‘ had been documented by the year 1995 (upper panels) and by the year 2015 (lower panels). Size of stars is proportional to the intensity of the documented events (after Vilibić *et al.,* 2016).

2.2 CURRENT ALERTING STATE

At present, all public alerts, warnings, and other products related to potential impacts from long waves sometimes referred to as 'MTs’, are delivered through National Meteorological and Hydrological Services (NMHS)—usually as notifications of anomalous storms surges, tidal fluctuations or coastal flooding—as opposed to National Tsunami Warning Centres (NTWCs) or IOC-designated Tsunami Service Providers (TSPs). In some cases, NMHS can be supported by NTWCs or TSPs, but no NTWCs or TSPs are currently designed or directed to provide public alerts on 'MT'.

NMHS will, in some cases, provide public alerts related to these weather driven long waves where such impacts are relatively common and may be destructive (*e.g.*, Mediterranean Sea, Yellow Sea, East China Sea, some areas of the North and Baltic Sea coastlines, northeastern Canada, and the US Great Lakes). A meteorological based approach is generally used emphasizing observations and Numerical Weather Prediction (NWP) techniques to identify conditions likely to generate ‘MT’. The guidance systems used in Spain is an example of this approach. Once the threat is identified and impacts anticipated, alerts are disseminated through NMHS as coastal flood, and strong currents, notifications. In Japan, atmospheric conditions from NWP models and observed data as well as water levels at tide stations are routinely monitored; information for long wave events is issued to the public through the Japan Meteorological Agency (JMA).

3. CURRENT METEOTSUNAMI MONITORING AND GUIDANCE SYSTEMS AND RELATED GAPS

The first ‘MT’ forecast system was developed for the Balearic Islands and has been operational since 1985 (Jansà and Ramis, 2021). The system, which is nowadays used by AEMET (the Spanish NMHS), is based on a premise that ‘MT’ occurs under distinguishable synoptic conditions, and that by assessing present and forecasted synoptic conditions one can assess the probability of ‘MT’ occurrence. Although this system is relatively successful in forecasting that a ‘MT’ will occur, it is less successful when it comes to determining its height (Jansà and Ramis, 2021). The main issue of a “synoptic-based” approach is that due to their relatively coarse resolution (~3-25 km) synoptic models do not reproduce ‘MT’ source (i.e., atmospheric disturbances) directly, but rather indicate the probability that such atmospheric disturbances and associated ‘MTs’ will occur.

The next means of predicting ’MT’ is through identifying meteotsunamigenic atmospheric disturbances that translate over potentially resonant depths, using different meteorological sensors, weather radar images and higher-resolution NWP tools. The goal of such sensing network is to capture rapid changes in air pressure and wind disturbances at small time periods, (e.g., 2.5 hPa or more over 5 min, Šepić and Vilibić, 2011), and to estimate in real-time the speed and direction of the disturbance. The latter may be estimated directly from air pressure measurements (Šepić and Vilibić, 2011), from sequential weather radar images (Wertman *et al.*, 2014), or through satellite top-cloud images (Belušić and Strelec Mahović, 2009). An example of a network that might be used to track ‘MT’ in real-time through measuring air pressure is the MESSI microbarograph network in the Adriatic Sea (Figure 2). However, due to operational issues, the MESSI network is presently used exclusively for analysis of the recorded events, and not for tracking of the ongoing ones.

Mesoscale NWP models capable of reproducing meteotsunamigenic disturbances, such as the Weather Research and Forecasting (WRF) model (Skaramock *et al.*, 2005), currently also provide guidance for ‘MT’ prediction along the Balearic Islands coasts (Figure 2; Balearic Rissaga Forecasting System, BRIFS, Renault *et al.*, 2011) and along the western South Korean coast (Korea Meteorological Administration's local data assimilation and prediction system, LDAPS, Kim *et al.*, 2022). Further, the BRIFS system includes a high-resolution ocean model (from 10 m to 1 km using Regional Ocean Modelling System (ROMS, Shchepetkin and McWilliams, 2005, 2009), that is forced by the NWP atmospheric model (Figure 2).

A novel ‘MT’ prediction system has been suggested and partly developed, but has not been put into operational mode yet, for the Adriatic Sea coast. In addition to real-time measurements of air pressure and sea level and high-resolution NWP and ocean modelling (Figure 2), this system also uses a stochastic surrogate approach based on essential ’MT’ variables (start location, direction, speed, period, amplitude, and width of the atmospheric disturbance; Denamiel *et al.*, 2019) and polynomial chaos expansion algorithms to allow for estimation of wave height probability exceedance at the sites of interest (Denamiel *et al.*, 2019).

To deal with forecast uncertainty, several NMHS operate ensemble NWP systems. Ensemble systems would be particularly useful to evaluate the weather conditions that drive 'MT' occurrence probability.

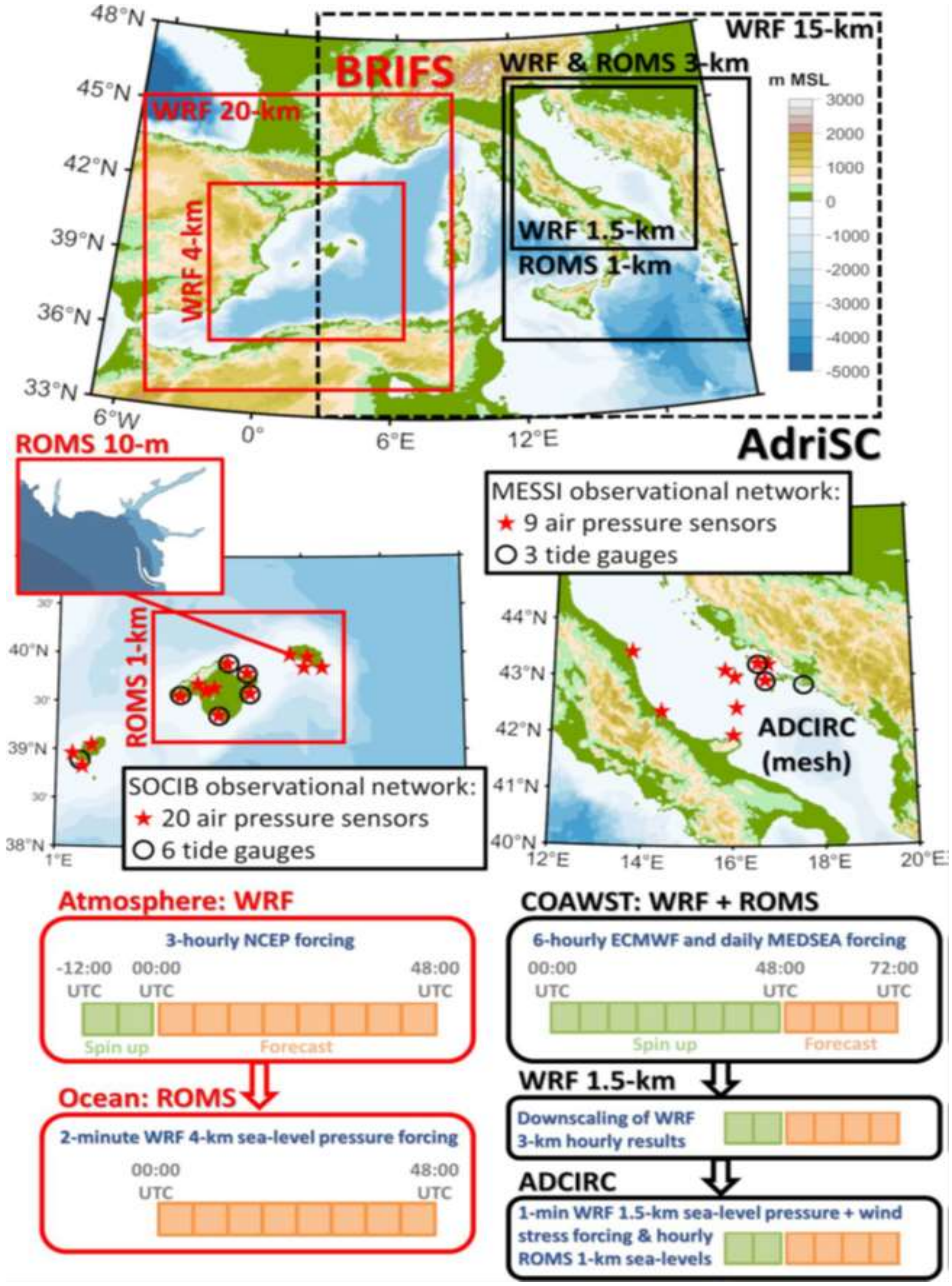


Figure 2. 'MT' monitoring and guidance systems in the Mediterranean Sea: BRIFS (in red) associated with the SOCIB observational network in the Balearic Islands and AdriSC pilot-phase system (in black) associated with the MESSI observational network in the Adriatic Sea (after Vilibić *et al.*, 2021). (Note: In September of 2024 the Spanish State Meteorological Agency (AEMET) has reported that the 4 km **1-minute** WRF is being used for sea-level pressure forcing.)

3.1 DATA NEEDS

(i) Meteorological sensors

At least atmospheric pressure, but also wind speed, should be measured to track meteotsunamigenic atmospheric disturbances. When considering data needs for an effective ’MT’ detection network, it should be noted that these disturbances have spatial resolution at the kilometre scale and temporal resolution at the minute scale. Standard recording intervals along national meteorological networks—that are 1 hour and 10-15 minutes respectively—are therefore insufficient for proper quantification. Ideally, temporal samplings should be carried with 1 minute or tens-of-seconds intervals, being a prerequisite for detection of a disturbance and for estimation of its speed and direction. This requirement in most cases can be met with state-of-the-art sensors and data flow possibilities. Further, the sensors should be placed upstream from a 'MT’ “hot spot”, i.e., the portion of coastline where 'MT’ waves are amplified the most and where 'MT’ risks are highest, towards the direction from which meteotsunamigenic disturbances are known to travel. The distance between the station network and 'MT’ hot spot should not be too large, e.g., up to 200 kilometres, as the meteotsunamigenic disturbances may intensify or diminish over such distances and therefore result in either no alarms or false alarms. Finally, at least three, but preferably more high-resolution barometric pressure sensors should compose the network, to allow proper estimation of the speed and direction of meteotsunamigenic disturbances. Placing sensors upstream from a ‘MT’ “hot spot” often represents an additional challenge and cost, as this might require that sensors be placed at open sea, e.g., at a buoy.

(ii) Coastal water level measurements

Tide gauges often sample at 1-minute or higher intervals, as listed on the IOC Sea Level Station Monitoring Facility portal at https://www.ioc-sealevelmonitoring.org. Such a resolution, or higher, is needed to properly resolve ‘MTs’, and tsunamis in general. Still, a great number of these stations are not offering sufficient resolution to meet the needs of MT monitoring (Zemunik *et al.*, 2021). Thus, improvement of data quality at 1-minute resolution for MT relevant risk areas should be a priority.

(iii) Bottom Pressure Recorders

Few ‘MT’ detection networks employ real-time bottom pressure data. This is mostly due to the systems being primarily based on predicting the potential ‘MT’ through analysis of synoptic patterns or through NWP. And while it is unlikely that the bottom pressure inversion techniques used by operational tsunami forecasters can be easily applied to ‘MT’, bottom pressure recorders could be of tremendous value in localized settings to verify the existence of and determine the temporal extent of the ‘MT’. Such instrumentation has recently been deployed in Ciutadella Bay, Mallorca. Similar deployments in other ‘MT’ “hot spots” could drastically reduce the false alarm rate and allow for better quantification of ‘MT’ amplitude and duration.

(iv) Bathymetry

Ocean models at high resolutions used for providing coastal inundation alerts need good bathymetry data (e.g., data with resolution of ca. 100 m or higher). In fact, inaccurate bathymetry may strongly underestimate, or overestimate modelled wave amplitude at endangered coasts. Even a small intervention to the bathymetry or coastline (e.g., dredging, protecting by a pier) may change the maximum amplitude by tens of percent (Fig. 3), which can be up to 1 m in the most endangered areas.

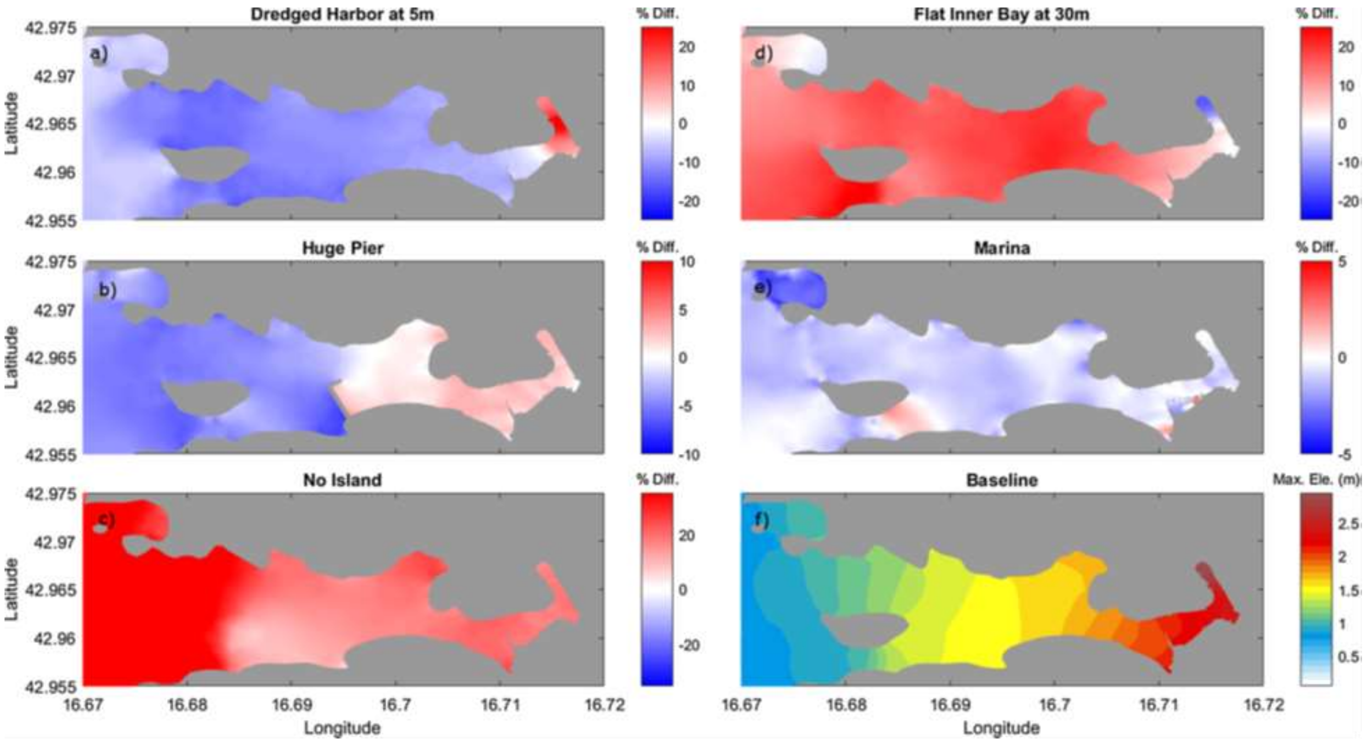


Figure 3. Relative difference (in %) of spatial evolution in the maximum elevation of modified domains versus ''Baseline'' domain for the Vela Luka Bay, Croatia (after Denamiel *et al.,* 2018).

3.2 NUMERICAL WEATHER PREDICTION AND SYNOPTICS

(i) Qualitative Approach

In some regions it is possible to produce a qualitative 'MT' forecast by assessing synoptic patterns that are known to eventually lead to coastal inundation events. Such an approach has been successfully applied in the Balearic Islands, where *rissaga* (local name for a 'MT') forecasts are provided a week in advance, being based on characteristic synoptic patterns commonly noted during 'MT' appearances in the Mediterranean Sea (Jansà and Ramis, 2021). This may be an appealing technique in regions where real-time data is limited and high-resolution numerical models are not available. A related approach could also be developed by assessing synoptic patterns and having them serve as a "trigger" that places an NWP system and supporting observations in an 'event' mode when deemed necessary, to save computational effort.

(ii) Deterministic Approach

Currently, operational NWP models are run at many NMHS. However, the specification of these models widely varies. Global models cover worldwide weather phenomena, but they are basically hydrostatic models and their resolution is around a few tens of kilometres. Regional models usually have a fine grid mesh with kilometre to several kilometres horizontal resolution, but their areas tend to be limited if resolution is finer. The models also have many differences such as being coupled or uncoupled with ocean models or wave models, or whether physical/ chemical processes are considered. Most are designed to resolve general (comprehensive) weather conditions, including atmospheric disturbances like low pressure systems, fronts, and some meso-scale systems, but small and sharp pressure dips which most often trigger ‘MTs’ are usually not well-resolved in operational models. For purposes of ‘MT’ forecasting it will be necessary to develop a specific system which can adequately resolve sufficient meteorological forcing with an aid of downscaling, and available in operational use. Several NWP systems have been applied in an effort to reproduce 'MT’ events, and some common issues that may prevent their usage in coastal inundation alerting include: (i) incapacity to reproduce or underestimation of intensity of meteotsunamigenic disturbances; (ii) improper spatial positioning of meteotsunamigenic disturbances; and (iii) an inability to precisely reproduce speed and propagation direction of meteotsunamigenic disturbances. The problem is that NWP atmospheric models underestimate the energy at timescales smaller than 7 Δx, where Δx is resolution of a model (Skaramock, 2004), which—for resolution of 2 km—implies an underestimation of up to 14 km for large meteotsunamigenic disturbances. A potential solution might be to increase NWP resolution to 1 km or less; however, this would require huge computational resources to cover wide areas and is therefore not at the moment feasible for operational use.

(iii) Probabilistic Approach

There have been attempts to improve results of NWP forecasts for ‘MTs’ using either stochastic approaches—e.g., having stochastic surrogate approach using polynomial chaos expansion method for propagation of uncertainties from the source to the sea level (Denamiel *et al.*, 2020), or by using neural networks to extract and quantify the most important meteotsunamigenic variables (Vich and Romero, 2021). Together with machine learning, this is perhaps the most attractive approach to improving deterministic NWP systems.

(iv) Combined approach

The technique used in Japan is an example of combining elements of the above approaches. JMA operational staff for marine information monitor NWP products and tide observations and analyze the possibility of an ‘*abiki*’ (which is a local name for ‘MT’), checking environmental weather conditions, Froude numbers, and vertical velocity (P-velocities) which are related to pressure fluctuations at the surface (Figure 4). Once forecasted, tidal information regarding a *secondary undulation* is provided to the public. This method of evaluating pressure disturbances is rather empirical and the main work is in manually modifying the NWP products, based on observed values, etc. While useful in operations, false alarms sometimes occur, and real events can be missed. The development of reliable scientific methods of analysing potentially meteotsunamigenic weather conditions, especially detecting small pressure changes, is desired. For that purpose, NWP models would need to resolve small-scale but sharp pressure drops, enabled by downscaling from current weather models whose main targets are synoptic and mesoscale conditions.

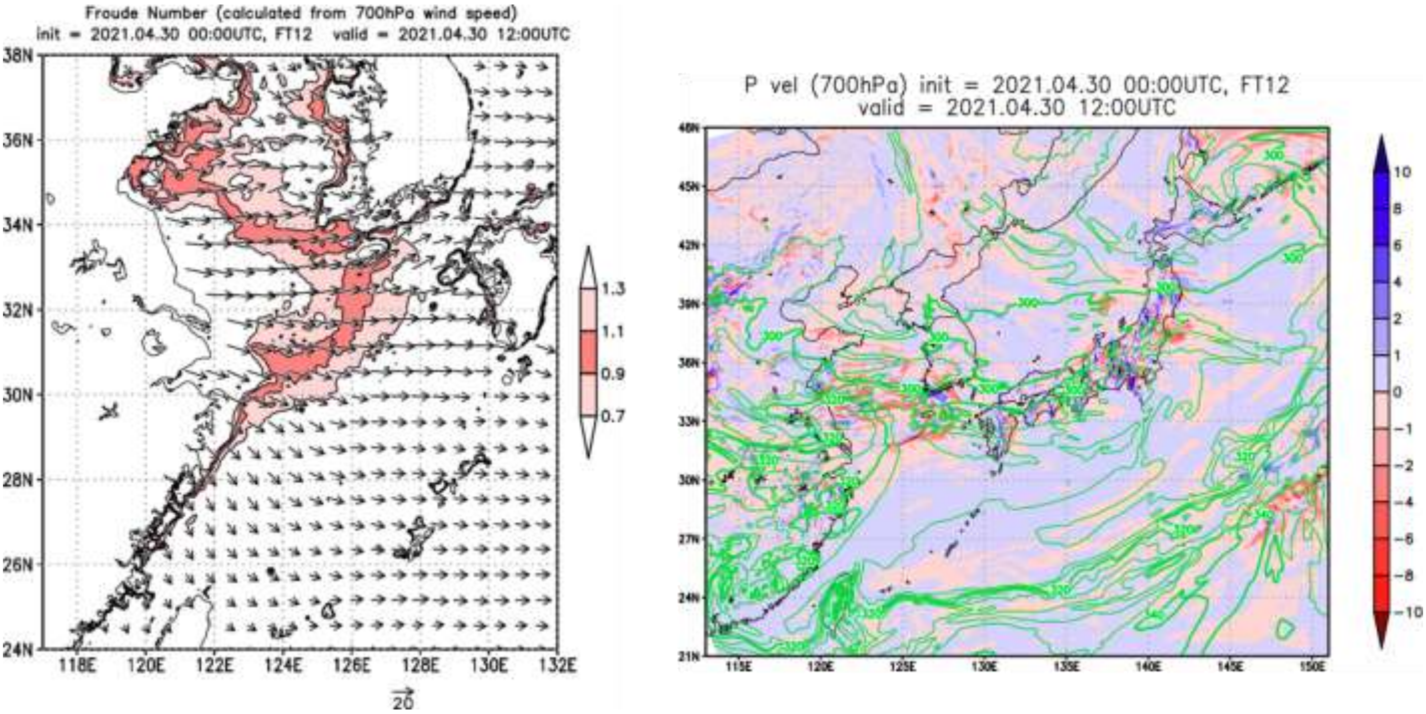


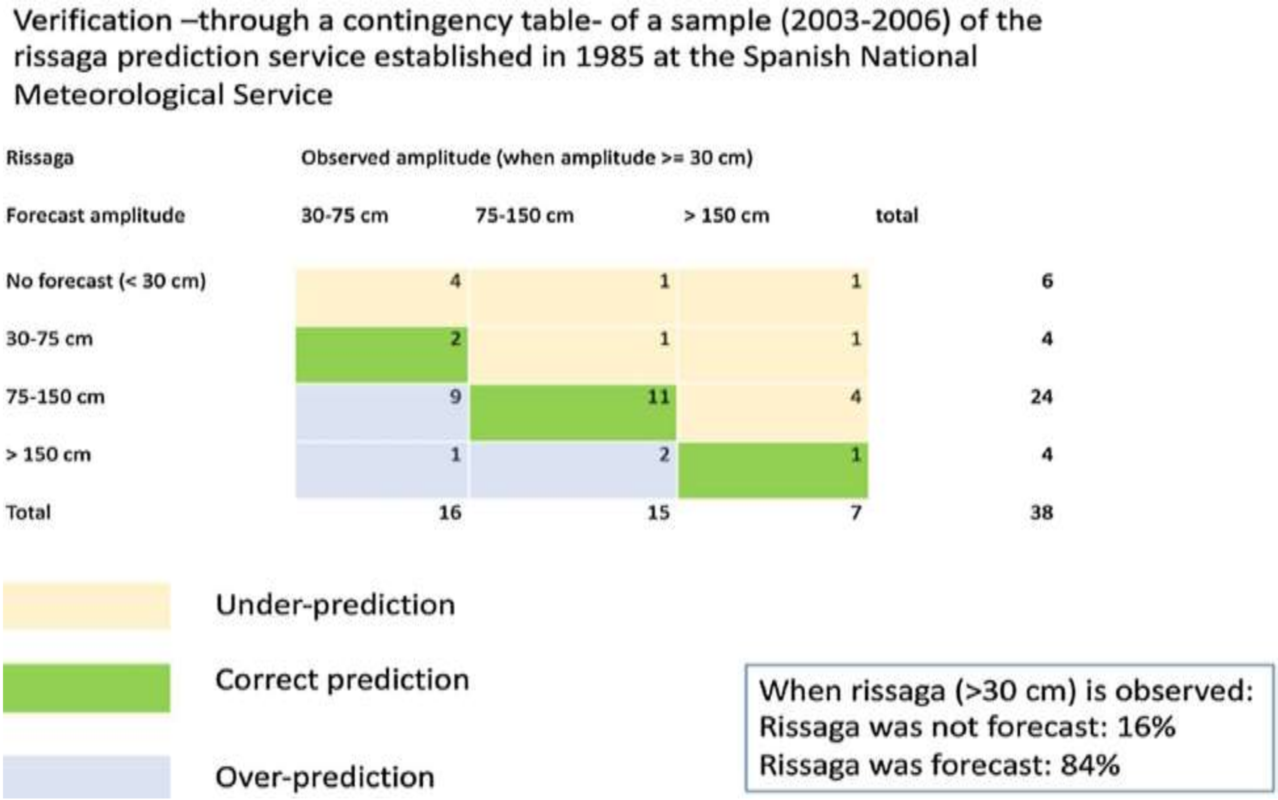
Figure 4. Charts for evaluating the possibility of abiki occurrence in Japan: Froude numbers (left) and p-velocities (right). (JMA, 2021).

3.3 LIMITATIONS AND GAPS IN METEOTSUNAMI FORECASTS

Existing 'MT' forecast guidance systems have several shortcomings related to the challenges described above. The most important is the ability to accurately forecast real 'MT' events, and—if successful—their proper quantification in terms of intensity and spatial outreach. For the Balearic system, observed 'MTs' were not forecasted for about 16% of cases between 2003 and 2006, of which one event was exceptionally strong (Figure 5; Jansà and Ramis, 2021), and only 38% of all 'MT' events were forecasted with proper intensity. Further, the verification report does not state the number of "false positives", i.e., number of situations in which 'MTs' were forecasted but did not occur (Figure 5). For the deterministic part of the pilot-phase Croatian 'MT' guidance system, goodness-of-fit for the researched 'MT' events show an underestimation of the forecasted meteotsunamigenic disturbances and ocean waves in 2014 and 2018 by 65% and 13.5%, respectively, while completely missing the events in 2020 due to an unpredicted shift in the meteotsunamigenic disturbance's trajectory (Tojčić *et al.*, 2021). Conversely, the guidance system based on the surrogate stochastic approach was successful at reproducing almost all observed meteotsunami events but was found to create false alarms at a relatively high rate.

Another problem, noted for example when testing the Korean system, is a lack of observational atmospheric data ahead of the at-risk coastlines, i.e., the sea over which a meteotsunamigenic disturbance is advancing (Kim *et al.*, 2022). Ideally, precise microbarographs with the possibility to measure propagation of atmospheric disturbances should be put upstream of endangered locations (like in Monserrat *et al.*, 1991). It is found that such observations might be useful to trigger an alarm for up to an hour at some locations (Marcos *et al.*, 2009). If not having existing fixed platforms or islands, such as off the endangered sites in Croatia (Figure 2), the cost of such observations may overcome the benefit of the projected guidance system. Usage of school or amateur networks may be a solution for some endangered coastlines (Rabinovich *et al.*, 2021) to increase the density of observations in some areas, but these are also rarely located upstream of the at-risk location.

Raising awareness of at-risk locations and providing alarms to civil protection agencies and local authorities would be a critical step in saving lives and protecting property. For example, in the Balearic Islands, the Spanish Metoerological agency has been providing qualitative rissaga ('MT') forecasts to the public since 1985, nowadays by the AEMET (Agencia Estatal de Meteorología) (Jansà and Ramis, 2021). Coastal States' NMHS where 'MT' risks exist are encouraged to consider pilot efforts to enhance awareness of this threat.



Verification –through a contingency table- of a sample (2003-2006) of the rissaga prediction service established in 1985 at the Spanish National Meteorological Service

Rissaga	Observed amplitude (when amplitude >= 30 cm)			
Forecast amplitude	30-75 cm	75-150 cm	> 150 cm	total
No forecast (< 30 cm)	4	1	1	6
30-75 cm	2	1	1	4
75-150 cm	9	11	4	24
> 150 cm	1	2	1	4
Total	16	15	7	38

🟨 Under-prediction

🟩 Correct prediction

🟦 Over-prediction

When rissaga (>30 cm) is observed:
Rissaga was not forecast: 16%
Rissaga was forecast: 84%

Figure. 5. Verification of 'MT' forecast issued by the AEMET experimental rissaga prediction service between 2003 and 2006 (after Jansà and Ramis, 2021).

3.4 TSUNAMI-SPECIFIC CAPABILITIES RELATED TO METEOTSUNAMI

As mentioned in the outset, the weather-driven long wave phenomena sometimes referred to as 'MTs' fall under the scope of NMHS for alerting purposes. In some cases, instruments typically monitored by operational tsunami forecasters (e.g., deep ocean tsunameters) can be leveraged to support servicing NMHS by providing direct confirmation of 'MT' generation. This is particularly important outside of localized regions supported by 'MT' guidance systems, where 'MT' formation can be predicted based on well understood, repeatable patterns with meteorological sensor cueing. Tsunami-specific instruments have only recently become relevant for 'MT', with a vast amount of real-time water level observation data becoming available in some regions. This can be traced to the 2004 Indian Ocean Tsunami (IOT), with the rapid expansion of the deep-ocean tsunami detection capabilities (including DART buoys and cable systems) and massive improvements of the real-time coastal sea-level network. These expanded tsunami detection capabilities have facilitated a significant improvement over the strictly earthquake-centric tsunami warning systems of the past (Bernard and Titov, 2016). Where these improved tsunami detection and measurement capabilities exist, they can now provide opportunities to assess tsunami-related events not only for the earthquake-generated tsunamis, but for sea level perturbations from other sources including ‘MT’. It is particularly important that NMHS that support coastal states with a known risk for experiencing ‘MTs’ but without a related targeted forecast system understands that it is feasible to leverage the broader tsunami detection networks, including identifying critical coverage gaps, to provide advance warning.

Even in regions where sophisticated detection networks do exist that can identify potentially meteotsunamigenic disturbances or resulting weather-driven long waves, tsunami-specific instruments can prove useful as a means of reducing false alarms. Since these instruments directly detect tsunamis (and other long-wave sea level perturbations such as ‘MT’) as opposed to inferring it through NWP-based procedures, the rate of missed events would be lower than any method that would rely strictly on a meteorological-based forecast of the weather- driven long wave events.

4. STANDARD OPERATING PROCEDURE CONSIDERATIONS

Regarding the wide range of impacts from ‘MTs’, as well as the low availability of data and varying risk tolerance in different parts of the world, it is difficult to suggest a single set of standard operating procedures to address the threat of a ‘MT’ occurrence. As these are weather-driven events, it falls within the remit of the WMO to provide such guidance to NMHSs. With this in mind, the ad-hoc team has identified a number of important considerations:

4.1 GENERAL CONSIDERATIONS

(i) Understanding risk

Along coastlines prone to impacts from ‘MTs’, NMHS could be encouraged to conduct detailed hazard and risk assessments to include:

(1) Identifying areas favourable to the development of ‘MTs’;

(2) Identifying the seasonal risk variation;

(3) Determining the range of impact that could be expected from ‘MTs’, particularly whether such phenomena impact an area deemed difficult to evacuate, or that the area could be prone to a more limited but still dangerous coastal impact; and

(4) Identifying and exercising the primary mitigation measures available to address these risks.

(ii) Available detection networks

Identify instruments available that can detect atmospheric disturbances or weather driven long-ocean waves within area of responsibility, including:

(1) Meteorological sensors that can identify precursor disturbances;

(2) Weather radar images that can be used to track propagation of mesoscale convective systems or individual convective cells which are often related to ‘MTs’;

(3) Coastal water-level gauges with the required sampling and data transmission frequencies that can verify ‘MT’ arrival in coastal locations and validate forecasts;

(4) HF ocean-radar that can identify tsunami current velocities and amplitudes in coastal areas (Lipa *et al.*, 2014); and

(5) Deep-water tsunameters that can provide positive detection of ‘MT’ once formed.

(iii) Available numerical modelling tools

(1) Regional-scale or global atmospheric models – to forecast general synoptic conditions.

(2) High-resolution atmospheric models – to forecast meteotsunamigenic atmospheric disturbances.

(3) High-resolution ocean models – to forecast long ocean waves and ‘MT’.

(iv) Communications

NMHSs with at-risk coastal areas should pay careful attention to communications status. This includes:

(1) Communications established between detection instruments and warning service support offices (internationally and nationally); and

(2) Regular testing of communications paths, and redundancies identified and conducted.

(v) Training and Awareness

The importance for training and awareness of warning authorities, disaster management and response authorities, and at-risk communities related to ‘MT’ risk factors cannot be overstated. This is an important consideration for servicing NMHSs and may also involve monitoring operational tsunami detection and forecasting networks and in some cases consulting with regional Tsunami Service Providers (particularly within the northeast Atlantic and Mediterranean Tsunami Warning System).

4.2 SPECIFIC CONSIDERATIONS FOR HIGH-RISK REGIONS

(i) Pre-event

(1) Check global and regional weather forecast products if there are synoptic-scale patterns (if any found in research) that are associated with 'MTs’ in a region (7 days in advance).

(2) Check if NWP operational models (deterministic or stochastic) are forecasting large (threshold-exceeding) probability for occurrence of meteotsunamigenic disturbances (2 days in advance).

(3) Check if related ocean models are forecasting ‘MT’ (2 days in advance).

(ii) Initial indicators:

(1) Check (in real-time) if intense air pressure or wind disturbance (threshold-exceeding in rate of change at weather or microbarograph stations) or extreme propagating mesoscale feature (seen on weather radar images) is propagating towards the endangered area (or off the coastline, like for the US and Canada east coasts); and Check if related ocean models are forecasting ‘MT’ (2 days in advance).

(2) Check if the speed and propagation direction are matching the predefined values for which 'MTs’ are known to occur in a region.

(iii) Alerting

(1) Based on the forecast of wave heights for regions vulnerable to ’MTs’, determine if wave heights match values in predefined NMHS criteria.

(2) Consider propagation of ‘MT’ independently of source weather disturbance (e.g. shelf reflection) to determine if additional alerts need to be issued outside of warned areas.

(iv) Monitoring and Cancellation

(1) Monitor weather station (microbarograph) data and weather radar images and recompute intensity, speed and direction of the meteotsunamigenic disturbance;

(2) Monitor available tide gauge data and endangered coastlines (e.g., through video surveillance) if ‘MT’ occurred, and quantify its intensity;

(3) In case of significant change in intensity, speed and propagation direction of the meteotsunamigenic disturbance, reassess the forecast and warning level, and re-alert authorities, civil protection authorities and population;

(4) In case of no or weak weather driven long waves observed 2 hours after the passage of the potentially meteotsunamigenic disturbance, warning to be cancelled; and

(5) In case of meteotsunamigenic disturbance propagating off the coastline toward a shelf break, or where the generation is known to generate ‘MT’ waves that hit the coastline with a time lag, the warning should be cancelled 1 hour after the expected arrival of these waves (e.g., 4 hours for the US East Coast).

5. ORGANIZATIONAL RELATIONSHIPS BETWEEN TSUNAMI SERVICE PROVIDERS, NATIONAL TSUNAMI WARNING CENTRES AND REGIONAL/NATIONAL HYDROMETEOROLOGICAL SERVICES

Since 'MT' are hazards driven by weather conditions, warning responsibility lies solely with the servicing NMHSs. However, since NWP-based 'MT' detection and forecast systems are imperfect, particularly as they do not normally provide direct tsunami detection and measurement, there are instances when monitoring tsunami-specific instruments such as deep ocean tsunameters and tsunami capable tide gauges can provide support to NMHSs. And while operational tsunami forecast and warning activities such as IOC-designated Tsunami Service Providers (TSPs) or National Tsunami Warning Centres (NTWCs) will play no role in real-time operational alerting, the Ad Hoc Team on MT does advise that NMHS' create working relationships with overlapping TSPs and/or NTWCs to become more familiar with monitoring tsunami-specific instrumentations.

6. SUMMARY

- While 'MTs' are known to occur along many coastlines, only infrequently do they pose a significant risk to life and property. This typically occurs in areas where transiting weather disturbances move over shallow-water regions at precise speed and strength values as to create relatively large, long-wave resonances (*e.g.* the Mediterranean Sea, Great Lakes, Yellow Sea, East China Sea, and some areas of the North and Baltic Sea).

- 'MTs' only form under a narrow range of parameters related to water depth and the translational speed of the source disturbance. This makes it possible to characterize the 'MT' risk for virtually any coastline in the world. Local understanding of the 'MT' threat posed to a given coastline is critical to ensuring the phenomena is addressed.

- Some guidance systems have been developed that rely heavily on identifying the meteorological parameters necessary for 'MT' development through NWP schemes. These systems have shown promise in providing advance notice on 'MT' development. However, since they are based on forecasted parameters and not actual 'MT' detection, false alarm rates are not insignificant.

- In some cases, tsunami-specific instrumentation can play a supporting role in terms of detection, though even in such rare cases, this will not typically be sufficient to fully characterize the wave field and support precise coastal impact forecasts. Nevertheless, there is value in creating relationships between NMHS' and TSPs/NTWCs to ensure these instruments are correctly monitored and utilized.

RECOMMENDATIONS

- **In consultation with the Joint WMO-IOC Collaboration Board (JCB), discuss use of the term 'meteotsunami'**, to understand its implications and ensure common vocabulary is agreed among UN agencies, recognizing the WMO's role as the authoritative voice on climate, water, and weather and noting that the agency does not presently recognize the term. Although the IOC/TOWS-WG awaits further guidance on this issue from the JCB, it is the consensus opinion of the Ad Hoc Team on Meteotsunami that the responsibility for issuing public alerts based on ‘MT’ threats be addressed wholly through NMHSs under WMO guidance.

- **Consider detection of ‘MT' in global tsunami instrumentation strategy**. Tsunami detection and measurement capabilities are rapidly improving, and this is expected to accelerate under the UN Ocean Decade. It is now possible to consider non-seismic tsunami sources in the global instrumentation strategy, including ‘MT’. Input from NMHS would be particularly useful as a new generation of tsunami detection and measurement networks are deployed.

- **Evaluate requirements and capabilities for improved early warnings and alerts.** Combining the direct tsunami detection capability of tsunami-specific instrumentation with the NWP-based algorithms tuned to ‘MT’ prediction may deliver significant advances in NMHS’ global MT forecast and warning capability. However, current operational global NWP models are not capable of resolving adequate pressure disturbances for ‘MT’ generation, nor could they be developed and operationally run within presently available resources.

In conclusion, this report serves as an initial investigation into the status of ‘MT’ observation, forecast, and warning capabilities. Limited by time and resource constraints, the ad hoc team acknowledges that this report is not a fully comprehensive review, however it is a starting point for further consideration.

ANNEX I

GLOSSARY OF TERMS

Intergovernmental Oceanographic Commission. Fourth Edition. Tsunami Glossary, 2019. Paris, UNESCO. IOC Technical Series, 85. (English, French, Spanish, Arabic, Chinese) (IOC/2008/TS/85 rev.4

Also available in Arabic, Chinese, French and Spanish

ANNEX II

LIST OF ACRONYMS

AEMET	Agencia Estatal de Meteorologia / (Spanish) State Meteorological Agency
DART	Deep ocean Assessment and Reporting of Tsunami
IOC	Intergovernmental Oceanographic Commission of UNESCO
IOT	2004 Indian Ocean Tsunami
JCB	Joint WMO-IOC Collaborative Board
JMA	Japan Meteorological Agency
MESSI	Meteotsunamis, destructive long ocean waves in the tsunami frequency band: from observations and simulations towards a warning system
MT	Meteotsunami
NMHS	National Meteorological and Hydrological Services
NTWC	National Tsunami Warning Centre
NWP	Numerical Weather Prediction
SOCIB	Balearic Islands Coastal Observing and Forecasting System
TOWS-WG	Tsunamis and Other Hazards related to Sea Level Warning and Mitigation Systems (IOC)
TSP	Tsunami Service Provider
UNESCO	United Nations Educational, Scientific and Cultural Organization
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

ANNEX III

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86	Pacific Tsunami Warning System (PTWS) Implementation Plan	*Electronic publication*

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121.	Exercise Indian Ocean Wave 14, an Indian Ocean wide Tsunami Warning and Communications Exercise, 9–10 September 2014	*In preparation*
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145	IOTWMS Users Guide for National Tsunami Warning Centres	(under preparation)
146	Definition of Services provided by the Tsunami Service Providers of the IOTWMS	E only
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