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Proposal for a new meteotsunami intensity index.

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Abstract

Atmospherically generated coastal waves labelled as meteotsunami are known to cause destruction, injury and fatality due to their rapid onset and unexpected nature. Unlike other coastal hazards such as tsunami, there exists no standardised means of quantifying this phenomenon which is crucial for understanding shoreline impacts and to enable researchers to establish a shared language and framework for meteotsunami analysis and comparison.

In this study, we present a new 5-level Lewis Meteotsunami Intensity Index (LMTI) trialled in the United Kingdom (UK) but designed for global applicability. A comprehensive dataset of meteotsunami events recorded in the UK was utilised and the index's effectiveness was evaluated, with intensity level and spatial distribution of meteotsunami occurrence derived. Results revealed a predominant occurrence of Level 2 moderate intensity meteotsunamis (69%) in the UK, with distinct hotspots identified in Southwest England and Scotland. Further trial implementation of the LMTI in a global capacity revealed its potential adaptability to other meteotsunami prone regions facilitating the comparison of events and promoting standardisation of assessment methodologies.

1 Introduction

If you live in a coastal zone, you are at risk from being impacted by various hydrometeorological hazards, one such hazard is the meteorological tsunami or meteotsunami. This is a globally occurring shallow water wave which tends to be initiated by sudden air pressure changes and wind stress from moving atmospheric systems such as convective clouds, cyclones, squalls, thunderstorms, gravity waves and strong mid-tropospheric winds (Vilibic and Sepic, 2017). The atmospheric disturbance transfers energy into the ocean initiating and amplifying a water wave that then travels towards the coastline where it is further amplified through coastal resonances (Sepic et al. 2012).

Due to the rapid onset and unexpected nature of these waves, they have the potential to pose a considerable threat to coastal communities, infrastructure and ecosystems (Sibley et al. 2016). This has been apparent throughout recent history with an increase in the number of meteotsunami being experienced around the world. With extreme events such as those in Vela Luka

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(Croatia, 1978) where a 6m wave caused US$7 million damage; at Nagasaki (Japan, 1979) where an event killed three people; Dayton Beach (Florida, 1992) where a single 3 m wave injured 75 people and caused damaged to dozens of cars and the Persian Gulf (2017) where a squall line initiated a 2.5 m wave leaving 22 injured and five dead (Gusiakov, 2021).

Understanding the intensity and impact of meteotsunami is crucial for effective coastal hazard management. The development of the LMTI index involved an extensive review of existing global meteotsunami scales and indices to which it was found that there is an absence of such a methodology. Due to this absence, we subsequently reviewed tsunami scales and indices, as these have a similarity to meteotsunami in wave types and impacts. The review revealed two types of indices used for defining and quantifying tsunami:

- A magnitude scale which relates to the physical quantities and parameters of the hazard including the source of the event and/or the wave height (Imamura-Iida scale, 1967). These scales tend to be logarithmic, and this allows for the compression of a wide range of values into a smaller range. This makes it easier to compare and visualise data that spans several orders of magnitude. However, it can make it difficult to translate the results to a non-academic community. Magnitude scales tend to compare only the wave size and not it's strength.
- An intensity scale that assesses the impacts of an event, including expected damage, based on observations (Papadopoulos and Imamura scale, 2001). It is easier to interpret and compare than other scales and can incorporate the human element without instrumentation. However, its reliance on descriptive evidence can lead to subjective results.

In this paper, we present a novel approach to assessing meteotsunami intensity by introducing a new 5 level meteotsunami intensity index named the Lewis Meteotsunami Intensity Index (LMTI). We provide an overview of the development process and implementation of this index, focussing on its application in the UK as a case study with a view to further global applicability.

2 Index development

Creating the LMTI involved four stages, (Figure 1).

2.1 Stage 1: Catalogue of events

Trials for the LMTI were conducted in the UK, where there is a long history of events dating back to at least 1750 AD (Haslett and Bryant 2009). Six main sources of UK meteotsunami events were utilised: Lewis et al. (2022), Williams et al. (2021), Thompson et al. (2020), Long (2015), Haslett and Bryant (2009) and Dawson et al (2000) all providing a comprehensive and coherent historical record. The collected data were analysed, with the meteotsunami identified and categorised according to a reliability and verification system adopted from Gusiakov (2021). Identified events were allocated a reliability score from 1 to 4 depending on the amount of evidence and data available across the sources (i.e., the number of components completed in the index), where 1= doubtful (1 to 3 components), 2= questionable (eyewitness report, 3 to 6 components), 3= probable (newspaper report, 6 to 9 components) and 4= definite (technical report, 9 to 12 components). Older events which are usually fragmented make it difficult to establish an informed judgement, so these were subsequently allocated a reliability score of 1; events with insufficient information remained unclassified and were considered highly uncertain.

2.2 Stage 2: Meteotsunami components and values

The proposed LMTI considers 12 various components of meteotsunami and the receptor sites, based upon descriptions of previous global events, current thresholds used by researchers and the characteristics of other related hazard indices (Table 1). This multifaceted approach allows for the LMTI to capture the complex dynamics of meteotsunami events and facilitate a single score which can be matched with a description on the LMTI index table (Table 1). The LMTI adopts this layout to allow for intensity evaluation based upon hazard only or receptor site only. By incorporating both parts this allows for analysis of a low height wave impacting a highly vulnerable coastline.

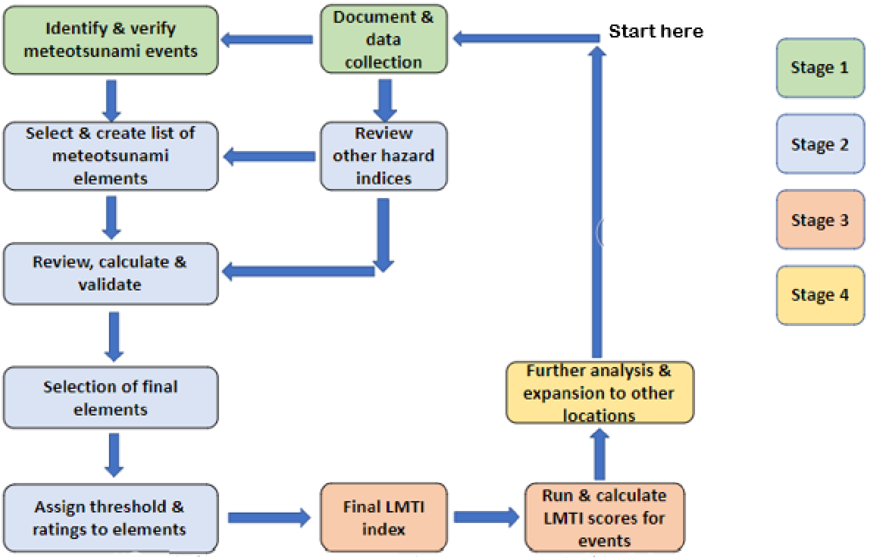


Figure 1: The adopted methodology for the development of the LMTI.

2.2.1 Physical hazard characteristics

Maximum wave height (Mw): the vertical distance between wave trough and crest (m) at the shoreline. This is the most frequently used element when discussing tsunami and meteotsunami (Williams et al. 2021, Gusiakov 2021) as wave height is the easiest form of data to observe. The greater the wave height, the greater the volume of water impacting people and structures along the shoreline. A wave height threshold of 0.30 m or less was selected as the baseline for Level 1 (minimal intensity), which was decided by analysing average wave heights of global and UK events, where 0.3 m was found to be the threshold for potential damage (Lynett et al.2014).

Currents (Cr): the velocity (m/s) of the water's movement produced by the meteotsunami wave as it inundates the shoreline. The faster the current the more the displacement of people, animals, and debris. The values for LMTI are based upon those laid out in Lynett et al. (2014) for tsunami waves which is calculated upon not only past event data from buoys and boats but also from experienced eyewitness accounts and videos.

Maximum inland intrusion of seawater (Di): the inland extent (m) of seawater flow past the high tide mark. The further inland the water reaches, the higher the risk to assets. However, this can be restricted by local topography which is addressed in subsection 2. This component is frequently used in coastal flooding indices (Rocha, Antunes and Catita, 2020).

Additional or compound hazards (Ch): considerations of other hazards and their potential to elevate the overall level of risk, one point is accumulated for each additional hazard that occurs parallel to the meteotsunami event. Existing tsunami indices do not include this component as it is deemed an external factor. However, we feel that due to the interactive nature of meteotsunami with other hazards it is imperative that it be considered. The risk from meteotsunami is not just restricted to elevated water level and velocity, if coupled with storm surge, seiching, precipitation, high winds, mudflows, and lightning compound issues can occur.

Air pressure change (Ap): the rate of change in the localised air pressure (mb) within a 3-minute period. This is included as a key component in the initiation of a meteotsunami via the inverse barometer effect. The sharper the air pressure changes the greater the potential for water displacement, 1 mb change equals 1cm change in static water level. The thresholds for this component have been derived from the data recorded from global events which range from 0.5 to 1.5 mb in approx. 3 minutes.

Tidal regime (Ti): the tidal stage at the time and location of maximum wave impact at the shoreline. This can be either neap, spring, low, mid or high. Coastal areas experiencing a spring or high tide are characterised as being highly vulnerable with the impacts being exacerbated by an already elevated water level.

2.2.2 Receptor site characteristics

Time of arrival of maximum wave at the shoreline (Pw): the time of day at the location of maximum wave activity and is sub divided into approximately 3-hour slots. This element is imperative to assessing the risk to human life. The highest scoring category (5 = extreme) equates to the most likely time of day where people, assets and commercial activity will be present along the shoreline.

Shoreline geomorphology (Sm): the composition of the dominant shoreline material type. The five classes are scored accordingly based on erosion capability of water, relative resistance, and the ability of the material to diffuse wave power and alter the flow characteristics. The five classes of coastline material range from the fastest and least resistant material of a sandy beach (5); bedrock and gravel shores (4); estuarine and vegetated zones (3); artificial frontage such as concrete seawalls (2) and finally to hard igneous rocks (1) which are more resistant to flooding and erosion (Masselink et al. 2020). In this paper, geomorphic classes were defined based on a visual interpretation of the immediate area of inundation using high resolution satellite imagery (Google Earth).

Shoreline gradient (Sg): the steepness of the coastal zone (°) and is linked to the susceptibility of the area to inundation and flooding by meteotsunami waves. The thresholds created for this index are adopted from the vulnerability index of Gornitz (1991). The gentler the slope the greater the loss of land to seawater and the higher the vulnerability. This is defined as the ratio of altitude change to the horizontal distance between any two points in the coastal hinterland behind the initial elevation and is calculated using Google Earth as a distance finder and then by applying the following calculation Eq. (1):

$$Sg = \frac{\mathrm{Hsl}}{\mathrm{Pd}} 100 \tag{1}$$

Where Hsl represents height above sea level in (m) of the selected feature point. Pd is the straight point distance from 0 m above sea level to a point of interest such as a hospital, school, or park.

Shoreline elevation (Se): average height (m) above sea level of the area in the immediate vicinity of the shoreline. The thresholds are again based on the vulnerability index of Gornitz (1991) where the elevation zone within 5 m of the shoreline faces the highest probability of inundation. The higher the elevation values the less vulnerable the area to inundation, as elevation provides more resistance to water flow. This can be calculated by using an online elevation finder (freemaptools.com) and is the average of six random elevation points within a 1000 m zone of the mean high-water spring (MHWS) level enabling measurement during all tidal stages.

Asset impact (Ai): This is one of two qualitative elements present in the index, and it represents the level of flooding and disruption experienced on infrastructure, historical, ecological, agricultural, livestock and property at the location. With scoring ranging from no impacts, to minor (short term inconvenience and disruption), moderate (repairable), to severe (structural damage with interruption of critical infrastructure) to extreme (long term damage where assets are lost and written off).

Fatality and/or injury (Fi): This is the second qualitative element and accounts for the number of individual fatalities and general injury to persons in the affected area as a direct result of the event. If we measured meteotsunami intensity solely in terms of loss of life this would be an inaccurate approach as it does not consider the hazard but rather just one aspect of its impact. With this element ‘minor’ relates to cuts and bruises, ‘moderate’ relates to broken bones and non-permanent trauma, ‘severe’ is permanent damage to a limb or organ and ‘extreme’ is fatality.

2.2.3 LMTI intensity levels

Once the thresholds were determined it was possible to then propose a five-stage index. This system incorporates a scoring regime to represent the level of contribution or weighting from each component towards the overall hazard. For this reason, each component is scored separately on a level of 1 to 5, with 1 contributing least and 5 contributing most strongly. This method allows for standardisation of the index and for each component that is measured in different units to be combined. Papadopoulos and Imamura (2001) proposed a 12-level scale to measure tsunamis, however, we have reduced and simplified the LMTI scale to 5 levels, as meteotsunamis, being smaller in scale and more localised in impact than tsunamis, do not need such a detailed breakdown.

The final meteotsunami intensity values exhibited in Table 2 contain brief descriptions highlighting the characteristics of each intensity level which have been devised from the characteristics of historical global meteotsunami events and are based around the events ability to be measured, its impacts and post event actions. The five levels are portrayed in a colour coded format as this is an effective way of communication as people tend to perceive risk better through colours, graphics, and visuals (Engeset et al. 2022).

2.3 Stage 3: Categorising events based on intensity: How to calculate LMTI

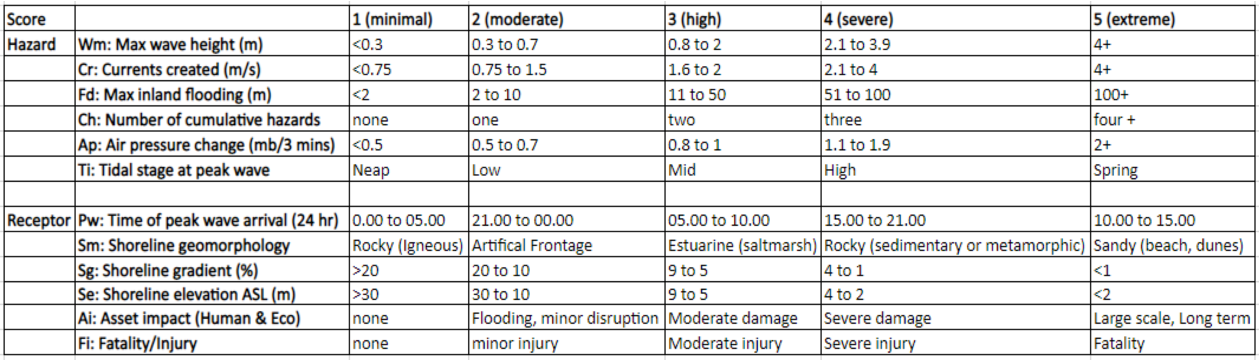
1. An event must be identified and verified as a meteotsunami (see Lewis et al. 2022).
2. The 12 elements are systematically allocated a score of 1 to 5 dependant on the threshold value (Table 1).
3. The component scores from each of the two subsections are added together and divided by the number of component cells containing data. Scores for the two subsections are then combined to give a single score by using the following conceptual calculation Eq. (2):

$$MTI = \frac{\Sigma z}{Nz} \tag{2}$$

Where LMTI (meteotsunami intensity) is a function of 12 potential components, where Z is component and N is the number of components.

4. The final LMTI score will be a number between 1 and 5 as shown in Table 2 and will give a standardised description of the level of intensity for that event. The higher the intensity score the higher the level of risk.

Table 1: Hazard and receptor components with associated thresholds as used in the LMTI.



Score		1 (minimal)	2 (moderate)	3 (high)	4 (severe)	5 (extreme)
Hazard	Wm: Max wave height (m)	<0.3	0.3 to 0.7	0.8 to 2	2.1 to 3.9	4+
	Cr: Currents created (m/s)	<0.75	0.75 to 1.5	1.6 to 2	2.1 to 4	4+
	Fd: Max inland flooding (m)	<2	2 to 10	11 to 50	51 to 100	100+
	Ch: Number of cumulative hazards	none	one	two	three	four +
	Ap: Air pressure change (mb/3 mins)	<0.5	0.5 to 0.7	0.8 to 1	1.1 to 1.9	2+
	Ti: Tidal stage at peak wave	Neap	Low	Mid	High	Spring
Receptor	Pw: Time of peak wave arrival (24 hr)	0.00 to 05.00	21.00 to 00.00	05.00 to 10.00	15.00 to 21.00	10.00 to 15.00
	Sm: Shoreline geomorphology	Rocky (Igneous)	Artifical Frontage	Estuarine (saltmarsh)	Rocky (sedimentary or metamorphic)	Sandy (beach, dunes)
	Sg: Shoreline gradient (%)	>20	20 to 10	9 to 5	4 to 1	<1
	Se: Shoreline elevation ASL (m)	>30	30 to 10	9 to 5	4 to 2	<2
	Ai: Asset impact (Human & Eco)	none	Flooding, minor disruption	Moderate damage	Severe damage	Large scale, Long term
	Fi: Fatality/Injury	none	minor injury	Moderate injury	Severe injury	Fatality

Table 2: LMTI intensity level descriptions.

MTI	Description
L1	**Minimal.** Only detectable on instruments, weak with no direct threat to life & assets, no action required.
L2	**Moderate.** Visible in instruments & observations, slight disruption, accompanied by other hazards, small debris & shallow flow, rarely a threat to life & assets.
L3	**High.** Large debris, violent movement of vessels & cars parked in flood zones, multi hazard situation with frequent threat to life & assets, fast water velocity with deep water extending past flood risk defences. Future coastal plan required.
L4	**Severe.** Violent movement & damage to infrastructure and assets. Pollution by contaminants. Significant threat to life & assets, coastline retreat & erosion with a multi-hazard situation. Large debris in fast flowing, deep water. Significant & active adaption methods required for the future.
L5	**Extreme.** Widespread & extensive threat to life & assets. Heavily damaging with long term changes to the coastal profile and ecological assets. Heavy objects washed away or moved to a higher elevation with fast and deep water. Multi hazard situation requiring extensive pre-event preparedness measures.

3 Stage 4: Application of the Index

We demonstrate the practical application of the LMTI in this paper by applying the index to the combined lists of UK meteotsunami events (Lewis et al. (2022), Williams et al. (2021), Thompson et al. (2020), Long (2015), Haslett and Bryant (2009) and Dawson et al (2000)). The full dataset of UK results can be found in S1: supplementary information and on an interactive map available at [https://www.google.com/maps/d/edit?mid=1RiSeW-DIPSylIVOLv_8-T8Gy_e0To08&usp=sharing.](https://www.google.com/maps/d/edit?mid=1RiSeW-DIPSylIVOLv_8-T8Gy_e0To08&usp=sharing)

To further demonstrate the LMTIs practicality and to lay the groundwork for its global application, a selection of 15 worldwide events as sourced from Vilibic, Rabinovich and Anderson (2021) and Pattiaratchi and Wijeratne (2015) had the index applied to them to extrapolate intensity scores (S2: supplementary information). The LMTI in this format offers a valuable tool for researchers, enabling comparative analyses between different regions and to facilitate a better understanding of meteotsunami dynamics in a global capacity.

3.1 UK meteotsunami intensity

The trial run of the LMTI provided valuable insights into UK meteotsunami events. A total of 100 events were analysed, amongst these events, Level 2 meteotsunamis accounted for 69 % of the occurrences (Figure 2). This finding suggests that the UK is prone to moderate intensity meteotsunami. Level 1 (minimal) meteotsunamis represented 12 % of events, in particular between 2009 and 2015. Level 3 (high) meteotsunamis accounted for 16 % of the events especially between 1883 and 1932. Finally, the results revealed a small number of severe intensity events (Level 4) which appeared in the hazard subsection, with all three events occurring in the winter months and along the Bristol Channel.

The results highlighted in Supplementary 1 show that the number of unreliable meteotsunamis (those classified as 1= doubtful and 2= questionable) decreases over time, with none recorded after 1968. 67 % of the events were classified as definite meteotsunamis having been attributed a high reliability score of 4. This enhanced reliability is apparent in the record since 2008, which is an indication of the abundance of data with increasing instrumentation.

The distribution of meteotsunami hotspots was also identified through the application. The southwest region of England exhibited a concentration of all levels of intensity type events, with the Bristol Channel exhibiting the only Level 4 type events. The south of England and north of Scotland also demonstrated notable meteotsunami activity in particular Level 2 (moderate) intensity events (Figure 3). These hotspots highlight the region's most at risk from meteotsunami occurrence and provide a valuable insight for future coastal management.

3.2 Global expansion of the Index

The findings from the trial implementation of the LMTI in a global context demonstrated that the index has the potential for adoption into other coastal regions prone to meteotsunami. Results for events such as Vela Luka (Croatia) in 1978, Nagasaki (Japan) in 1979, Ciutadella (Menorca) in 2006 and Dayyar (Persian Gulf) in 2017, all scored an expected Level 3. On the LMTI index this equates to high intensity, where large debris is deposited from high velocity water flow and there is a threat to life and assets (Table 2). On the opposite end of the intensity scale at Level 1, corresponding to minimal intensity events which are only detectable on instruments and with no impact to life or assets, we find events such as Pellinki (Finland) in 2010. However, even though the LMTIs ability to assess meteotsunami intensity was demonstrated through this trial run as the sample size is so small this will require further testing to ensure complete confidence.

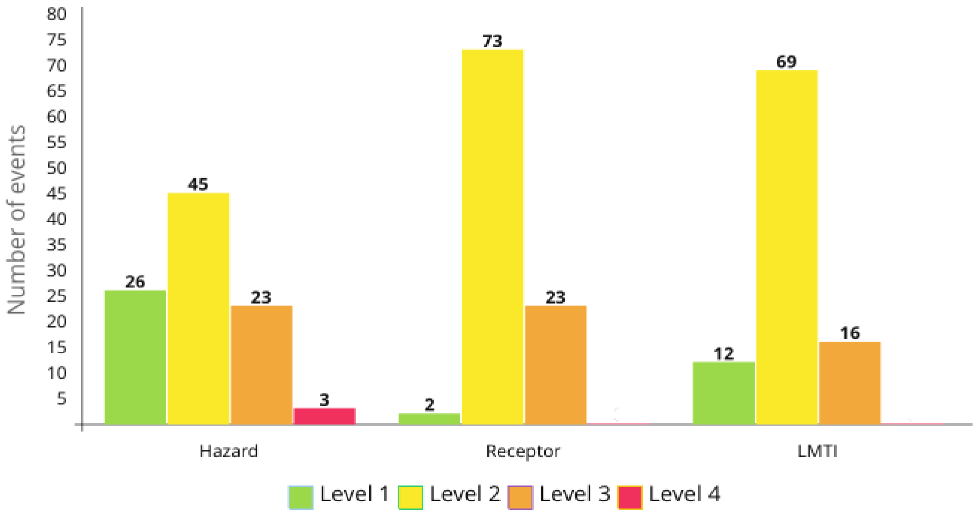


Figure 2: Hazard, receptor and LMTI index scores for UK meteotsunami (1750 to 2022).

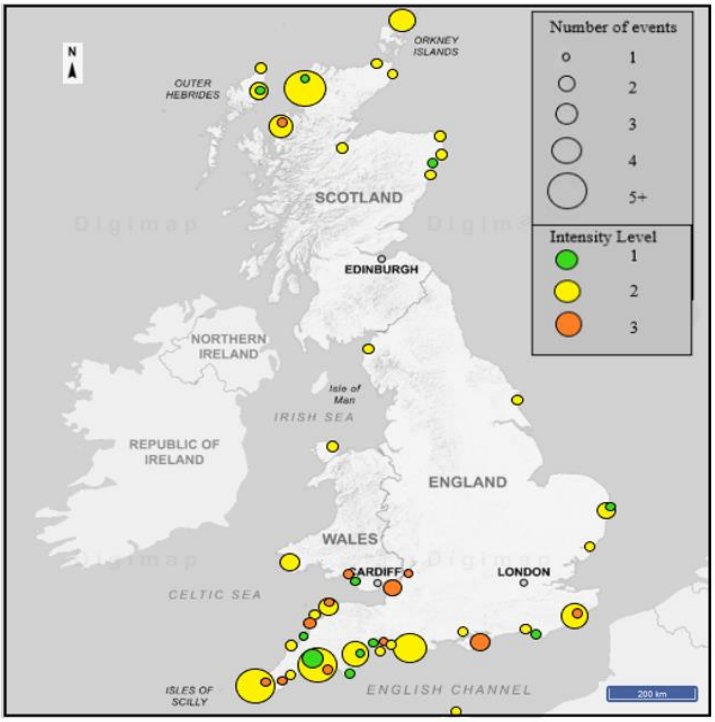


Figure 3: Geographical distribution of UK meteotsunami, with the number of events and the final LMTI intensity level shown at each location. Full results are in supplementary S1. Base map © Crown copyright and database rights 2022 Ordnance Survey (100025252).

4 Discussion

4.1 The LMTI and UK meteotsunami

Upon successful implementation of the LMTI in the UK, results have shown that meteotsunami have tended to be of moderate intensity with an overall Level 2. Table 2 describes a Level 2 type event as representing visibly on instruments but rarely a threat to life. Coastal communities will experience a slight disruption including flooding, the movement of small sized debris and shallow water flow which will usually be accompanied by other hazards such as precipitation and lightning. The identification of southwest England and Scotland as hotspots underscores the importance of the ability to run comparisons between regions and events, allowing researchers to track changes in meteotsunami frequency, intensity and spatial distribution over time. This hotspot tendency is most likely due to the dominant weather direction coming in from the west, off the Atlantic Ocean and from strong convective storms building over Spain and France during the summertime.

The rareness of the combination of atmospheric, marine and topographical factors required for meteotsunami propagation is why Level 4 (severe) events are small in quantity and observed at a limited number of locations. The strongest intensity meteotsunami tend to appear in funnel shaped bays and harbours with a wide shelf which is necessary for Proudman resonance to occur and the transfer energy from the atmosphere to the water. The western English Channel is sufficiently wide and deep, with a shoaling coastline for meteotsunami to become well developed. The noticeable run of Level 3 and Level 4 hazard events that occurred between 1883 and 1932 also coincided with a series of severe storms. The run of Level 1 hazard events between 2009 and 2015 are again due to a series of severe storms but in this instance, we can extrapolate a more accurate picture due to the emergence of more refined quantitative data.

4.2 Application of the LMTI index

Motivated by the absence of a meteotsunami intensity index, in this paper we have presented the new LMTI which will allow for comparative analysis and the standardisation of terminology thus eliminating potential confusion and inconsistencies with a more effective communication media. The index is different from other hazard indices as it does not require sophisticated technology and analyses both the hazard and the receptor site as two independent elements which provides a more holistic view of meteotsunami. Understanding how these events have behaved and evolved historically can be a precursor to establishing future trends and issues to promote forward thinking in terms of coastal planning. The methodology dictates that the index is more appropriate as a post event assessment tool. However, as the field of meteotsunami forecasting and warning progresses, the LMTI will play an important role in assisting in this process. One of the primary strengths of the LMTI lies in its adaptability and potential for global application. While the index was developed and trialled in the UK, it’s under lying principles and methodology can be applied to other meteotsunami prone regions worldwide.

4.3 Constraints and limitations

While the expected results from the LMTI implementation are encouraging, there are certain limitations that should be considered. The availability and quality of historical data may vary across regions, with events missing and the severity of other events being underrepresented this may potentially affect the applicability in certain areas. Addressing this limitation requires efforts to enhance data collection and establish robust monitoring networks.

The index contains two thresholds that rely on qualitative descriptors and many of the historical accounts used may have been subjective in nature, especially with documents such as pamphlets and newspapers tending to misreport, exaggerate or invent characteristics to boost sales. Results have revealed that the further back in time you go the less available and reliable the accounts become. However, as time progresses this will be remedied with improved quantitative data collection methods.

Finally, sea level, shoreline slope and elevation in historical times would have been different from present day and the geometric and topographic nuances of an area can have effects on the propagation of waves. As adjustment of this is beyond the scope of this study; we must assume a static shoreline position based up on current data. Despite the limitations, the index proves to be a useful indication of meteotsunami intensity, and these limitations should not be an issue in moving forward as data becomes more available and at a higher frequency.

4.4 Further work

Successful implementation of the LMTI in the UK allows for further research and refinement. The index has been future proofed not only to allow for the expansion into higher intensity levels but for the analysis of different geographical locations. In the UK, the results can be used to champion the need for higher frequency data sampling on tide gauges and for the consideration of the inclusion of meteotsunami into coastal management regimes. From a global perspective, researchers and practitioners can establish a consistent framework for data collection and expand the knowledge of meteotsunami through the implementation of this index. This can allow for cross regional studies containing a robust identification and comparison of trends.

5 Conclusions

After a review of the field of research for meteotsunami it was revealed that there was an absence of a standardised format for quantifying this phenomenon. In this paper, we introduced a novel meteotsunami intensity index (LMTI), the first of its kind. The successful implementation of the LMTI in the UK signifies an advance in meteotsunami research with results revealing a 69 % prominence of Level 2 (moderate intensity with slight disruption and a rare threat to life) type events occurring and the presence of distinct geographical hotspots in southwest England and Scotland.

Additionally, we successfully assessed the applicability and adaptability of the LMTI in a global context. As further trials and refinements are carried out, the LMTI has the potential to become a widely accepted standard, contributing to coastal planning and early warning systems worldwide.

Supplement. The supplementary UK map related to this article is available online at: https://www.google.com/maps/d/edit?mid=1RiSeW-DIPSylIVOLv_8-T8Gy_e0To08&usp=sharing

Author contributions. C. Lewis developed the concept, designed, and executed the study and prepared the original draft. T. Smyth, J. Neumann, and H. Cloke supervised the project, provided advice, reviewed, and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Data availability. The datasets used in this study were derived from resources available in the public domain.

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