Draft Report by
IOC-UNESCO Ad Hoc Team on Meteotsunami
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Section 1: Introduction

Meteotsunamis (heretofore MT) form when a transitory weather disturbance moves over a body of water at roughly the depth-dependent tsunami phase velocity. This can create ocean resonance and a tsunami wave that becomes disconnected from the source disturbance and propagates according to the shallow water wave equations and Green's Law.

MT formation, propagation and impact is well cataloged and good background references can be found in Monserrat et al (2006), Pattiaratchi and Wijeratne (2015) and Rabinovich (2020).

The purpose of this report is to:

a) Review current global status and advise on gaps related to MT monitoring and warning systems.

b) Identify guidelines for Standard Operating Procedure (SOP) development to monitor and warn for MTs.

c) Review relationships and coordination required between Tsunami Service Providers/National Tsunami Warning Centers and Regional/National Meteorological Services activities to monitor and warn for MTs

Background

Global Meteotsunami Risk

Meteotsunamis can, and have, occurred over many ocean regions, inland seas, and lakes. In general, however, certain locations are much more prone to impactful MT than others. 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 40m/s (80knots), this limits the amount of ocean area susceptible to MT formation to shallower regions, such as coastal margins. The areas where MTs have been observed are depicted in Figure 1. An analysis is required to identify all areas where the prerequisite atmospheric and water depth conditions occur where. It should be noted that many MT tend to amplify already impactful weather phenomena, such as landfalling tropical cyclones, but in some cases the MT can become fully disconnected from the source disturbance. These cases are particularly dangerous since the MT impacts are not covered within broader meteorological alerts.

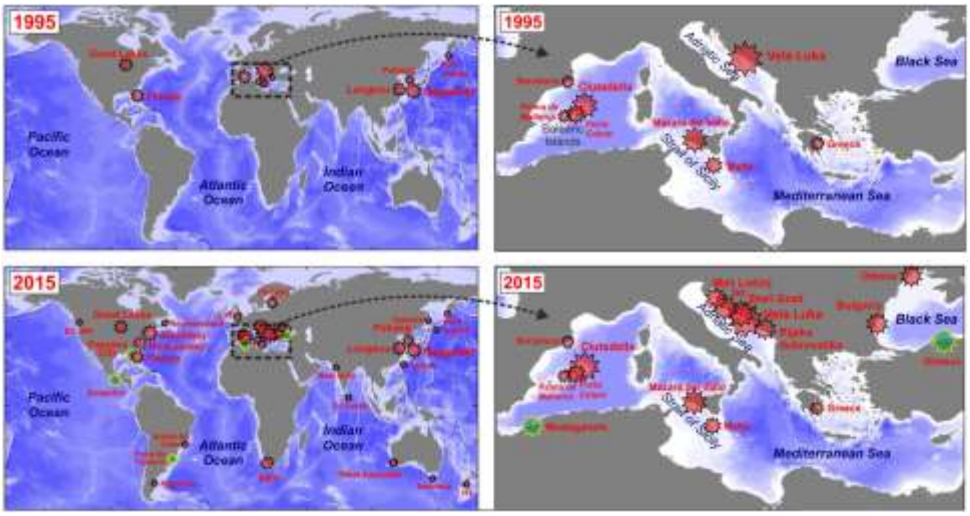


Figure 1. Locations where meteotsunamis had been documented by the year 1995 (upper panels) and by the year 2015 (lower panels). Size of stars is proportional to the intensity of the documented events (after Vilibić et al., 2016).

Current Alerting State

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

National Met Services currently provide public alerts related to MT through two primary means:

1. **Targeted approach**. In parts of the world where MT impacts are relatively common and known to be destructive (e.g., Mediterranean Sea, South Korean coastline, and some areas of the North and Baltic Sea coastlines), a meteorological based approach is generally used emphasizing Numerical Weather Prediction (NWP) techniques to identify conditions likely to generate MT. The Operational system in Croatia is an example of this approach. Once the threat is identified and impacts anticipated, alerts are disseminated through national meteorological services as coastal flood notifications.
2. **Generalized approach**. Alerts, or other forecast-related products that address meteotsunamis that occur outside the targeted areas—if they are addressed independent of the source weather disturbance—generally depend on broad, high-uncertainty advisory statements based on an anticipated alignment of characteristics conducive to MT formation. How, if, or by what nomenclature MT is addressed through National Met Services varies significantly between or even within individual national agencies. However, occasionally the Global Tsunami Warning System (GTWS) observing system can play a key role in confirming MT generation through either the deep-ocean tsunameter network, or coastal water-level instruments. It is this confluence of the GTWS and Met Services we will explore in the Generalized Approach. The GTWS is in no way "tuned" to the MT threat, rather it treats MT as within the general tsunami

class, albeit typically without corresponding cueing information. As such, there must be a determination made by the activity making the observation to either alert directly, or to inform National Met Services of the detection for their consideration as part of their alerting procedures (as typically occurs when an MT detection is made on the east coast of the US).

This report will strive to describe both of these approaches in terms of existing gaps, Standard Operating Procedure (SOP) guidelines, organizational relationships, as well as potential future capability gains and opportunities that possibly combine both approaches. The report is prepared based on the expertise of an ad-hoc group of Meteotsunami experts including Dr. Ivica Vilibic, Dr. Alexander Rabinovich, Dr. Sebastian Monserrat, Dr. J Sepic, Dr. Vasiliy Titov, Dr. Emile Okal, Dr. Mohammad Heidarzadeh and Dr. Charitha B. Pattiaratchi. The report is edited and submitted by Mr. Michael Angove (NOAA NWS) as the Chair of the IOC-UNESCO Ad Hoc Team on Meteotsunamis, which was established by the IOC-UNESCO Task Team on Tsunami Watch Operations (TT TWO) of the IOC-UNESCO Working Group on Tsunami and Other hazards related to sea level Warning and mitigations Systems (TOWS-WG) in February 2022.

<u>Section 2</u>: Current MT monitoring and warning systems and related gaps

1. Targeted (meteorological) approach

Background

This approach relies on predicting generation of meteotsunamigenic atmospheric disturbances that translate over potentially resonant depths, using different meteorological sensors, weather radar images and NWP tools. The primary goal of this sensing network is to capture rapid changes in air pressure and wind disturbances at minute 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 also from sequential weather radar images (Wertman et al., 2014), or through satellite top-cloud images (Strelec Mahović and Belušić, 2009). An example of such a network is the MESSI microbarograph network in the Adriatic Sea (Fig. 2).

Mesoscale NWP models capable of capturing meteotsunamigenic disturbances, such as the Weather Research and Forecasting (WRF) model (Skaramock et al., 2005), are currently being used operationally for this purpose in the Adriatic Sea (Adriatic Sea and Coast, AdriSC, Denamiel et al., 2019a), along the Balearic Islands coasts (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 AdriSC and BRIFS systems include ocean models at high resolutions (from 1 or 4 km using Regional Ocean Modelling System (ROMS, Shchepetkin and McWilliams, 2005, 2009), to ca. 10 meters in coastal regions using unstructured Advanced Circulation models (ADCIRC, Luettich et al., 1991) that are forced by NWP atmospheric models.

As deterministic models may fail in forecasting meteotsunamis, a stochastic surrogate approach has been implemented in the Croatian meteotsunami Early Warning System (EWS), based on essential meteotsunami variables (start location, direction, speed, period, amplitude, and width of the disturbance; Denamiel et al., 2019b) and polynomial chaos expansion algorithms. Such a system both improved reliability of the meteotsunami forecast and allowed for estimation of wave height probability exceedance at the sites of interest.

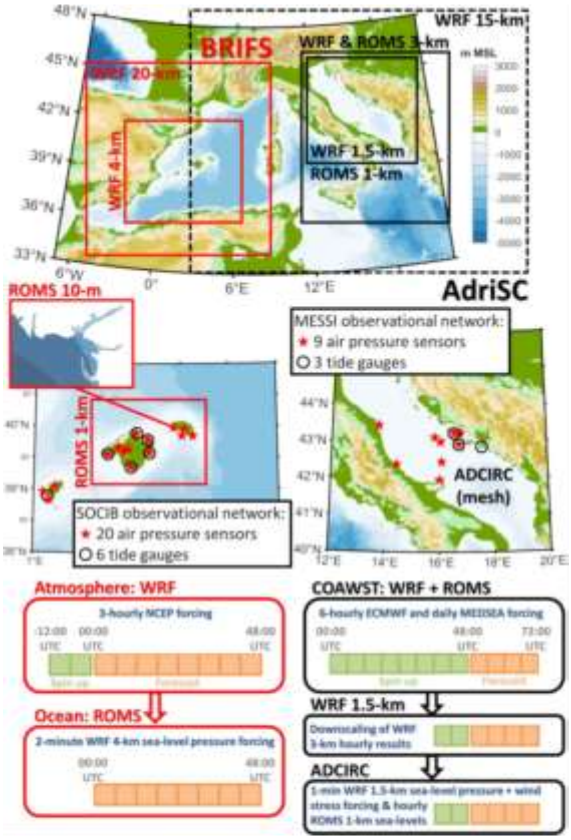


Fig. 2. Existing meteotsunami monitoring and forecasting systems in the Mediterranean Sea: BRIFS (in red) associated with the SOCIB observational network in the Balearic Islands and AdriSC forecast system (in black) associated with the MESSI observational network in the Adriatic Sea (after Vilibić et al., 2021).

a. Data needs

(i) Meteorological sensors. When considering data needs for an effective meteotsunami detection network, it should be noted that meteotsunamigenic disturbances have spatial resolution needs at the kilometre scale and temporal resolution needs at the minute scale. Standard recording intervals along national meteorological networks – that are 1 hour/10 minutes respectively – are therefore insufficient for proper quantification. Instead, temporal samplings should be carried with 1 minute or higher resolutions, being a prerequisite for detection of a disturbance and for estimation of its speed and disturbance. 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 meteotsunami "hot spot", i.e., the portion of coastline where meteotsunami waves are amplified the most and where meteotsunami risks are highest, towards the direction from which meteotsunamigenic disturbances are known to travel. The distance between the station network and meteotsunami 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 weather stations should compose the network, to allow proper estimation of the speed and direction of meteotsunamigenic feature's propagation.

(ii) Coastal water level measurements. There are many tide gauges with 1-minute or higher sampling 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 meteotsunamis, or tsunamis in general. Still, a great number of these stations are producing water level data of very low quality, insufficient for proper detection of meteotsunami waves (Zemunik et al., 2021). Thus, improvement of data quality at 1-minute resolution is a must for coastal tide gauge stations. Further, some tide gauge networks are still not providing the data with a minute resolution, like the UK tide gauge network, which has resolution of 15 minutes. Increasing reporting resolution of coastal tide gauges to 1 minute, especially in the vicinity of MT risk areas, should be of priority emphasis.

(iii) Bathymetry. Ocean models at high resolutions used in MT EWS' need good bathymetry data (e.g., having resolutions of ca. 100 m or higher), particularly in coastal regions and in regions where meteotsunamis may be destructive. In fact, inaccurate bathymetry may strongly underestimate or overestimate meteotsunami amplitude at endangered coasts, while 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) that can be up to 1 m in the most endangered areas. In the case of non-existence of such bathymetry data, a coarser bathymetry (e.g., having resolutions of ca. 1 km) may be used in EWS', provided that proper scaling of meteotsunami hazard at the coastline is achieved.

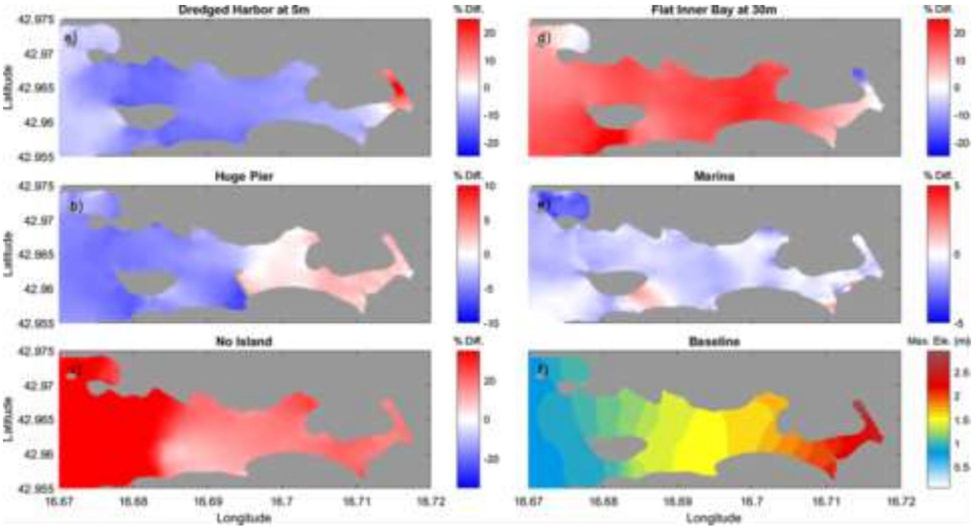


Fig. 3. Relative difference (in %) of spatial evolution in the maximum elevation of modified domains versus ''Baseline'' domain for the Vela Luka Bay, Croatia (after Denamiel et al., 2018).

b. NWP and synoptics

(i) Deterministic Approach. Currently, operational NWP systems are run worldwide, mostly by national weather services, at kilometre to several kilometres horizontal resolution. A variety of systems are in operations, from hydrostatic to nonhydrostatic models, coupled or not coupled with ocean models. For purposes of meteotsunami forecasting it is important to ensure the proper operational modeling system attributes are incorporated, including adequate quantification of mesoscale processes, representation of orography and appropriate parameterization schemes. Several NWP systems have been applied in an effort to reproduce meteotsunami events, and some common issues that may prevent their usage in MT EWS include: (i) Underestimation of intensity of meteotsunamigenic disturbances; (ii) Improper spatial positioning of meteotsunamigenic disturbances; and (iii) Inability to precisely reproduce speed and propagation direction of meteotsunamigenic disturbances. The problem here 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 is to increase the NWP resolution to 1 km or less, though this is computationally intensive over the areas needed.

(ii) Probabilistic Approach. There have been several attempts to improve results of NWP forecasts for meteotsunamis 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 for the purpose of forecasting meteotsunamigenic disturbances.

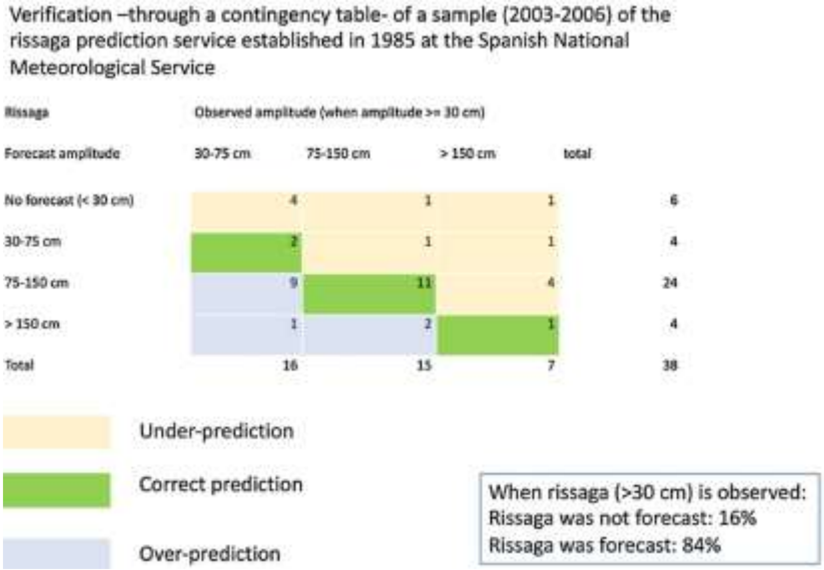
(iii) Qualitative Approach. In some regions it is possible to produce meteotsunami forecasts by simply assessing synoptic patterns that are known to eventually lead to meteotsunamis. Such an approach has been successfully applied in the Balearic Islands, where *rissaga* (local name for a meteotsunami) forecasts are provided a week in advance, being based on characteristic synoptic patterns held in most of the Mediterranean Sea (Jansà and Ramis, 2021). This may be an appealing technique in regions where real-time data is limited data and high-resolution numerical models are not available. A related approach could also be developed by assessing synoptic patterns and having them serve as an early warning system “trigger” that places an NWP system and supporting observations in an ‘event’ mode when deemed necessary, to save computational effort.

c. Limitations and Gaps of MT EWS

Meteotsunami early warning systems, including these developed as demonstrations and not implemented operationally by a service, have several shortcomings related to the challenges described above. The most important is the ability to accurately reproduce real meteotsunami events, and – if successful – their proper quantification in terms of intensity and spatial outreach. For the Balearic early warning meteotsunami system, observed meteotsunamis were not forecasted for about 16 % of cases between 2003 and 2006, of which one event was an exceptionally strong event (Fig. 4; Jansà and Ramis, 2021). Further, only 38 % of all meteotsunami events were forecasted with proper intensity. For the deterministic part of the Croatian meteotsunami early warning system, goodness-of-fit for the researched meteotsunami events shows an underestimation of the forecasted meteotsunamigenic disturbances and ocean waves between 2014 and 2018 by 65 % and 13.5 %, respectively, while completely missing the events in 2020 due to an unexpected shift in the meteotsunamigenic disturbance's trajectory (Tojčić et al., 2021). Conversely, the warning system based on surrogate stochastic approach was successful at reproducing almost all of observed meteotsunami events, but was found to create false alarms at a relatively high rate.

Another problem, noted for example when testing the Korean meteotsunami early warning 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). 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, like off the endangered sites in Croatia, the cost of such observations may overcome the cost of the projected early warning system benefit. Usage of school or amateur networks may be a solution for some endangered coastlines (Rabinovich et al., 2021), as reaching a considerable density in some regions – if not, a precise microbarograph with possibility to measure propagation of atmospheric disturbances should be put in place (Monserrat et al., 1991).

Finally, and perhaps most importantly, raising awareness of at-risk locations and providing alarms to the civil protection agencies and local authorities is a critical step which is, to our knowledge, so far only implemented in the Balearic Islands. Indeed, AEMET (Agencia Estatal de Meteorología) agency is the sole agency providing qualitative rissaga forecasts to the public since 1985 (Jansà and Ramis, 2021). IOC Member States with MT risk are encouraged to consider pilot efforts leading to greater awareness of the threat within their respective operational meteotsunami services.



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%

Fig. 4. Verification of meteotsunami forecast issued by the AEMET experimental rissaga prediction service between 2003 and 2006 (after Jansà and Ramis, 2021).

2. Generalized (Tsunami-based) approach

Background

As mentioned in the outset, MTs generally fall under the scope of National Met Services for alerting purposes, though the term meteotsunami is rarely used as previously noted.. But in many cases, the GTWS can be leveraged to support Met Services by providing direct confirmation of MT generation. This is particularly important outside of localized regions described in the previous section, where MT formation can be predicted based on well understood, repeatable patterns with meteorological sensor cueing. Otherwise, MT detection relies on broader global and national tsunami detection and measurement networks. Detection means can include the global tsunameter network (e.g Deep Ocean Assessment and Reporting of Tsunami (DART)), coastal water-level gauges, or other detection means such as orbital velocities measured by coastal HF radar. It is particularly important that coastal states with a known MT risk, but without targeted MT forecast and warning systems, understand how to leverage the broader tsunami detection networks, including identifying critical coverage gaps, to provide advance warning.

The generalized tsunami detection-based approach can additionally be useful for regions where targeted MT forecasts are available, as a means of reducing false alarms. Since the generalized warning approach is based on actual meteotsunami instrumental detection, the rate of missed events would obviously be lower than any method that would rely strictly on a meteorological-based forecast of the MT event. The generalized approach, on the other hand, has many unique challenges and gaps that may hinder the ability to provide the consistent, reliable MT detection and measurement data Met services offices require. This immediately implies that the combination of the targeted meteotsunami warning, and the generalized tsunami approach may produce a warning system that would be superior to the existing systems, at least in case of the meteotsunami warning and forecast (we address this in more detail in the “Future goals” section).

The generalized tsunami warning and forecast system has only recently become a relevant tsunami warning strategy for tsunamis such as MT, as ample amounts of real-time direct tsunami observations have become available in certain areas of the world. This can be traced to the 2004 Indian Ocean Tsunami (IOT), with the rapid expansion of the deep-ocean tsunami detection capabilities (including DARTs 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 & Titov, 2016). Where available, direct tsunami detection and measurements have become a primary data source to confirm tsunami warnings and provide the most reliable data to produce the tsunami forecast.

Where these improved tsunami detection and measurement capabilities exist, they can now provide opportunities to assess events and issue warnings for not only the earthquake-generated tsunamis, but for tsunamis from other sources including MT. There are, however, several challenges that need to be overcome to implement the generalized tsunami warning approach into effective operational warning capability.

The following specifics of the MT phenomena have to recognized and addressed in the generalized approach to support a useful warning capability:

- MTs are usually localized phenomena impacting a small portion of a coastline, often just one location (a beach or a port). Only in rare cases, the MT can become a regional threat. MT, as we define them in this report, is never a global threat.
- The details of the source of the MT are rarely known in real-time. Outside of the areas supported by MT EWS, only very general descriptions of weather systems that generate MT are usually known in real-time, without specifics of the propagation speeds or details of

atmospheric pressure distribution.

- Tsunami models can, in general, reproduce the MT propagation, however the source of the waves has to be specified in a drastically different manner from the earthquake-generated tsunamis. Therefore, the model forecast capabilities need to be re-developed using different data streams for model source definition.
- Enhanced tsunami observations are not available everywhere and are currently focused on optimal positioning for earthquake generated tsunamis. Further enhancements may be required in meteotsunami source zones.

To address those MT-specific features, the generalized approach requires several improvements in data streams and analysis tools to move from the ad-hoc advisory capability with uncertain goals to a reliable operation warning system with established SOPs.

a. Data needs

The general tsunami measurement data that are used currently in Tsunami Warning Systems can be readily applied to detect MT. However, to fully extend the tsunami warning capabilities to address the MT threat, the data streams need special consideration to account for the MT specifics. In particular, the mostly local nature of the MT threat puts additional requirements on the density of the measurement systems. This, however, would be a similar requirement for addressing the problem of the near-source tsunami threat for the earthquake-generated tsunamis. Therefore, improvement in the density of the tsunami detection can improve the general tsunami warning, not only the MT-specific capabilities.

(i) Deep ocean pressure. Deep-ocean bottom pressure gages (BPRs) have proven to be robust detectors of meteotsunamis. Many confirmed known events have been detected by just a single DART 44402 off the U.S. East coast. There are many more unknown, most probably MT events, that have been observed in the records of the same DART 44402 over the years (NCTR, 2013). The cable systems with BPRs have recorded meteotsunamis with unprecedented density of observations (Kubota et al., 2021). The BPRs record not only the water level changes, but the combination of the atmospheric change and the water level response (tsunami amplitudes). This makes the BPR measurements well suited for meteotsunami detection, since they record the MT along with the atmospheric forcing that generates them.

(ii) Coastal sea-level stations. Coastal sea-level stations have proven to be a reliable means of detecting MT events. The coastal gauges that are part of tsunami warning operations are usually refurbished to provide real-time data with improved time frequency to resolve tsunami periods. In addition, many coastal sea-level gauges have atmospheric pressure measurements co-located at the same site, often with the barometer data available in real-time (however, caution must be taken as often the coastal sea level gauges may not be in the best position (e.g., on protected wharves and behind ships) to monitor atmospheric conditions for Met services forecasting). In some cases, the coastal sea-level gauges provide not only the detection of the MT event that has already reached the coastline, but the data for early warning of the MT event that would follow (Titov and Moore, 2021). Therefore, the existing tsunami coastal sea-level network is readily available for the MT event detection and analysis.

(iii) Sea surface (e.g., radar, satellite). Sea surface observation with high-frequency (HF) radar is an emerging technology that can be used for event detection. The advantage of the HF radar is extended coverage of the large portion of a coastline. The capability can be developed that uses HF data with pattern-recognition tools for MT detection, especially in combination with other detection systems. Satellite-based detection of MT could provide even wider coverage theoretically. However, documented satellite-based tsunami detections have been so far limited to large-amplitude global tsunamis, the tsunami subclass which most MTs events would not belong to. Polar-orbiting satellite altimeters measuring sea surface heights may also not be positioned above the meteotsunami at the time of generation and propagation. Often the data requires post-analysis and is not available in real-time for warning.

(iv) Bathymetry. Bathymetry data requirements for modern Tsunami Warning System forecasts are similar (or higher) to the need of the meteorological approach described in section 2.1.b.iii. Therefore, excising bathymetry data for tsunami analysis tools could be used for MT analysis as is. However, the required higher-resolution data is not available in many locations.

(v) Meteorological sensor observations (precursor). Meteorological observations are not normally a part of the standard data stream of the Tsunami Warning Systems. While the data is normally available from the servicing meteorological services offices, communication channels would need to be established and data analysis tools developed for meteorological data to be analyzed at existing Tsunami Warning Centers (TWC). In lieu of real-time ingest and analysis of meteorological data at TWCs, it may be more important to establish relationships between met services offices and TWCs that would allow for direct communication between met offices and TWCs if a potentially meteotsunamigenic event is considered likely.

b. MT Analysis.

Analysis and forecast capabilities of existing TWSs can potentially be used for MT event analysis, forecast and especially the development and issuing of warnings. Several research efforts showed the potential for using tsunami data and models to provide MT event analysis (NCTR, 2013; Titov & Moore, 2021). However, implementation of such tools as an operational capability would require additional research transition efforts. Similar to the section above, establishing an analytic relationship between national TWCs and Met Services offices is likely the most effective way to address MT analysis capability gaps, at least in the near future.

c. Key gaps and limitations

(i) Data density

Possibly the main limitation of the generalized approach to MT warning using existing tsunami capability is data density. Since the MT event is often detected without definite source determination and the source is dynamic, it requires many detections to determine at least the directionality of the MT disturbance propagation. This is in contrast with earthquake-generated tsunamis, where the source can normally be estimated before the wave is detected at sea-level gauges. In the case of a known source location, the analysis of the impact can be done with limited direct tsunami observations. The MT event without a prior source detection would require detections at several sea-level gages to make even initial analysis of the event for forecast and warning.

Increased sea-level gauge density would address, at least partially, another limitation of the general tsunami detection-based approach – the timing of the warning and forecast. The meteorological approach has potential advantage of earlier warning based on advance detection of the meteorological event that would cause the MT, even before MT is generated. While this may lead to high false alarm rate, it does provide more time for warning. The generalized tsunami-detection based warning for MT would have lower false alarm rate, but in general would have less reaction time. A strategic increased density of the tsunami sensors can improve the timing performance of the generalized approach.

There are examples of very high-density tsunami sensor networks that have been used for MT analysis (Kubota et al., 2021). The S-net cable BPR network offshore Japan provides impressive data coverage that can be used for generalized tsunami warning approach regardless of the tsunami sources.

(ii) Correlation

A major challenge when using the traditional tsunami detection network for MT purposes is determining correlation. The global tsunami warning network is designed largely to match observations with seismic sources, but with MT, there is no correlation with seismic source estimates. It is therefore important to have an understanding of current weather phenomena, and its potential to generate MT before detections are made. In this way qualitative correlations can be made to assist in validating MT formation.

(iii) Training and awareness

The need 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 responsibility may typically fall to meteorological services offices, but may involve interactions with NTWCs, or in some cases TSPs. MT awareness training should be a regular activity in cases where there is (1) verified MT risk and (2) a dedicated MT EWS is not established.

Section 3: Standard Operating Procedure Guidance

a. General procedures include:

(i) Understanding risk. Member States prone to MT impact should conduct detailed hazard and risk assessments to include: (1) Identify areas prone to MT development); (2) Identify types of weather disturbances that can create MT in the risk-prone areas, and what the seasonal variation is; (3) Determine the range of impact that can be expected from MT, particularly if this an evacuation hazard or a more limited, but still dangerous marine impact; and (4) Identify and exercise the primary mitigation measures available to address these risks.

(ii) Available Detection networks: Identify instruments available that can detect MT within area of responsibility including: (1) Meteorological sensors that can identify precursor disturbances; (2) Tsunameters that can provide positive detection of MT once formed; (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 radar that can identify tsunami current velocities and amplitudes in coastal areas (Lipa et al., 2014).

(iii) Triggering considerations. Ensure tsunami detection instruments are tuned to alarm or trigger upon detecting tsunamis. Some guidelines include:

1. Tsunameters trigger on >3cm detection in deep water
2. Coastal gauges trigger upon tsunami detection
3. Coastal radars (if available) trigger upon tsunami detection

(iv) Communications. Member States with at-risk coastal areas should pay careful attention to communications status. This includes ensure: (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

b. Specific considerations for Targeted approach:

(i) Pre-event: Check global and regional weather forecast products if there are synoptic-scale patterns (if any found in research) that are associated with meteotsunamis in a region (7 days in advance). Check if NWP operational models (deterministic or stochastic) are forecasting large (threshold-exceeding) probability for occurrence of meteotsunamigenic disturbances (2 days in advance).

(ii) Initial indicators: (i) 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 East Coast); and (ii) Check if the speed and propagation direction are matching the predefined values for which meteotsunamis are known to occur in a region (meteotsunami warning matrix).

(iii) Alerting: Based on the forecast of meteotsunami wave heights for endangered regions, determine if wave heights matching values in a predefined meteotsunami warning matrix.

(iv) Monitoring and Cancellation: (i) Constantly monitor weather station (microbarograph) data and weather radar images and recompute intensity, speed and direction of the meteotsunamigenic disturbance; (ii) Monitor available tide gauge data and endangered coastlines (e.g., through video surveillance) if meteotsunami occurred, and quantify its intensity; (iii) In case of significant change in intensity, speed and propagation direction of the meteotsunamigenic disturbance, reassess the meteotsunami forecast and warning level, and re-alert authorities, civil protection authorities and population; (iv) In case of no or weak meteotsunami observed 2 hours after the passage of the potentially meteotsunamigenic disturbance, warning to be cancelled; (v) In case of meteotsunamigenic disturbance propagating off the coastline toward a shelf break, or where the generation is known to generate meteotsunami waves that hit the coastline with a time lag, the warning should be canceled 1 hour after the expected arrival of these waves (e.g., 4 hours for the US East Coast).

c. Specifics for Generalized approach.

(i) Pre-event: Understand seasonal risk; review and broadly monitor likely MT generation areas; ensure detection networks are functional and tested.

(ii) Initial indicators: Typically, initial indicators of MT using the generalized approach will be positive detections of a possible MT on either a coastal water-level or deep ocean instrument. This detection will normally be made by a Tsunami Service Provider or NTWC.

(iii) Initial actions; Upon positive detection, efforts should be made to correlate the reading with a potential source and what type of source. This is where some awareness of the general meteorological conditions is helpful to TSP/NTWCs. If a likely source correlation can be made, TSP/NTWC should immediately open dialogue with national met services and notify them of the detection and potential source correlations. If a correlation with a transiting weather disturbance or phenomena cannot be made, TSP/NTWCs should investigate other causes.

(iv) Alerting: For either the targeted, or generalized approaches described in this report, it must be determined which authorities nationally have responsibility for issuing the warnings/alerts of meteotsunamis. In the case of the generalized approach, when general MT favorable conditions are anticipated by met services, TSP/NTWC operations should be notified for heightened awareness. If a positive MT detection is subsequently made, the NTWC/TSP will normally provide initial MT detection to the warning authority. Correlation tables should be developed and available to met services office to help estimate risk. Once in receipt of this information, thewarning authority will make a determination of the risk and the level of alert to be issued. In the US, this includes a wide range of potential alerting products ranging from awareness statements to coastal flood alerts depending on perceived severity. Warning authority must also pay particular attention to the relationship between the MT and the source disturbance. If these phenomena are significantly disconnected, there is more urgency to the MT alert than if their impacts are observed as combined.

(v) Monitoring and Cancellation: Once an MT alert is established by the responsible warning authority, communications between Met Services and warning authority must remain open. The TSP/NTWC will have access to coastal tsunami gauge data and provide on any observed tsunami-related water level changes. Warning authority should rely on TSP/NTWC to determine when the event has passed and alerts can be safely taken down.

Section 4: Organizational relationships and other considerations between TSPs/NTWCs and Regional/National Met Services to monitor and warn for MT.

General. Successful public alerting related to MT requires considering a wide spectrum of ocean and meteorological capability, and requires significant coordination between governing and national bodies. For regions where MT is a targeted hazard, meteorological services may play the primary role but in areas where the threat is more generalized, there must be coordination between tsunami services and meteorological services. Tsunami detection systems that can support that generalized MT approach typically fall under either NTWCs (domestically) and the IOC (internationally). These relationships can be complex and should be well understood by individual UN Member States and international bodies. Some generalized roles and responsibilities of the different supporting components based on either the targeted or generalized approach are suggested here as follows and for further discussion by the relevant bodies:

a. Targeted approach

The UN mandate for tsunami warning and the coordination of all related activities lies with the IOC. However different types of tsunami warning products are provided through met services and should be coordinated and standardized where possible. Community education for all types of tsunami warnings should be integrated. In Member States where meteorological based MT detection and warning is possible, the resultant warning products should be coordinated with the Global Tsunami Warning System. When issuing MT warnings to the public, it should be considered whether they are prepared by the Met Service, but issued along with all other tsunamis warnings via the NTWC (which in many cases is NTWC in any respect), rather than as a different type of warning for MT types of tsunami. The Ad Hoc Team recommends as a minimum:

Commented [1]: I think this needs to be discussed at a higher level first.

1. Training exercises jointly facilitated by IOC and WMO
2. Summary of MT impacts tabled at TOWS-WG
3. Seasonal awareness campaigns facilitated jointly by IOC/WMO

b. Generalized approach

The generalized approach can be supported by detections made within the Global Tsunami Warning System operating under the IOC, since this system is capable of observing anomalies in the global tsunami detection network for many areas (but may need expanding to also meteotsunamis). What is critical to recognize, however, is that there may not always be meteorological expertise resident within National Tsunami Warning Centers, or IOC Tsunami Service Providers. Therefore, strong relationships between TSPs/NTWCs and Met Services Offices should exist where required and be regularly exercised. At a minimum the Ad Hoc Team suggests:

1. Annual training exercises between NTWCs and Met Services offices to review MT risks, detection networks and alerting protocols
2. Regular review and cataloging of events and tabling at TOWS-WG
3. Wide area awareness and education campaigns as part of IOC Tsunami Ready and related initiatives

Section 5: Future Goal: Unified approach

A significant finding of this report is that immediate improvement of the existing MT warning capability can likely be achieved by unifying the generalized and targeted approach for the meteotsunami warning. The implementation and organizational difficulties of unifying the approaches may be substantial, however. Some initial steps in unifying the systems are described in previous sections. A **fully** unified capability would be functioning as one operation, and not as two separate but coordinated systems. Noting the IOC has the UN mandate for tsunami warning services and the WMO for meteorological services, it needs to be discussed if such a system should fall under the Global Tsunami Warning System that would provide warning for any tsunami regardless of the source, or be undertaken within Met services with support from the GTWS, or be some other combination of services.

The two approaches to MT warning and forecast exist today at different regions of the world and function mostly independently, as described above. The targeted approach is used in several locations addressing specific MT environments that may not be applicable to other locations. The generalized approach covers many more coastlines in the world, but may not be as effective as the targeted approach in terms of specific alerting.

The advantage of the unified MT warning system would be in addressing the main limitations of both described approaches. The main problem of the targeted meteorological approach is the relatively high false alarm rate or over-prediction, since the forecast and warning are based on indirect meteorological data with large uncertainties, but it provides substantial lead time for the forecast. The problem of the generalized approach is the very limited time for the warning and forecast about the MT event that has already been detected (hence, no false alarms). The conceptual unified approach would use the meteorological data to provide an initial forecast and would constantly improve the accuracy of the forecast using direct MT observations. This unified system would provide significant lead time, low false alarm rate and improved accuracy. The unified approach would also leverage substantial development, data, and warning dissemination capability of the Global Tsunami Warning System. The unified approach is not a strictly notional concept, as there have been several studies that looked at potential for MT forecast and warning using both meteorological and tsunami data (see for example Titov & Moore, 2021). The initial coordination steps between Met Services and Tsunami Warning System may be the first steps toward such a unified system that could potentially include all other sources of tsunamis under one umbrella.

Section 6: Summary and Recommendations.

Key Takeaways:

- Meteotsunami (MT) occurrence is common along virtually many coastlines. Only infrequently does MT pose a significant risk to life and property and this is typically in areas with particularly strong MT forcing characteristics, such as the Balearic Islands region of the Mediterranean Sea. In several of these cases, specific MT Early Warning Systems have been developed that rely heavily on identifying the meteorological parameters necessary for MT development through NWP schemes. These systems have proven effective in providing hours-to-days advance warning on MT development, but since they are based on forecasted parameters and not actual MT detection, false alarm rates are not insignificant. A number of approaches are being investigated in order to reduce the false alarm rate, and more investigation is required in this area.

- Outside of dedicated MT EWS, all other meteotsunamis are generally addressed within the SOPs of National meteorological services. Procedures and understanding are inconsistent, however, and this approach will not always address less frequent occurrences. In some cases, the Global Tsunami Warning System can play a supporting role in terms of making direct tsunami detection, though even when a tsunami is detected by the network, this will not typically be sufficient to fully characterize the tsunami wave field and support precise coastal impact forecasts. Still, there should be coordination between meteorological services offices and NTWCs to ensure rapid transfer of critical information.

- A future unified system in which a combination of direct tsunami detection from the ever-expanding global tsunami sensing network and NWP-based hydrodynamic MT forecasts is considered worthwhile. Even in areas where well established MT EWS exist, direct MT measurement using tsunami detection instruments would both improve hydrodynamic forecasts as well as reduce false alarms. Outside of MT EWS, the unified system would be equally beneficial in providing Met Services offices with guidance on when to monitor GTWS instruments based on MT cueing algorithms.

- MT 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 thoroughly 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 through tsunami warning services.

Follow-on recommendations—Meteotsunami

1. **Joint WMO/IOC coordination on MT alerting**. This report initially sought to look at MT from the perspective of global tsunami services. But it was discovered, responsibility for issuing public alerts related to MT currently is typically addressed by national or regional Met services offices, but usually in the context of storm surge or anomalous coastal flooding events. It has become clear that a comprehensive dialogue between the IOC and WMO is necessary to ensure full exchange of information in support of a robust international alerting system for meteotsunamis. It is the ad-hoc MT team's recommendation that this report be used as a starting point of those discussion
2. **MT consideration in GTWS 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 volcanoes and MT, among others. Input from national and regional met services offices would be particularly useful as the GTWS considers a new generation of tsunami detection and measurement networks
3. **Establish Framework for a Unified MT Global System.** Combining the direct tsunami detection capability of the GTWS with the NWP-based algorithms tuned to MT prediction could deliver significant advances in global capability at minimal cost. It is recommended that a task team made up of experts from both GTWS and NWP communities be formed with the expressed intent of outlining the potential construction of such a system.
4. **Ad-hoc team on MT continue through 2023**, including WMO representatives for the purpose of recommending a global altering strategy to include specific roles of met services and TSP/NTWCs. It is recommended that the ad-hoc team conduct a global MT hazard assessment, providing to all MS an expert document of the existence of MT risks on their coasts.

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