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Meteotsunamis at global scale: problems of event identification, parameterization and cataloguing

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Abstract
Meteorological tsunamis (meteotsunamis) are defined as anomalous long-period (2 to 120 min) sea-level oscillations resulting from atmospheric forcing. In the current version of the Global Historical Tsunami Database covering almost 4000 years and including about 2500 tsunamis and tsunami-like events, meteotsunamis constitute a very small fraction of all events (4.1%). In the twenty-first century, when digital instruments for sea-level recording became widely available, identified meteotsunamis still only constitute 5.8% of all catalogued tsunami events. At the same time, there are many regions (Great Lakes, northeastern Gulf of Mexico, US East coast, southern Britain, Balearic Islands, Adriatic Sea, Yellow Sea, south-west coast of Japan, south-east coast of Brazil), where meteotsunamis dominate over all the other types of tsunamigenic events. Cataloguing of meteotsunami events, as reported in mass media, and described in scientific publications, faces the problems of their correct parameterization within the adopted format of the tsunami database. This format was developed in the late 1980s primarily for parameterization of seismogenic tsunamis, which at that time constituted more than 90% of the database's content. As a result, most of the meteotsunamis included in the database lack some basic parameters, such as time of origin, location of source as well as run-up heights. The present paper addresses these issues and discusses the ways for their possible resolution. Several well-known cases of recent meteotsunamis are considered from the standpoint of their parameterization and hazard assessment.

Keywords Tsunami · Meteotsunamis · Seiches · Storm surges · Rogue waves · Historical catalogs · Parameterization · Databases · Data formats

1 Introduction

Among the numerous definitions of meteotsunamis given in recent research and review papers, the best, probably, is the shortest: "Meteotsunamis are atmospherically-induced destructive long ocean waves in the tsunami frequency band" (Vilibić et al. 2020). Despite

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its brevity, this definition correctly points out the three main features of meteotsunamis: a frequency band that coincides with that of ordinary (tectonic) tsunamis, their destructive potential, and their relation to atmospheric forcing. However, there is yet another important characteristic of meteotsunamis that is omitted by this definition, namely the resonance nature of their generation process which profoundly distinguishes meteotsunamis from other types of tsunamis (seismogenic, volcanic, landslide-generated). A meteotsunami is an anomalous sea-level phenomenon that occurs at some coastal locations under specific weather conditions, when relatively small initial sea-level perturbations, of order of a few centimeters, can be significantly amplified through a chain of multi-resonant phenomena (Proudman resonance Greenspan resonance; coastal shoaling; resonant harbor response), which can act independently or sequentially to create destructive impact at the coast (Monserrat et al. 2006). Thus, taking into consideration this important feature of meteotsunamis, an improved definition might be: “Meteotsunamis are hazardous atmospherically-induced multi-resonant ocean waves in the tsunami frequency band”.

The atmospheric phenomena that are usually suggested as potential generators of meteotsunamis are moving pressure disturbances such as squall lines, thunderstorms, frontal passages, atmospheric gravity waves, mesoscale convective storms, rain bands in tropical cyclones, passages of typhoons and hurricanes, derechos, CISK-waves (Convective Instability of Second Kind), tide-generated internal waves, atmospheric shock waves from volcanic explosions and other atmospheric instabilities (Vilibić et al. 2020).

In some areas, meteotsunamis have been known for such a long time that they have been given their own local names which are widely used in scientific literature. In these areas, called as meteotsunami “hot spots” (Šepić and Rabinovich 2014), they are very common phenomena that occur regularly due to the quasi-cyclical characteristics of their forcing mechanisms. For instance, in Ciutadella, the Balearic Islands, meteotsunamis with amplitudes higher than 0.2 m occur every summer, higher than 0.5 m once in 5–6 years and higher than 3–4 m once every 15–20 years (Rabinovich 2009). Other well-known areas of regular meteotsunami occurrences are the Adriatic coast of Croatia (Orlić 2015), the Nagasaki Harbor in Japan (Akamatsu 1982), the Pusan Harbor in South Korea (Cho et al. 2013), and the south-east coast of Brazil (Candella and Araujo 2020).

Seismogenic tsunamis, especially the largest ones known as trans-oceanic mega-tsunamis that are generated by magnitude ≥ 9 subduction earthquakes, are notorious for their ability to propagate over large distances (Gusiakov 2014). They can reach the opposite coast of an oceanic basin and cause extensive damage, in some exceptional cases like the 2004 Indian Ocean tsunami propagating into other oceanic basins (Thomson et al. 2007). In contrast, meteotsunamis are almost exclusively a local phenomenon. Even in cases, when they are observed over a large region (for example, along the entire US Atlantic coast or throughout the Mediterranean basin), their manifestation is always local, meaning that they make their impact within a particular bay or harbor or along a limited part of a beach and never propagate far outside of their area of origin. A single meteorological event can generate many meteotsunamis along the extended part of a coast, as the atmospheric disturbance propagates over the coastal area; however, at each location, the local manifestation is determined entirely by the local resonance characteristics which, in turn, are defined by topography and local bathymetry.

Normally, meteotsunamis are not so catastrophic events as major seismogenic tsunamis, but they can cause large-scale damage to boats and harbors and, in some cases, can be fatal. Also they may occur much more frequently than tectonic tsunamis, since the atmospheric disturbances responsible for their generation are more common than large earthquakes or volcanic eruptions. However, even in the well-known “hot spots”, destructive meteotsunamis occur under very specific combinations of resonant effects. The rarity of such combinations is perhaps the main reason why destructive meteotsunamis are exceptional events even in these locations (Pattiaratchi and Wijeratne 2015).

Even small amplitude meteotsunamis (smaller than the swell waves co-existing in the same water area), in some specific situations, can be dangerous and potentially lead to damage. Goring (2009) describes a case that occurred in July 2003 at Marsden Point, New Zealand where a fully laden oil tanker navigating to its berth at an oil refinery was grounded due to the unexpected occurrence of long waves of just 0.3 m in height. As a result of this incident, a long-wave nowcasting system has been implemented at Marsden Point and procedures for calculation of under-keel clearance have been elaborated. As Goring stresses, these waves present an insidious threat to navigation because they often occur in balmy weather with low swell.

2 Classification of meteotsunamis

Recently A. Rabinovich has proposed dividing meteorological tsunamis into two major groups: "*good-weather*" and "*bad-weather*" events (Rabinovich 2020). The former are normally generated by small-scale atmospheric disturbances (squall lines, gust fronts, propagating atmospheric gravity waves, etc.) and associated generally with good weather conditions, while the latter are generated by large-scale atmospheric disturbances (severe storms, deep tropical cyclones, hurricanes and typhoons) and are associated with stormy conditions (Heidarzadeh and Rabinovich 2020). This phenomenological classification, being useful for discrimination of weather conditions typical for meteotsunami occurrence, can hardly serve as the basis for their global cataloguing, because the generation mechanisms of both types of meteotsunamis (combination of several types of resonance) are similar. Also, as there are too many types of weather conditions, the assignment to one of these two classes may not always be clear, especially for historical events with limited descriptive data.

Rabinovich (2020) also proposed dividing meteotsunamis into two other groups such as "*harbor oscillations*" and "*solitary waves.*" This classification actually divides meteotsunamis by the morphological types of their areas of occurrence. Harbor oscillations are common for meteotsunami "hot spots," most of which are long narrowing bays with favourable orientations relative to dominating weather systems, where harbor resonance is the leading factor. The solitary waves typically occur at the long open beaches where their predominant generation mechanism is the Greenspan resonance at extended shelf. Again, while possibly being useful, this classification can hardly be applied to event parameterization within a comprehensive historical database, since on a global scale, meteotsunamis can occur in very different locations and many of them cannot be clearly associated with just two types of coast.

3 Meteotsunami cataloguing

The wide research interest in meteotsunamis has increased over the past 2–3 decades after several cases of destructive waves such as the 1978 Vela Luka (Croatia) meteotsunami and the 1992 Daytona Beach (Florida, USA) event which become widely known publicly and pushed the scientific interest in their investigation. The close attention to the problem of tsunamis of meteorological origin revealed a high prevalence of this phenomenon in many areas known now as meteotsunami “hot spots”. However, their global cataloguing is still at an unacceptably low level. The early period of tsunami cataloguing (before 1980s) was characterized by an incidental occurrence of information about meteotsunamis in the general tsunami catalogs. The catalog compilers, collecting information about unusual sea-level rises, made notes such as “possibly meteorological origin” or “unknown origin” for cases when such waves could not be associated with any identifiable tectonic source. Such events can be found in large numbers in the tsunami catalogs published in the 1960s and 1970s. In the catalog of Japanese tsunamis (Iida 1984) covering the period from 684 to 1984, for the first one thousand years (684–1684) there are 13 entries marked as having *M* (meteorological) or *U* (unknown) origin. In the summary of historical tsunamis in the northeastern South China Sea (Lau et al. 2010) there are 5 damaging tsunami-like events from 1076 AD to 1782 that were associated in chronicles with bad weather conditions. The tsunami catalog for the Mediterranean region (Soloviev et al. 2000) lists 14 events of non-seismic origin that occurred in the region from 2000 BC to 1900.

A systematic search for meteotsunami traces in the available sea-level records reveals their permanent presence along many parts of the oceanic coast. Dusek et al. (2019) carried out such a study using the records of 125 tide gauges along the US East coast from 1996 to 2017. A total of 548 meteotsunami events were detected, giving an average of about 25 events per year. The majority of these events (73%) were relatively small, under 0.30 m in height. There were 30 instances when a gauge measured a wave height exceeding 0.60 m, with three of them exceeding 1 m. The authors note that the largest meteotsunamis tend to occur in places where frequent meteorological events have been observed. Along the US East coast, these are Atlantic City, Cape Hatteras, Providence, and Port Canaveral. The largest meteotsunamis recorded over the 22-yr data record include a 1.04-m event at Providence during a winter storm on December 9, 2005 and a 1.19-m event at Port Canaveral on June 19, 1996. They further note that there are clear seasonal (summer and winter) peaks in meteotsunami occurrence (June, July and December through March), a phenomenon never observed for regular tectonic tsunamis. It is worth noting that during the same 22-yr period the only seismogenic tsunami recorded along the US East cost was the 2004 Indonesian tsunami with a maximum height of about 0.33 m at Trident Pier, Florida (Thomson et al. 2007).

Along the north-east coast of the Gulf of Mexico over 500 cases of possible meteotsunami waves, over 0.3 m in height, were found from 2007 to 2015 in the de-tided data from the three primary NOAA coastal tide gauges in western Florida located at Cedar Key, Clearwater Beach, and Naples (Paxton 2016). Along the north-eastern coast of Argentina, 15 meteorological tsunamis (with height more than 0.2 m) were identified in the records of just one tide station (Mar del Plata), from April 2010 to January 2013 (Dragani et al. 2014). In the recent study of meteotsunami occurrence in the Gulf of Finland, based on the careful analysis of mareograph records from three station (Helsinki, Honko and Hamina) from 1922 to 2014, 121 potential meteotsunami events were identified, 70% of them being confirmed as having a jump in air pressure occurring shortly before or simultaneously with the sea-level anomalies (Pellikka et al. 2020).

These examples of systematic search of meteotsunami traces on high-resolution instrumental records show that the number of detected events quickly grows with decreasing wave height. Monserrat et al. (2006) suggested a threshold criterion for an event to be classified as a meteotsunami as a wave amplitude which exceeded 4σ, where σ is the standard deviation of the current water-level record. An alternative approach could be to consider “meteotsunamis” only as damaging or potentially damaging events. This approach looks more favorable from practical point of view since it leaves in the catalogs only those events which can make essential input in the overall tsunami hazard.

While the majority of papers published on the subject during the last 30 years describe individual meteotsunami cases, only a few studies provide accounts of meteotsunami occurrence within a specified geographical area. The very first catalog of the large seiches observed in Nagasaki Bay from 1961 to 1980 (Akamatsu 1982) remains one of the most essential and comprehensive summaries on meteotsunami occurrence. H. Akamatsu analyzed about 600 records of seiches with an amplitude of more than 0.4 m and performed a detailed analysis of their occurrence. He demonstrated that the yearly frequency of the events in the bay varies from 20 to 70 cases being 30 in average. Moreover, based on the collected data, H. Akamatsu even attempted to obtain the recurrence curve (frequency-amplitude relation) making it possible to probabilistically assess the meteotsunami occurrence rate in Nagasaki Bay.

Haslett and Bryant (2009) published a historical overview of 8 damaging meteorological tsunamis having occurred in southern Britain from 1824 to 1979. Orlić (2015) gave a list of 21 flooding events observed at the Croatian coast of the Adriatic Sea from 1931 to 2010. Rabinovich (2020) examined and described 51 selected meteotsunamis that occurred globally, from 1992 to 2020. Candella and Salles de Araujo (2020) described 8 major meteotsunamis observed along the southern coast of Brazil from 1977 to 2020. Most events resulted only in material losses, sometimes severe, but at least one fatality was registered (for the event of March 8, 2008). One of their conclusions is quite important for an understanding of the nature of meteotsunamis: despite the synoptic situations (near coast passage of low atmospheric pressure systems) favorable for the repeated occurrence of meteotsunamis in this area, generation of large damaging events is quite rare (only 8 events in 43 years).

In the current version of the Global Historical Tsunami Database (NCEI/WDS 2020) covering almost 4000 years and including about 2500 tsunamis and tsunami-like events, meteotsunamis constitute a very small fraction (4.1%). For the twentieth century, where the database is more complete, their fraction is only slightly higher (4.2%). Even in the twenty-first century, when high-resolution (1–2 min) digital sea-level data became available for many regions, the identified meteotsunamis constitute 5.8% of all the catalogued tsunami events. Yet in a recent study Gusiakov (2020), it was shown that meteotsunamis provided 9 out of 120 yearly maxima in distribution of maximum wave heights observed or measured globally within the instrumental period (from 1900 to 2019). The lack of cataloguing efforts and problems with meteotsunami parameterization are the main reasons that meteotsunamis are poorly represented in the global database. In next sections we consider these problems in more detail.

4 Tsunami databases

Currently, two global historical tsunami databases exist and are separately maintained by the NOAA National Centers for Environmental Information (NCEI) and the Novosibirsk Tsunami Laboratory (NTL) of the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Division of the Russian Academy of Sciences (ICMMG SD RAS). In this paper, they are referenced as NCEI/WDS database (NCEI/WDS 2020) and NTL ICMMG database (NTL/ICMMG 2020). Both databases cover the same historical period (from 2100 BC to present) and contain about the same number of tsunamigenic events (about 2500).

For the instrumental period (twentieth and twenty-first centuries), the two databases are fairly close in the total number of events and run-up observations. The difference concerns mainly event classification by type of sources, validity index, etc. For pre-instrumental period, the difference is more essential, as in number of events as in their basic parameters. The reason for this is that in the absence of instrumental data the event parameterization is made solely by expert judgments which can be based on different approaches adopted and different descriptive sources used.

Anyone dealing with historical tsunami data should bear in mind several intrinsic problems closely associated with this type of information (Gusiakov 2009). These problems derive from inaccuracy and from the fragmentary nature of available information especially about old or geographically remote events. Quite frequently, the information on an older event is so incomplete that it is difficult to make a reliable judgment on the phenomenon's nature and to evaluate its physical scale. The main reason for confusion with other similar phenomena (storm surges, extreme seiches) is the scarcity of information and the lack of details in the description of events. Regarding these types of errors, the catalog compilers can do almost nothing but assign a low validity index $V=1$ (doubtful) or $V=2$ (questionable) to the events of doubtful nature, thus alerting users to practice caution in treating these data. Sometimes it happens that additional data are found later thus allowing one to resolve the uncertainty and to increase the validity index up to $V=3$ (probable) or $V=4$ (definite) or to exclude the event from the list. In practice, the events are not excluded at all, but assigned validity $V=0$ or -1 (false entry) to prevent their re-entry because the information about them exists in publications and on the Internet. Both NCEI/WDS and NTL/ICMMG databases have about 5–6% of such entries.

An additional complication is that the two databases have slightly different validity scales (a 5-grade on the NTL/ICMMG database and a 6-grade for the NCEI/WDS database). In the NCEI/WDS database a false entry has the grade -1 while the grade 0 is reserved for "an event that is caused by a seiche or disturbance in an inland river". In the author's point of view, this subdivision is not quite correct because $V=0$ relates to the type of an event but not to its validity. Actually, it reflects the initial approach to the database compilation going back to the early 1980s when the database was seen mainly as a collection of data on oceanic tsunamis of seismogenic origin, while nowadays there is a tendency to include within the same dataset the data on "tsunami-like events" that occur not only in marine basins but everywhere including rivers, lakes and other in-land waters.

The presently adopted format of both databases was initially developed by the ITIC in the middle of 1970s (Kong et al. 2015). At that early stage of computer application to data storage and processing, a primary goal was "to collect and maintain the historical tsunami database that should facilitate decision-making process in operational centers" (Summary Report…1987). The adopted format was almost entirely oriented to parameterization of seismogenic tsunamis which at that time constituted more than 90% of the content of the historical catalogs. All the parametric tsunami data were converted into two tables—the Tsunami Event Table and the Tsunami Run-up Table. The Tsunami Event Table includes the basic parameters (date, time, location, magnitude) of a source (earthquake, volcano or landslide) and some set of parameters characterizing the tsunami impact (maximum run-up, intensity, damage, fatalities, etc.). The Tsunami Run-up Table includes tsunami height measurements in a particular coastal location (run-up, inundation distance, type of measurement, arrival time, etc.). This format fits the needs of parameterization of tectonic tsunamis that have their source clearly localized in space and time. However, it turns out to be less appropriate for parameterization of tsunamis of atmospheric origin that typically have a spatially and temporarily distributed source (moving atmospheric forcing) whose impact can last for hours or even days.

5 Meteotsunami data

As noted in the introduction, the current representation of meteorological tsunamis in the NCEI/WDS database is quite low. In short, the database contains only 49 events with validity $V=1$–4 marked as having meteorological origin. Additionally, there are 6 events having validity $V=0$ ("seiches"). As a result of special efforts undertaken after the author's participation in the First International Meteotsunami Symposium, held in Split, Croatia in May 2019, the level of representation of meteotsunamis in the NTL/ICMMG database was significantly increased, yet remains insufficient if compared with the amount of information available in primary historical sources and in numerous research publications on meteotsunamis. Currently, the NTL/ICMMG database contains 235 meteorological events of different validity levels covering the period from 855 AD to the present. Figure 1 shows a spatial distribution of these events that is based on their validity score (shown by color) and their maximum reported height (shown by size of markers). The temporal occurrence can be seen in Fig. 2.

The first and the most prominent feature in their geographical spread is the large difference in the number of events between the northern and southern hemispheres (82% and 18%, respectively). Such imbalance can be possibly explained by shorter written history for many areas in the southern hemisphere and lower level of reporting. Secondly, the map demonstrates the increased number of meteotsunamis in the long-known "hot-spots" like the Great Lakes and north-east US coast, the Balearic Islands, Croatian coast, and Nagasaki Bay. Thirdly, the map clearly highlights the areas that were recently in focus by the

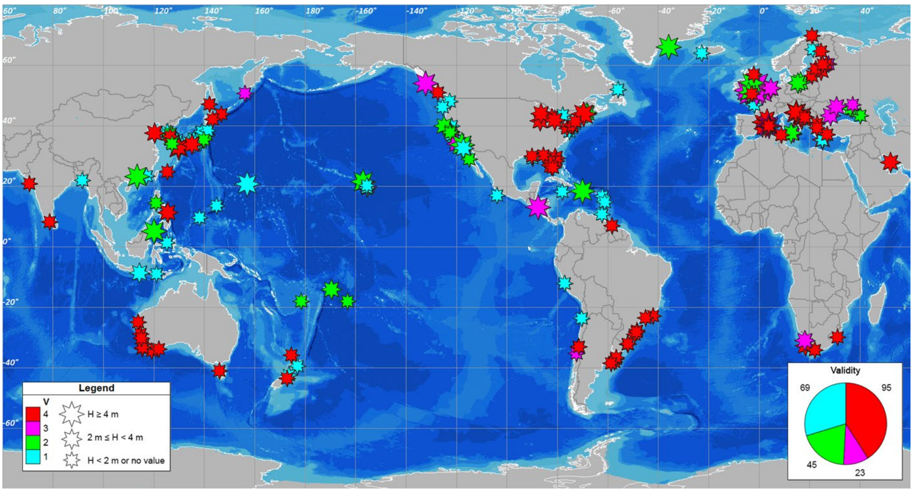

Fig. 1 Global map of 235 confirmed or suspected meteotsunamis shown as 8-pointed stars. Color represents the event validity: red for $V=4$ (confirmed), magenta for $V=3$ (probable), green for $V=2$ (questionable), light blue for $V=1$ (doubtful). Symbol size is proportional to the reported wave height: large for $H \geq 4$ m), medium for 2 m $\leq H < 4$ m, small for $H < 2$ m or no value. Inset figure shows the event distribution over the validity index

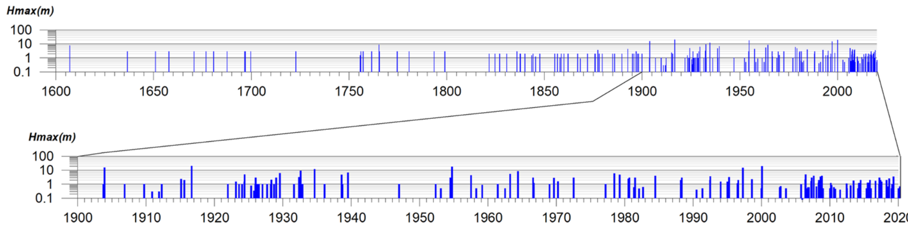

Fig. 2 Temporal occurrence of meteotsunami events observed or measured in the World Ocean during the last 400 years (from 1600 to 2020) (above) and during the last 120 years (1901–2020) (below)

close-up studies devoted to the systematic search of historical data and of traces of meteotsunamis on mareograph records. Examples are the UK coast (Haslett et al. 2009; Thompson et al. 2020), the south-west coast of Australia (Pattiaratchi and Wijeratne 2014, 2015), the north-east coast of Argentina and south-east coast of Brazil (Dragani et al. 2014; Candella 2009; Candella and Araujo 2020), South Africa (Shillington 1984; Okal et al. 2014), and the north-eastern part of the Baltic Sea (Pellikka et al. 2014, 2020).

Table 1 lists 20 confirmed meteotsunamis which occurred within the 50-year period from 1969 to 2018, sorted by their reported wave height (maximum level range). Of these 20 meteorological events, 12 occurred in the long-known "hot spots" (Great Lakes, Balearic Islands, Adriatic coast of Croatia, Nagasaki harbor). This confirms the comment expressed by Dusek et al. (2019, p.1336) that "the largest meteotsunamis tend to occur in places that observed frequent events". Only one event (August 27, 1969) in Table 1 has its location in the southern hemisphere. Among the 20 largest meteotsunamis, three were fatal and caused in total 16 fatalities. As for the meteotsunami of September 4, 2018 caused by the Jebi typhoon, its 13 fatalities resulted from joint action of a hurricane force wind, storm surge and rain-induced floods and cannot be directly associated with the meteotsunami.

If we go beyond the 50-year period covered by the events in Table1 and consider the meteorological events of lower validity ($V=3$, 2 and 1) as well as the potentially meteorological events that were not associated with any tectonic activity and are kept in catalogs as having unknown origin, we obtain a set of much more significant events with heights well above the largest heights of the confirmed meteotsunamis. The 20 largest such events are listed in Table 2. Their temporal coverage is almost 400 years (from 1607 to 2000) and the minimum wave heights for these events is on the level of the maximum heights of the confirmed meteotsunamis in Table 1. Their spatial coverage can be seen in Fig. 3 where they are overlaid on a source map of 330 events of unknown origin currently included in the database. In fact, the spatial distribution of the latter events outlines the areas where a further search for historical meteotsunamis could be most fruitful.

In the absence of instrumental records for events in Table 2 we cannot be sure that all of them represent real meteotsunamis. Some could be produced by severe storm surges (like the 2000 Tawi-Tawi flood in the Philippines) or by rogue waves (like the 1916 "monster" 24-m wave in Santo Domingo which caused the destruction of the armored cruiser USS Memphis); some could have been extreme storm-induced harbor seiches overlying an exceptional high tide (the 1607 Bristol Flood). However, together they demonstrate the significance of events of non-seismic origin and their potentially great impact on the overall tsunami hazard in various parts of the World Ocean.

The presence of the January 1607 event in this table is especially interesting for it indicates that a rare combination of several extreme factors, such as an exceptionally high (7.9 m) tide (Horsburgh and Horritt 2006), intense (up to 5–6 m) storm surge (Bryant and

Table 1 The 20 largest meteotsunamis having validity index $V=4$ (confirmed), listed in order of their measured/estimated wave height

Date	*H*m,	Type	V^{a}	FAT	INJ	Location	Reference
1978 06 21	6.0	GWHO	4	–	–	Vela Luka, Croatia	Orlić (1980)
2006 06 15	5.0	GWHO	4	–	–	Cuitadella, Spain	Monserrat et al. (2006)
1979 03 31	4.8	GWHO	4	3	–	Nagasaki Bay, Japan	Hibiya and Kajiura (1982)
2008 10 28	4.0	BWSW	4	–	–	Boothbay, USA	Whitmore and Knight (2014)
1977 09 20	4.0	GWHO	4	–	–	Vela Luka, Croatia	Orlić (1980)
1984 10 05	4.0	GWHO	4	–	–	Ist Island, Croatia	Vilibic and Šepić (2009)
2007 08 22	4.0	GWHO	4	–	–	Ist Island, Croatia	Vilibić and Šepić (2009)
1992 07 04	3.6	GWHO	4	–	75	Daytona, USA	Churchill et al. (1995)
2003 06 27	3.5	GWHO	4	–	–	Stari Grad, Croatia	Vilibić et al. (2004)
2008 08 15	3.5	GWHO	4	–	–	Mali Losinj, Croatia	Belušić and Mahović (2009)
2019 04 14	3.5	GWHO	4	–	–	Lake Erie, USA	Rabinovich (2020)
1995 03 25	3.3	GWHO	4	–	–	West. Florida, USA	Paxton and Sobien (1998)
1981 07 02	3.0	GWHO	4	–	–	Costa Brava, Spain	Rabinovich and Monserrat (1996)
1984 06 21	3.0	GWHO	4	–	–	Cuitadella, Spain	Rabinovich and Monserrat (1996)
954 06 26 3	3.0	BWHO	4	7	–	Michigan City, USA	Ewing et al. (1954)
2014 06 25	3.0	GWHO	4	–	–	Vela Luka, Croatia	Šepić et al. (2015)
2017 03 19	3.0	GWHO	4	6	–	Dayyer, Iran	Salaree et al. (2018)
1969 08 27	2.9	GWHO	4	–	–	Dwarskersbos, SA	Okal et al. (2014)
1980 09 01	2.9	GWHO	4	–	–	Longkou, China	Wang et al. (1987)
2018 09 04	2.6	BWHO	4	13	600[b]	Osaka, Japan	Heidarzadeh and Rabinovich (2020)

Date yyyy. mo. da, H_m maximal observed sea-level range in m, Type the types of the event (according to Rabinovich 2020), *GWHO* good weather harbor oscillations, GWSW good weather solitary wave, *BWHO* bad weather harbor oscillations, *BWSW*, bad weather solitary wave, *V* validity index, *FAT* number of reported fatalities, *INJ* number of injured people

[a]In this table, $V=4$ means that the event was a meteotsunami with clearly identified atmospheric source and it occurred on the indicated date

[b]These digits may include fatalities and injured people resulted also from a storm surge, wind action and river floods

Haslett 2002) and a possible meteotsunami on top of the surge, can lead to a catastrophe of immense proportions as happened in 1607 along the coasts of Bristol Channel. With its 2,000 fatalities it turned out to be "the worst UK coastal flooding on record" (Long and Wilson 2007). The transported and imbricated boulders and bedrock sculpturing in many locations around Bristol Channel may have been the geomorphic evidence of meteotsunami presence in this case, since they require large flow velocities (more than 5–6 m/s) that are normally not achieved during storm surges (Bryant and Haslett 2007).

6 Parameterization of meteotsunamis

Unlike seismogenic tsunamis propagating in the ocean as free long-period waves following a tectonic source, meteotsunamis are modified by atmospheric forcing during propagation and during interaction with the coast. That is why their generation cannot be localized in space and time in a manner similar to tectonic tsunamis and this presents a problem

Table 2 The 20 largest tsunamis of supposedly meteorological or unknown origin listed in order of their measured/estimated wave height

Date	*H*m	CAU	*V*[a]	FAT	Location	Reference
1923 03 04	35.0	U	2	–	San Felix Is., Chile	Soloviev and Go (1975)
1916 08 29	21.0	M	2	43	Santo Domingo	Pararas-Carayannis (2019)
2000 01 26	20.0	M	2	–	Tawi Tawi, Philippines	Lander et al. (2003)
1954 10	18.3	M	2	–	Aputiteq, Greenland	Berninghausen (1968)
1903 11 29	15.7	M	2	–	Oahu, Molokai, USA	Soloviev and Go (1975)
1997 04 10	15.0	M	3	–	Cedeno, Honduras	Lander et al. (2003)
1934 08 21	12.0	M	2	–	Newport Beach, USA	Lander et al. (1993)
1791 05 13	11.0	U	3	–	Ryukyu Is., Japan	Iida (1984)
1932 08 02	9.3	M	2	4	Aberavon, UK	Haslett et al. (2009)
1765 05	9.0	M	2	10,000	Guanzhou, China	Lau et al. (2010)
1964 05 14	8.6	M	2	2	Arnside, UK	Haslett et al. (2009)
1997 12 14	8.0	U	2	–	Kamchaka, Russia	Lander et al. (2003)
1607 01 30	7.7	M	2	2000	Bristol Channel, UK,	Bryant and Haslett (2002)
1939 07 04	6.7	M	3	3	Milford Haven, UK	Haslett et al. (2009)
1929 07 20	6.4	M	3	2	Folkestone, Kent, UK	Haslett et al. (2009)
1926	6.3	U	2	–	Tolaga Bay, New Zealand	Downes (2008)
1868 10 02	6.1	U	2	–	Hawaii I., USA	Lander and Lockridge (1989)
1925 05 04	6.0	U	1	–	Off coast of Mexico	Soloviev and Go (1975)
1963 03 28	5.5	M	3	–	Graham Is., Canada	Stephenson et al. (2007)
1911 05 11	5.0	U	2	–	Lome, Gold Coast, Africa	Berninghausen (1964)

Date date of event (yyyy, mo, da), *H*m maximum reported wave height in *m, CAU* type of source (M meteorological, U unknown), V validity index, *FAT* number of reported fatalities

[a]In this table, validity index *V* means the degree of confidence that an event is a meteotsunami resulted from an atmospheric source: $V=3$ (75%), $V=2$(50%), $V=1$(25%)

for their parameterization and cataloguing within the present database format. As a rule, reports on meteotsunamis include description of their manifestation at a particular coastal location (bay, harbor or beach). Tracing back the atmospheric source of these anomalous sea-level oscillations is possible only for recent events that have occurred within the last 2–3 decades when meteorological data with sufficient temporal and spatial resolution have become available. However, even for well-studied recent events with properly established atmospheric sources like the 1978 Vela Luka, 1979 Nagasaki, 2008 Boothbay Harbor meteotsunamis, further parameterization within the adopted format of the Tsunami Event Table can be problematic. It is not quite clear how one should approximate a moving atmospheric front by the three parameters (location and time of origin) that are used for parameterization of a seismic source. The only solution to be implemented without a major revision of the database format is to use the coordinates of an observational site and the time of meteotsunami onset. In fact, this approach is used for parameterization of historical seismogenic tsunamis having occurred in pre-instrumental era when even a rough localization of seismic sources was not possible.

As an illustration of this type of problems, we can refer to the recent case of meteotsunami developed all along the entire Chilean coast during a severe storm that hit the coast of central Chile on August 8, 2015 described in Carvajal et al. (2017). The

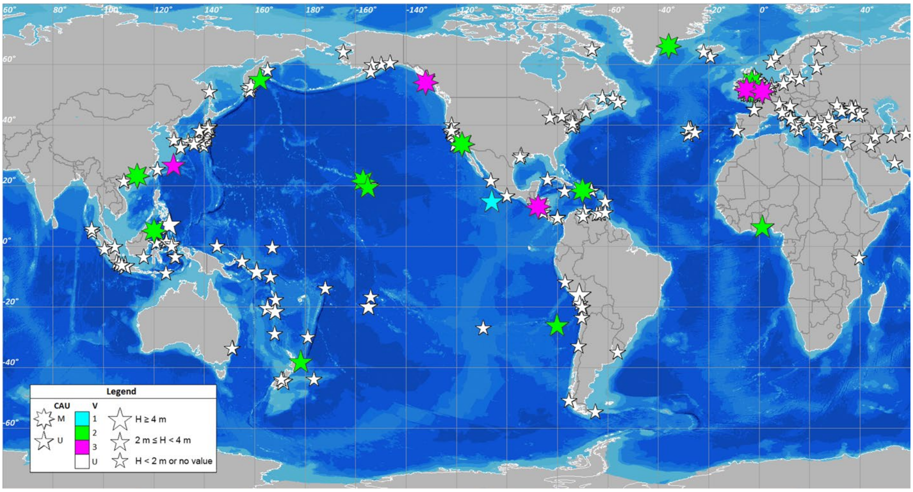

Fig. 3 Global map of 330 historical tsunamigenic events that are kept in the NTL/ICMMG database as having unidentified sources shown as white 5-pointed stars. The events listed in Table 2 are shown as colored stars (8-pointed for $C = M$ and 5-pointed for $C = U$) with color representing the event validity: magenta for $V = 3$, green for $V = 2$, light blue for $V = 1$. Symbol size is proportional to the reported wave height: large for $H \geq 4$ m, medium for 2 m $\leq H < 4$ m, small for $H < 2$ m or no value

storm caused significant waves of up to 7.2 m in height off the coast of Valparaıso and resulted in six casualties, massive beach erosion, and destruction of port facilities. The storm travelled from the Pacific eastward almost perpendicular to the shore at an average speed of 30 m/s and made landfall near Talcahuano where it induced sea-level oscillations in the tsunami frequency band that were observed at 28 tide stations located along a 2000-km segment of Chilean and south Peruvian coasts with a maximum range of 1.25 m detected at the Bucalemu station.

Another issue is the type of parameter that characterizes the magnitude or intensity of a meteotsunami. For the seismogenic tsunami it is the run-up height that is defined as a maximum vertical elevation reached by seawater on a coastal slope. However, this type of measurement is only sporadically presented in meteotsunami descriptions. In most cases, observers indicate the maximum level rise (inundation level) at some point within a harbor or bay or give the difference between the maximum level drop and rise that corresponds to a "wave height" measurement in the instrumental (tide gauge) record.

The lack of reported run-up heights or instrumental wave height measurements does not allow us to evaluate the intensity of meteotsunami using one of the intensity scales, e.g., the Soloviev-Imamura scale (Soloviev 1972) used for assessment of the overall "size" of tectonic tsunamis as a "proxy" for their magnitude (Gusiakov 2015). That is why in Figs.1 and 2 the meteotsunamis are presented in very rough classification by their "size", being divided just into three groups by their reported maximum wave heights H_m—destructive ($H_m > 4$ m), damageable ($H_m = 2$–4 m) and observable ($H_m < 2$ m). However, the 12-grade intensity scale proposed by Papadopoulos and Imamura (2001) for assessment of the local impact of a tsunami is totally applicable for meteotsunamis, at least in cases when a detailed description of the wave action is available.

7 Discussion

The comparative characteristics of tectonic tsunamis, meteotsunamis, storms surges, seiches and rogue waves are shown in Table 3. Contrary to frequently repeated statements like "meteotsunamis are similar to seismic tsunamis except for their atmospheric origin" (Pattiaratchi and Wijeratne 2015), out of seven meteotsunami characteristics listed in this table, only three (typical period, typical duration and area of impact) are similar to those of tectonic tsunamis. The four other characteristics (type of source, maximum height, maximum in-land flooding, scale of spatial manifestation) are quite different from those of tectonic tsunamis. While seismogenic tsunamis are notorious for their ability to propagate over great distances, meteotsunamis are always local events that arise at some coastal location under a specific combination of atmospheric conditions and never propagate far outside of their area of origin. Even in cases of a meteotsunami outbreak resulting from a large-scale atmospheric disturbance, e.g., on June 22–24, 2014, in the Mediterranean or on October 28, 2008, in the North-East of the US, their manifestations in various locations can be quite different and determined mainly by resonance characteristics of relevant sites.

Stormy conditions in the coastal areas quite often (although not necessarily always) lead to meteotsunami occurrence. Comparing the characteristics of meteotsunamis and storm surges, we can see that despite their clear difference in frequency range (storm surges are aperiodic sea-level rise while meteotsunamis are alternating level oscillations) there is a problem with discrimination between these two phenomena because the total coastal impact results from a joint action of astronomical tide, storm surge, meteotsunami and wind waves. In cases when high-resolution (1–2 min) sea-level data are available, an extraction of meteotsunami signal can be made on the basis of standard signal processing technique such as de-tiding and high pass filtering (e.g., Rabinovich et al. 2011; Rabinovich and Eblé 2015).

In several published studies of meteotsunami occurrence during the coastal impact of large hurricanes (Olabarrieta et al. 2017) clear evidence of their presence on top of a storm surge was found. Among them, the landfall of Hurricane Wilma on October 24, 2005, produced one of the highest (0.9 m in height) meteotsunamis on record in Naples, Florida (Olabarrieta et al. 2017). Hurricanes Dennis (2005), Katrina (2005), and Hermine (2016), and tropical storm Colin (2016) also produced meteotsunamis that impacted Naples and Clearwater Beach. Heidarzadeh and Rabinovich (2020) studied two recent typhoons (Lionrock in August 2016 and Jebi in September 2018) that destructively affecting the coast of Japan and demonstrated that a clear signal of meteotsunami can be extracted from the raw records obtained at several coastal tide-gauges. They estimated that the relative inputs of meteotsunami waves during these events into the total observed sea-level heights varied from 39 to 67%.

Thus, we can see that in cases where close study of instrumental records obtained during the coastal impact of large hurricanes was made (e.g., Olabarrieta et al. 2017; Heidarzadeh and Rabinovich 2020), a clear meteotsunami signal could be found. However, the question yet to be answered is whether it takes place for all hurricanes or only for the strongest of them (of category 4–5)? The answer should be given keeping tsunami hazard assessment in mind, because large-scale atmospheric disturbances (tropical cyclones, hurricanes and typhoons) are much more frequent events compared with large earthquakes and volcanic eruptions, and for many regions their input can lead to an essential change in the hazard estimates especially for short-term recurrence intervals (tens of years).

Table 3 Comparative characteristics of tectonic tsunamis [seismogenic (E), volcanic (V) and landslide-generated (L)], meteotsunamis, storm surges, seiches and rogue waves

	Tectonic tsunamis	Meteotsunamis	Storm surges	Seiches	Rogue waves
Source	Submarine earthquakes, volcanoes, landslides	Atmospheric disturbances	Tropical and extratropical cyclones	Atmospheric and seismic forcing	Storm waves
Typical period	From 2 min to 3 h	From 2 min to 3 h	Aperiodic	From tens of seconds to several hours	Typically observed as a single wave or water splash
Typical duration	From one hours to several days	From a few minutes to several days	From a few hours to several days	From few hours to several days	From 5–6 to 20–30 s
Max observed height	40–45 m (E) 35–40 m (V) 525 m (L)	6 m	7–8 m	~1 m	26 m
Max in-land flooding	Up to 5–10 km	From a few meters to several hundred meters	Up to 50 km	A few meters	Coastal flooding is rare
Spatial manifestation	From 1 to 25,000 km	From 1 to 1,000 km	Hundreds of km	From a few tens of meters to several hundred km	Less than 1 km
Area of impact	Coastline areas	Coastline areas	Coastline areas	Closed and semi-closed water basins	Mostly in deep open ocean

Parametric data in the table were taken from the NCEI/WDS and NTL/ICMMG databases, published tsunami catalogs and from books and overview papers by Pugh and Woodworth (2014), Monserrat et al. (2006), Pattiaratchi and Wijeratne (2015), Rabinovich (2020), and Didenkulova (2020)

The absence of high-resolution data for the past events does not allow tracing of hurricane-induced meteotsunamis back in history, in particular to determine their contribution in coastal flooding and the total fatality rate during some of the largest historical events like the 1780 Great Hurricane of the Antilles, 1938 New England hurricane, 1935 Florida hurricane, 1959 Vera super-typhoon in Japan and 1970 Bhola Typhoon in the Bay of Bengal. The separation of the meteorological effect from a general destructive storm impact on the coast is a problem even for recent events. As Carvajal et al. (2017) state in their paper devoted to the analysis of the severe August 2015 storm in central Chile "The relative contribution of meteotsunamis, storm surge, and wind waves to the effects observed in the storm's aftermath remains unknown and should be addressed in further studies".

From the data presented in Table 3 we can see that the general characteristics of meteotsunamis are much closer to the characteristics of seiches. In fact, the wide use of such expressions as "large-amplitude seiches", "extreme storm seiches" in publications on meteotsunami confirms that in closed or semi-closed basins they manifest themselves as large seiches and quite often this term is actually used as a synonym for meteotsunamis (cf Vilibić et al. 2014, p.1). However, in the author's opinion, meteotsunamis should not be fully associated with seiches because the term "seiches" means all standing wave oscillations caused by any disturbance including those coming from the sea bottom, e.g., seismic shaking.

Another important source of unexpected large waves in coastal waters is the impact of rogue waves. Despite the fact that most rogue waves arise in the open sea, quite frequently they are observed in shallow waters and produce a destructive effect at the coast. According to a recently published catalogue of rogue waves that occurred in the World Ocean from 2011 to 2018 (Didenkulova 2020), out of 210 reported events resulting in material damage and human loss, 120 (57%) had coastal impact. In total, for this period rogue waves killed 386 and injured 184 people giving a fatality rate much higher than that of meteotsunamis. In several cases they washed cars and motorcycles into the sea and damaged houses and buildings in the coastal zone thus causing damage similar to that of ordinary tsunamis. Therefore, in old chronicles, descriptions of their impact could well be confused with the effects of both ordinary tsunamis and meteotsunamis.

A part of the problem of meteotsunami identification is that a large single event (like the March 25, 1995 Florida meteotsunami) can be observed along an extended part of a coastline where the phenomenon manifests itself as "a large wave, a surge or a seiche" depending on type of coast at a specific location (Paxton and Soblen 1998). The case becomes more complicated with an outbreak of meteotsunamis due to large-scale atmospheric disturbances propagating over large distances. Examples of such outbreaks include a series of meteotsunamis that occurred on June 25–27, 2014 in many parts of the Mediterranean region extending from Spain to Ukraine (Šepić et al. 2015), or the pronounced water level oscillations in Lake Michigan, Chesapeake Bay, and along most of the US Atlantic coast produced by the widespread derecho event of June 29–30, 2012 propagating devastatingly over more than 1000 km from western Iowa to the US Atlantic coast (Šepić and Rabinovich 2014). In these cases, manifestations of a phenomenon in particular locations (in terms of amplitudes, periods, number of waves, total duration) were quite different, reflecting local features of sites and specific atmospheric conditions in various areas. In the past, in the absence of instrumental meteorological data, such events, being noted and reported, could be considered as independent phenomena thus hindering their correct interpretation.

8 Conclusions

Meteotsunamis are long-known and widely observed marine hazards. Until recently, it was thought that they occurred within a few geographical locations, known as meteotsunami “hot spots”, but the above analysis suggests that they can actually occur at any coast with favorable bathymetry and coastline configurations under some specific combination of atmospheric conditions. As some areas have more favorable conditions for meteotsunami generation, their recurrence in these areas is much more frequent than in other places. Examples of such regions are the Great Lakes region, the Gulf of Mexico, the US North East coast, the British Islands, the Balearic Islands, the Adriatic Sea, the Yellow Sea, the south-west coast of Japan, and the south-east coast of Brazil. The relative scarcity of reports of meteotsunamis in other regions is partly due to a lack of interest in studying detectable, but largely non-damaging sporadic sea-level oscillations in the tsunami frequency band, as well as by the problem of discriminating them from other hazardous anomalies in sea level, such as storm surges, harbor seiches, rogue waves, and extreme tides, which often occur in combination.

With the growing availability of high-resolution sea-level data, more meteotsunami events will be identified and catalogued in the near future. What is more important is the search for evidence of meteotsunamis that occurred in the past. It is appropriate to quote here G. Pararas-Carayannis speaking long ago on a slightly different, but related matter: “As a starting point, we need to develop a uniform and standardized program of tsunami, seismic and geologic data collection. A wealth of such data already exists but this data is not properly organized, is not uniformly collected, and of course it is not readily available” Pararas-Carayannis (1989). This was said in relation to tsunami data in general, but these words are even more relevant to data on meteorological tsunamis, since now it is possible to look at evidence and reports on sudden sea-level oscillations that have reached us through the veil of time, from a new angle and through the prism of a present day understanding of the nature of this phenomenon. Re-reading published historical tsunami catalogs (the total number of which now approaches 160) and a reassessment of the descriptive materials presented therein, appears necessary and desirable. This should allow us to resolve the cause of numerous events (currently numbering 330) that are listed in the databases as having unidentified sources.

Despite the fact that the current formats of both global databases do not fully correspond to the parameterization of meteotsunamis, their cataloguing within the databases should be continued by means of adding new events and by reconsidering many old events that have a low validity index ($V=1$–2), in particular those listed as having unknown sources. For better parameterization of meteotsunamis within the global database, a modification of its format is necessary. At the very least, a validity $V=0$ (event that only caused a seiche or disturbance in an inland river) should be excluded from the validity index options, since it relates not to “validity” but to the type of source and its location.

Meteotsunamis are dangerous events and in some cases can even be fatal. Issuing operational warning is of primary importance for many areas of the world oceans where their recurrence is high and their inclusion in overall tsunami hazard estimates is essential. The existing regional and national Tsunami Warning Systems, being entirely oriented for forecast of seismogenic tsunamis, cannot now provide timely and reliable warning of meteotsunamis. At present, there is a potential for development of operational tools based on local statistics of meteotsunami occurrence, analysis of real-time meteorological data, and advanced numerical modeling (Vilibić et al. 2020). However, even in the well-known meteotsunami “hot spots”, destructive meteotsunamis occur rather rarely. This suggests that the specific resonance conditions needed for excitation of dangerous oscillations are realized only in some exceptional cases. This fact makes it difficult to develop a robust and reliable operational system for meteotsunami forecasts that would function with acceptable levels of true/false/missed warning ratio.

The author concludes this paper with the words said almost a century ago by Finnish geophysicist Henrik Renqvist. Describing a meteotsunami observed on May 15, 1924 along the southern Finnish coast, he wrote the following remarkable words: “I have said what I have said in order to make it understandable that the phenomenon is a natural wonder in the eyes of the coastal dweller and a complex problem for science” (Renqvist 1926, cited by Pellikka 2020, p. 35). In fact, meteotsunamis, after 30 years of intensive study and more than 300 published research papers are still a poorly understood phenomenon which in historical chronicles has been masked by other sea-level anomalies in the tsunami frequency band such as infra-gravity waves, large seiches, storm surges, extreme tides, coastal impact of rogue waves or, in some cases, tsunamis of geological origin (e.g., generated by underwater landslides or far-field seismogenic sources). The thorough cataloguing of present-day meteotsunamis along with the re-assessment of old historical events is of primary importance since it allows researchers to evaluate their spatial and temporal coverage. Only availability of long-term observational data can give a sound basis for obtaining reliable estimates of meteotsunami occurrence and imposed hazard at specific coastal locations.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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