Meteotsunami in the United Kingdom: The hidden hazard.

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Abstract.

This paper examined the occurrence and seasonality of meteotsunami in the United Kingdom (UK) to present a revised and updated catalogue of events occurring since 1750. Previous case studies have alluded to a summer prevalence and rarity of this hazard in the UK. We have verified and classified 98 events using a developed set of identification criteria. The results have revealed a prominent seasonal pattern of winter events which are related to mid latitude depressions with precipitating convective weather systems. A geographical pattern has also emerged, highlighting three ‘hotspot’ areas at the highest risk from meteotsunami. The evidence reviewed, and new data presented here shows that the hazard posed by meteotsunami has been underestimated in the UK.

Keywords: meteotsunami, UK, hazard, mid latitude depressions.

1 Introduction

Meteotsunamis or meteorological tsunamis are globally occurring progressive shallow water waves with a period of between 2 to 120 minutes which results from an air-sea interaction. They tend to be initiated by sudden pressure changes and wind stress from moving atmospheric systems with sources ranging from convective clouds, cyclones, squalls, thunderstorms, atmospheric gravity waves and strong mid-tropospheric winds (Vilibic and Sepic, 2017). The atmospheric pressure changes are typically only a few mb over a few tens of minutes which corresponds to only a few centimetres of sea level change occurring in a process known as the inverse barometer effect (for example, a 3 mb pressure jump will produce a 30 cm ocean wave). The atmospheric disturbance transfers energy into the ocean initiating and amplifying a water wave which travels at the same speed as the atmospheric wave, in a process known as Proudman resonance (Proudman, 1929). When the water wave reaches the coastline and shallower water, it becomes a multi resonant phenomena and is further amplified through coastal resonances. For example, if the wave reaches the entrance of a semi enclosed basin it can induce an oscillation in the basin known as harbour resonance. However, if the wave reaches a beach type environment and the along shore component of the disturbance equals the phase speed of the edge wave this is a process known as Greenspan resonance (Monserrat et al. 2006). The resultant waves can elevate the coastal water level and can substantially increase flow velocities with the potential for rip currents (Linares et al. 2019). Due to the rapid onset and unexpected nature of meteotsunami waves, they have the potential to cause destruction, injuries and even fatalities (Sibley et al. 2016). For a global perspective and overview of meteotsunami observations we recommend Pellikka et al. (2020) for observations in Finland, Sepic et al. (2018) for the Adriatic, Belche et al. (2016) for seasonality of meteotsunami in the Great Lakes, Pattiaratchi and Wijeratne (2016) for observations in southwest Australia and Monserrat, Vilibic and Rabinovich (2006) provide a general overview of the mechanisms of meteotsunami.

Meteotsunami research and monitoring is more advanced in the Mediterranean, the East Coast of the USA, and the Great Lakes due to the higher number of recorded events. However, events in the UK appear to be rare and are believed to be less devastating, meaning that research has been limited to date.

The two principal factors contributing to this belief are:

1. The current (since 1993) 15-minute sampling interval that is used at UK tide gauges is incapable of detecting waves with periods of between 2 – 120 minutes. This means that many events go unobserved, wave heights are underestimated, or meteotsunamis are mischaracterised as seiches, tsunamis or surge.
2. Until recently research has suggested that UK meteotsunamis are generated by precipitating, convective weather systems associated with hot weather. Such mesoscale convective systems may be associated with synoptic “Spanish plume” events. These synoptic events are more prevalent between May - October (Haslett et al. 2009b; Tappin et al. 2013; Sibley, 2012 and 2016; Thompson, 2020), leading to the belief that meteotsunami occurrence is a summer-time phenomena. However, it is now emerging that embedded convection within winter frontal systems may also be responsible for a sizeable proportion of these waves (Williams et al. 2021).

Several issues have resulted from the untested assumption that meteotsunami events are 1) low frequency and 2) predominantly occur in summer, which has been combined with 3) the lack of high-resolution temporal data. Firstly, there is no central database of UK events. Secondly, there is no standardised methodology of meteotsunami identification. Thirdly, there is no Government or regional policy in place to cover impacts from a meteotsunami event. There is a misconception of the risk posed by meteotsunami especially for coastal areas that are already at risk from storm impacts associated with pluvial (extreme precipitation) and fluvial hazards (high levels of river discharge). In the future the overall level of risk is likely to be greatly exacerbated by rising sea levels and an intensification of storm frequency and severity (Vilibic et al. 2018; Masselink et al. 2015).

As stated by Sepic et al. (2015) the assessment of meteotsunami should become the standard in coastal hazard assessments, event cataloguing is a pre-requisite for any coastal hazard assessment especially in identifying the geographical areas that have experienced meteotsunami and the frequency of exposure.

The aim of this paper is to compile, update and extend the existing list UK meteotsunami to include winter events, and to highlight the occurrence, frequency, and spatial distribution of events. Where seasonality was alluded to in Williams et al. (2021), their study was principally focused on meteotsunami in Northwest Europe from 2010 to 2017. This paper will further their study by focussing in on UK waters only and will add new events up to the end of 2022. The methodology fulfils this aim by applying a set of developed identification criteria to the re-assessment of fragmented historical accounts and to the analysis of tide gauge and atmospheric data to identify new events. The outcome also highlights the potential element of winter compound hazard risk which may occur when meteotsunami waves arrive at the coast in short succession or concurrently with other storm associated hazards.

We propose the following research questions:

1. What standardised criteria should be used to identify meteotsunami?
2. Have events occurred which were ignored or misidentified?
3. In which regions of the UK and in what months do meteotsunami occur most frequently?
4. What are the atmospheric variables that can be correlated with meteotsunami events?

2 Methodology

This section outlines the data sources and identification criteria used to fulfil the objective of cataloguing and characterising UK meteotsunami. We have extrapolated as much quantitative data as possible, to verify the event with the standardised criteria and to then arrange the results into tabular form to allow ease of use (Table 1).

2.1 Meteotsunami identification criteria

As there are currently no fixed criteria for what qualifies as a meteotsunami, in this paper we bring together various aspects used by other researchers in the field, into one standardised system. Figure 1 (a – d) displays a visual representation of the commonly used criteria, which we explain in more detail in sections 2.1.1 – 2.1.2. The methodologies that have been previously used by researchers and studies have variations, with some using qualitative methods that base events on eyewitness accounts (Haslett et al, 2009a/b) and others using quantitative data from sea level and atmospheric observations (Tappin et al. 2013; Sibley, 2016). For the purpose of this paper, we have classified meteotsunami as atmospherically induced sea level oscillations meeting at least one sea level and one atmospheric characteristic. This allows for the distinguishing of meteotsunami from other types of waveforms and is applicable to either qualitative accounts or quantitative data.

2.1.1 Sea level criteria (Category 1)

a. Periods of sea level disturbance ranging from between 2 and 120 minutes (Figure 1a).

b. Wave heights exceeding 0.20 m. This threshold is within the peak thresholds of 0.2 m and 0.3 m as used by other researchers in the field such as Williams et al. (2021); Dusek et al. (2019); Belche et al. (2016); Sepic et al. (2012) and Monserrat, Vilibic and Rabinovich (2006). A 0.3 m water elevation may not appear to be dangerous, but a meteotsunami in 2003 in New Zealand caused a fully laden oil tanker to be grounded through strong currents (Goring, 2009). Lynett et al. (2014) also states that any wave over 0.3 m will start to float vehicles regardless of flow velocity and is enough to sweep people off of their feet. These thresholds are a tried and tested set of characteristics that reflect meteotsunami especially those in UK waters. 0.2 m was opted to be used as the lower end of the threshold as this is more suitable for distinguishing a greater number of events that may have been missed at the higher end of the threshold (0.3m). Any anomaly below 0.2m would not be large enough to allow for accurate verification and for its separation from any other water disturbances. (Figure 1a illustrates the meteotsunami wave height criteria in the data as recorded on 27 June 2011).

c. A wave disturbance registering at two or more locations or tide gauge stations (Williams et al. 2021; Kim et al. 2021).

2.1.2 Atmospheric criteria (Category 2)

a. The presence of a convective weather system at the time of the wave event displaying high radar reflectivity with precipitation rates exceeding 2 mm/h^{-1}, initiated over the sea. (Figure 1b represents the radar reflectivity of the various convective weather systems present during four different meteotsunami events).

b. An atmospheric pressure of 1005 mb or less with a rapid change of ±1 mb in 30 minutes or a 3 mb fall over three hours or less (Monserrat, Vilibic and Rabinovich, 2006). (Figure 1c illustrates this distinct air pressure change as recorded during the 28 October 2013 event).

c. Convective Available Potential Energy (CAPE) showing the unstable vertical profile of the atmosphere that leads to convective activity (Williams et al. 2019). (Figure 1d displays a radiosonde ascent showing sufficient CAPE to produce the event that occurred on 1 July 2015 at Stonehaven, East Scotland. Even though CAPE is a bulk atmospheric measurement and meteotsunami are localised, if this element is present in conjunction with the other indicators it supports the presence of convective activity which aids in the generation of meteotsunami.

d. A change in wind speed exceeding 10 m/s^{-1} (anything under this is too weak for a meteotsunami to generate) or/and a drop in air temperature of 1.5°C in 30 minutes (Figure 1c demonstrates this increase in wind speed as recorded during the 28 October 2013 event).

2.1.3 Geological criteria (Category 3)

a. The absence of any other explanation or data to imply an alternative source trigger. For example, the presence of seismic triggers within the continental shelf area which would produce a geological tsunami wave. However, there is one exception to this rule which for the purpose of this paper we include as a meteotsunami trigger. Volcanic eruptions, this was demonstrated on 28 August 1883 (Krakatoa) and recently on 16 January 2021 (Tonga Ha'apai) where wave anomalies occurred and were the product of air pressure waves created by the eruptions. It may be argued that they are not to be classed as meteotsunami waves. However, for the purpose of this catalogue, we are classifying them as meteotsunami as they are sourced from air pressure disturbances which couple with water waves and have a wave period of 2 to 120 minutes. The force of the Tonga Ha'apai explosions sent a shockwave through the atmosphere that circled the globe three times. The resultant pressure wave travelled at close to the speed of sound and as a result coupled with ocean waves to create a meteotsunami which was detected as far away as Portugal and the UK (Burt. S, 2022).

To ease the interpretation of results, the UK coastline has been partitioned into six coastal regions based on the National Tidal and Sea Level Facility (NTSLF) tide gauge network (Supplementary Table S1). The data are also separated into two seasons (each comprising of six months) that divide up the calendar year at the spring and autumn equinoxes (Haigh et al. 2016). April to September inclusive is referred to throughout this paper as 'summer' and October to March is referred to as 'winter'. Finally, due to the nature of the data, two time series of meteotsunami are being referred to throughout this paper, one based primarily on historical eyewitness accounts due to a lack of high frequency instrumentation (the years 1750 to 2009 AD), and one based on and verified by quantitative instrumental data (the years 2010 to 2022 AD).

2.2 Historical record (1750 to 2009)

To gain a complete understanding of these events we follow Long (2015) and Haslett and Bryant (2008) who dated their historic tsunami catalogues back to approximately 1000 AD. We noted that any events preceding 1750 AD were vaguely recorded, making validation problematic so we opted to date our catalogue back to 1750. References to meteotsunami like events in historical accounts tend to be based on descriptions of the state of the water at the coast with a lack of instrumental tidal data. There is a lack of or limited weather data so tracing back the atmospheric source is not as straightforward. It is only until the last few decades that meteorological data with sufficient resolution have been readily available. With tide gauge data, prior to 1993 the resolution was hourly, and it was not until 1996 that all the current tide gauge sites became fully operational. Therefore, we have used 2009 as the upper limit of the historical record. The historical reports tend to be derived from newspaper articles, parish records, harbourmaster records and eyewitness accounts. Although there is reason to be sceptical of these accounts as they afford a level of biased review and sensationalism, they do still hold value in terms of a societal viewpoint and may help to fill in any gaps (Haslett and Bryant, 2009a/b).

There are certain characteristics that flag up in an historical account to verify whether it is a meteotsunami event or not. To illustrate this, we can highlight the historical account for the event of 23 May 1847 where we can look at a letter from Robert Blight of Penzance dated 24 May and published in the Cornwall Royal Gazette on 28 May. The full extract can be found in supplementary extract S1 of this paper and in Long (2015, p26).

“… The changes in the atmosphere during the day were very remarkable. In the morning, about six o’clock, we had a breeze from the southeast; by eight, it was a perfect calm; between ten o’clock and two, the mercury sunk several degrees; about three in the afternoon a breeze sprung up suddenly from the west, and the sky, as suddenly, became overcast……. It is very probable that all these changes, and even the agitation of the sea, were produced by electricity…”

In this particularly detailed account (supplementary extract S1) we can identify six of the nine criteria, including a drawback and sudden in rush of water, accompanied by a rumbling noise and the water being higher than expected at eight feet (criteria 1A and 1D), all indicating a tsunami like event. The key to the identification of a meteotsunami is in the atmospheric portion of the account, what started out as calm morning led to a change in wind speed and direction, veering from south easterly in the morning to westerly in the afternoon (criteria 2D). This variable wind was accompanied by a drop in temperature (criteria 2D) and finally, there was mention of the presence of a storm in terms of overcast sky, threatening rain and lightning (criteria 2A). As such, we identify this wave as a meteotsunami by applying both of our oceanographic and atmospheric criteria to the historic account.

2.3 Tide gauge analysis for the 2010 to 2022 record

To identify meteotsunami from 1 January 2010 to 31 December 2022 we use data records that are available at higher frequencies meaning meteotsunami are more distinctly observable. The information for this portion of the catalogue is sourced from the British Oceanographic data centre (BODC) website (https://www.bodc.ac.uk/) and the International Oceanographic Commission (IOC) website (https://ioc-sealevelmonitoring.org/) where data are displayed from the 'Class A' network of tide gauges owned and funded by the Environment Agency (EA). We also use the postprocessed data of Williams et al. (2021) where the raw sea level tide gauge data has been high pass filtered to isolate high frequency disturbances. This removes periods of over 120 minutes and separates out the tidal components. In this way any signals in the tsunami frequency band (2 to 120 minutes) are isolated from the sea level elevations. Any remaining signals larger than the background noise are then identified and checked against our threshold criteria to verify events as potential meteotsunami. Apart from the standard processing to remove any erroneous spikes outside of the parameters, a visual quality control was carried out, where a seven-day plot of the data was evaluated to highlight any clear artificial spikes or gaps. Also, any data points that had no accompanying air pressure changes were also excluded from any further analysis.

2.4 Atmospheric data analysis for the 2010 to 2022 record

The time of the potential meteotsunami events are noted from the tide gauge data and they are then linked to specific precipitating convective atmospheric systems by using the meteorological C-band radar network, which is pre-processed by the UK Meteorological Office before download (Met Office 2003). The convective systems highlighted by the radar are classified into four distinct types (as shown in Figure 1b). These are: (1) open cells which are situated behind the cold front of cyclonic weather, usually where cold dry air passes over the warm sea creating shallow convection; (2) Quasi linear systems which tend to be multi-cellular and linearly organised with high CAPE, heavy precipitation, and strong winds (this type of weather feature are sometimes called squall lines and can occur within synoptic Spanish Plume events); (3) Isolated small short duration (<1h) thunderstorm cells and (4) Nonlinear clusters which are large circular, long lived clusters of precipitation and thunderstorm cells.

The atmospheric ascent soundings are obtained from the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html) with the UK stations at Camborne (station number: 03808) and Lerwick (station number: 03005) being used. Soundings are available for 0000 UTC and 1200 UTC on each day and if a CAPE value of greater than 0 occurs then this shows a marginally unstable atmosphere leading to convective activity. Finally, the synoptic charts allow for verification of the storm system including the location of the pressure centres and fronts at the time of the meteotsunami wave event.

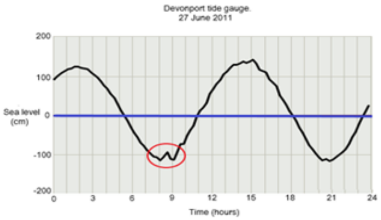


Figure 1a: Devonport (50°36N 4°18W) tide gauge for 27 June 2011 showing a distinct sea level disturbance at 0830 UTC as highlighted with a red circle. This is a representation of criteria 1b. The timing of this 0.25 m rise and fall in the sea level corresponds with the arrival of the meteotsunami event at that specific location.

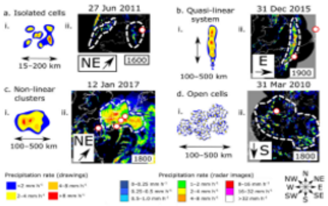


Figure 1b: The four different types of convective activity as shown on radar reflectivity identifying meteotsunami events . A representation of criteria 2a. Orange and red in the images shows high precipitation rates (>4 mm/h^{-1}). With idealised images shown on the left and actual examples taken from UK events on the right. All showing date, time, and direction of the storm as well as the location of the tide gauges (white dots). Image by David Williams, Journal of Physical Oceanography (https://doi.org/10.1175/JPO-D-20-0175.1), licensed under a Creative Commons — Attribution 4.0 International — CC BY 4.0

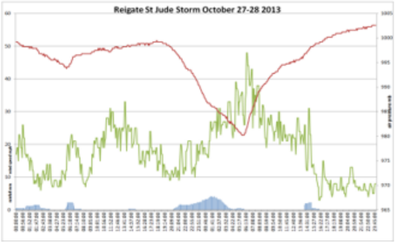


Figure 1c: The atmospheric pressure, wind speed and precipitation at Reigate (51°14N 0°11W) during the 27 to 28th October 2013 storm associated with the meteotsunami. A representation of criteria 2b and 2d. The graph shows atmospheric pressure (red line) of less than 1005 mb and falling as the atmospheric disturbance moves over the area, with a corresponding rising wind speed of 20 mph (green line) and precipitation (blue bars). Reproduced with the kind permission of Simon Collins. https://rgsweather.com/2013/10/29/st-jude-causes-and-impacts-of-the-october-storm-27-28-2013/amp/

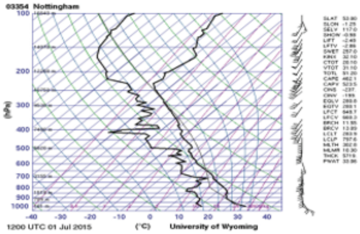


Figure 1d: The Nottingham radiosonde ascent at 1200 UTC on 1 July 2015 during a meteotsunami event in the North Sea. A representation of criteria 2c which indicates sufficient CAPE (462.1 J Kg) to produce high base convective activity, with the cloud base at an approximate height of 3000 m and cloud top at 11000m. http://weather.uwyo.edu/upperair/sounding.html

3 Results

In this section we highlight the seasonal occurrence and distribution of UK meteotsunami events in both the historical record and the more recent instrumental data record. This is augmented by the identification of trigger systems associated with the events where available. It is prudent to note here that the catalogue cannot be considered as complete, and this is signified by dashed lines (i.e., -) in the columns where data or information are either unavailable or have not been located.

3.1 Historical record (1750 to 2009)

We identify 98 events as being meteotsunami occurring in UK waters between January 1750 and December 2022 (Table 1), with 48 of these occurring within the historical record (1750 to 2009). This record shows that 67% of documented meteotsunamis occur in summer (April – September), with 44% of documented meteotsunamis occurring in July and August. The single year experiencing the most documented events was 1802 AD, numbering three, and the decade experiencing the most documented events was the 1840s, with six in total. The presence of a storm and/or characteristics of convective activity (thunder, and lightning) at the time of the wave event was noted for 42 of the 48 events (91%) in the historical record. There was also a defined southwest prevalence of meteotsunami in historical documents, with Devon, Cornwall and Somerset recording a combined total of 29 events. Within the historical record we have identified four new events and reclassified four tsunamis, three storm surge and nine events of unknown origin as meteotsunami. Seven of these occurred within winter months (Table 1).

3.2 Seasonal and locational frequency of UK meteotsunami events (2010 to 2022)

Meteotsunamis have been thought to be a rare phenomenon in the UK and that when they do occur, it has been tended to be in the summer months due to the more abundant convective activity (Haslett et al, 2009b; Tappin et al, 2013; Sibley, 2016; Thompson, 2020). However, of the 98 identified meteotsunami events verified in this paper, 50 have been interpreted as occurring since 2010, 33 (66%) of those occurring during the winter months and nine of the winter events are identified as new. We find that not only are UK meteotsunami more common in occurrence than previous research indicates, but that they are a year-round phenomenon, as exhibited in Table 1 and Figures 2 and 3.

The historical section of the catalogue shows an estimated return period of 5.4 years. This return period considerably decreases for the instrumental data section where the UK return period reduces to an estimated 0.25 years. With an average of four events per year, we can see that certain years have experienced above average numbers and high proportions of winter events, with seven winter events out of eight in 2013, four out of seven in 2021 and five out of seven in 2022. Figure 3 displays the seasonal distribution of these events, with 34% of meteotsunami recorded in December and January, and no events being recorded in March or April. Following statistical analysis, the recorded maximum wave amplitude for each event resulted in a mean wave height of 0.33 m for winter and 0.35 m for summer. With a t-test score of 0.30 and a P-value of 0.07, the tests indicate a similarity between the two sample sets, where the difference between seasonal wave heights is considered to be not statistically significant.

Summarising the results from the catalogue in its entirety, we suggest that there are three ‘hotspot’ regions where meteotsunami events appear to be most frequent, these are 1) northwest Scotland, 2) Wales and 3) the southwest UK. Up until 2009, Penzance in the southwest UK had experienced the most meteotsunami with eight in total. Then from 2010, Kinlochbervie in Northwest Scotland experienced the maximum wave height of 0.51 m during the 16 November 2016 event. This same location was exposed to 14 separate meteotsunami events in the 12 years from 2010 to 2022. Harbour style geomorphology appears to be more susceptible to meteotsunami resonance recording 71% of the events and beach environments with the remaining 29%.

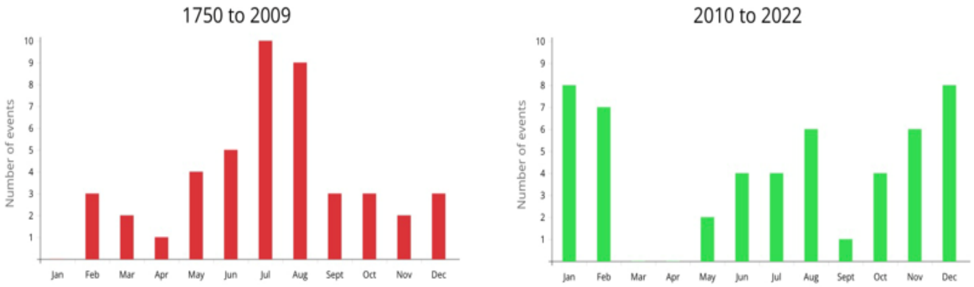


Figure 2: Seasonal distribution of UK meteotsunami events, historical record (1750 to 2009) and current record (2010 to 2022).

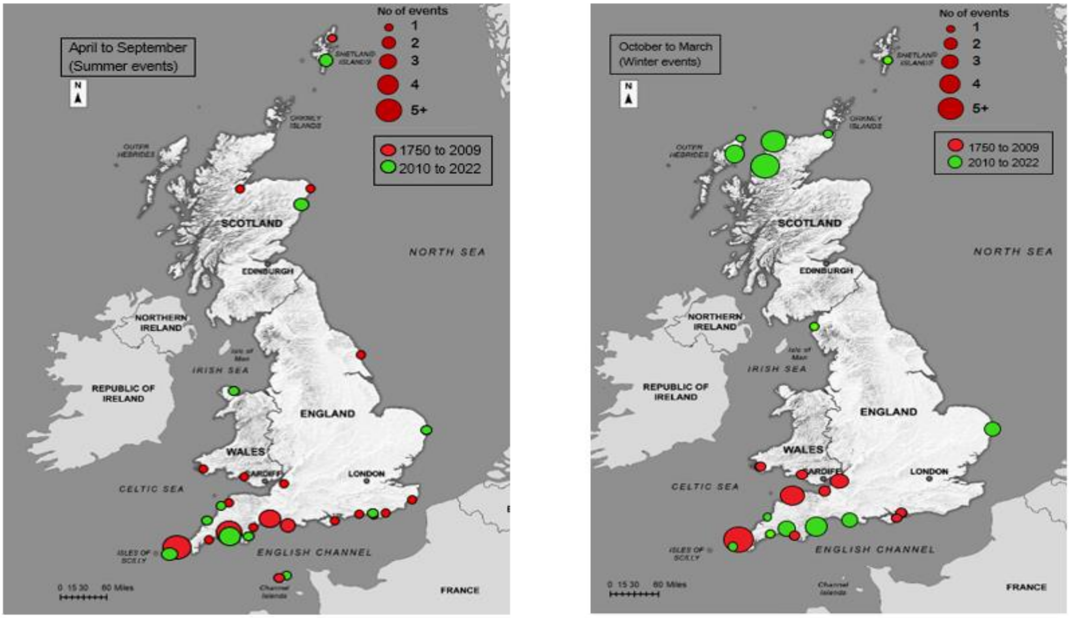


Figure 3: Seasonal and locational distribution of maximum wave heights from 1750 to 2022. Number of events at specific locations are represented by dot size as shown in the key. Base map © Crown copyright and database rights 2022 Ordnance Survey (100025252).

3.3 Relationship between meteotsunami and winter storms

In this section, we highlight two specific meteotsunami events that occurred in two consecutive winter seasons. These two events have been picked as they are new events to the catalogue, and they represent a typical winter meteotsunami hidden in the associated storm data. The winter of 2021/22 saw seven sequential named storms with five verifiable meteotsunami events, one of which was the 20th of October 2021. The winter of 2022/23 saw 3 likely / numerically verifiable meteotsunami events, one of which was the 1 November 2022. Both meteotsunami events were low profile, localised in nature and hidden within larger scale heavily precipitating low-pressure systems.

3.3.1 Event 1: 20 October 2021

Two low pressure systems developed in the Atlantic Ocean and propagated eastwards towards the southwest UK. The first system which was detected as a mature echo signature on radar contained a sharp cold front (squall) which moved into Cornwall at approximately 0400 UTC (criteria 2a and Figure 4a) with a simultaneous leading air pressure rise of 1.6 mb over 4 minutes followed by a sharp 2°C air temperature drop (criteria 2b/d and Figure

4c). A flattish ridge between this first system and the second system named Aurore by Meteo France led to a yellow rainfall warning being issued in the UK. At 1600 UTC the second system with a low-pressure centre of 992 mb moved into the Isles of Scilly and propagated across Cornwall and Devon, it contained a heavily precipitating non-linear system with convective activity and strong winds (+70 mph) rapidly veering from west to south (criteria 2d). This system initiated a sharp air pressure rise of 0.5 mb over 2 minutes which coincided with a high tide. Both low pressure systems initiated a series of meteotsunami waves that tracked eastwards along the coast of Cornwall, Devon, and Dorset. Wave anomalies were recorded in Plymouth at 1645 UTC with a maximum wave height of 0.36 m, Totnes at 1700 UTC and Port Isaac, Weymouth, and the Isle of Wight at 1800 UTC before dissipating (criteria 1b/c).

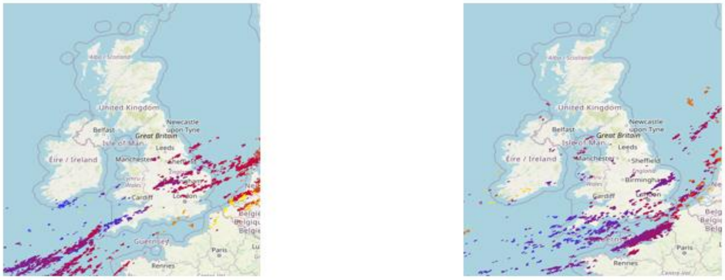
Event 2: 1 November 2022

A series of low-pressure systems over the Atlantic Ocean, swept into the southwest UK on 1 November, the first one with its centre over Cornwall at 0000 UTC, followed by a second low pressure system arriving along the southwest coast at approx. 0600 UTC then moving northeast up over the UK.

This synoptic situation was complicated by a series of associated cold fronts followed by low pressure troughs. A quasi-linear precipitation system with its associated convective cells developed in the vicinity (criteria 2a and c, Figures 4d and e). The arrival of the storm feature was detected in surface observations with a sharp 1 mb/35 minutes air pressure rise (Figure 4f) which coincided with a series of unpredictable meteotsunami waves which reached a maximum wave height of 0.3 m (criteria 2b). The waves tracked along the southwest UK alongside of the movement of the cold fronts, the heavily precipitating cells and the convective activity where it was recorded at five tide gauge sites along the southwest coast at Port Isaac, St Marys, Newlyn, Plymouth and Totnes (criteria 1c). The first series of wave anomalies occurred at 0900 UTC coinciding with a high tide followed by a second set of wave anomalies at 1600 UTC coinciding with a low tide.

a. Rain radar 20 October 2021 at 0300 UTC

d. Rain radar 1 November 2022 at 0900 UTC



b. Lightning 20 October 2021 at 0000 UTC

e. Lightning 1 November 2022 at 0600 UTC

c. Air pressure 20 October 2021

f. Air pressure 1 November 2022

Figure 4: The relationships between criteria of two winter meteotsunami events.. All images are open source: Rain radar : www.ventusy.com Lightning : www.lightningmaps.org Air pressure: www.starlingsroost.ddns.net

Table 1: Descriptions and references for events that can be identified as UK meteotsunami events from 1750 to 2022. 1750 to 2009 are principally derived from historical sources and 2010 to 2022 are principally derived from instrumental data. The threshold criteria outlined in the methodology section was used to verify previous (V) or identify new (N) events, including new winter events (NW). (Wm represents maximum wave height in metres).

Date	Location	Wm	Time	Notes	Id criteria	Id status	Reference
1 Nov 1755	Ilfracombe	0.3	14.00	4 waves in 2 h, calm, NE wind, low tide, damage to sandbanks	1A, 1B, 2A,	NW	Dawson et al 2000
27 Feb 1756	Ilfracombe	1.8	18.00	4 mins wave period, 30 mins duration, rumbling sea	1A, 1B, 2A, 3A	NW	Dawson et al 2000
31 May 1759	Lyme Regis	-	-	3 waves in 1 h, ebb and flow	1A, 2A, 3A	N	Dawson et al 2000
31 Mar 1761	Mounts Bay	1.2	12.30	Ebb and flow 5 times in 1 h, NNE wind, cloudy, thunder	1A, 1C, 1C, 2A	NW	Long 2015
18 Sept 1763	Weymouth	3	-	3 waves, ebb, and flow	1A, 1B, 3A	N	www.phenomena.org.uk
11 Feb 1764	Bristol	3	-	2 waves, ebb in 30 mins	1A, 2A, 3A	NW	www.phenomena.org.uk
23 Dec 1791	Cornwall	-	04.00	Rain, hail, extreme lightning, boats moved	2A, 3A	NW	Borlase 1758
17 July 1793	Plymouth	0.6	07.00	3 waves in 1 h, boats damaged	1A, 1B, 2A, 3A	N	-
18 Aug 1797	Lyme Regis	3	-	3 waves in 1 h, lightning	1A, 2A, 3A	N	Dawson et al 2000
9 Aug 1802	Devon	0.35	06.00	3 waves in 1 h, ebb and flow twice in 20 min	1A, 1C	N	Long 2015
10 Aug 1802	Teignmouth	0.6	08.00	10 min interval waves, fish on shoreline	1A, 1B	N	Long 2015
30 Aug 1802	Jersey	1.2	-	3 ebb and flows in 8 mins	1A, 1B, 2A	N	Long 2015
31 May 1811	Plymouth	2.4	03.00	4 h duration, rain, low pressure, ebb and flow, SW wind	1A, 1B, 2A, 2B	N	Dawson et al 2000
4 Mar 1818	Portsmouth	1.5	08.00	Rain, W to SW wind, high water for 3 h	1C, 2A, 2D	NW	www.surgewatch.org
13 Sept 1821	Plymouth	1	14.00	Ebb and flow, boats moved	1A, 1B, 1C, 3A	N	Long 2015
13 July 1824	Plymouth	0.6	22.00	Ebb and flow, 4 m/s currents, ESE light wind, boats moved	1A, 1C, 2D, 3A	N	Archer, 2016
23 Nov 1824	Plymouth	2	01.00	3 waves in 10 min intervals, storm surge, 180 metres inland	1B, 1B, 2A, 3A	V	Haslett and Bryant 2009
5 July 1843	Plymouth	1	11.00	4 waves in 20 min, storm moved north, strong wind	1A, 1B, 1C, 2A	N	Thompson et al 2020
3 July 1845	Weymouth	0.6	10.30	Ebb and flow 5 times in 30 mins	1A, 2A, 3A	V	Long 2015
5 July 1846	Cornwall	0.5	04.30	Thunder, severe storm reported	1C, 2A, 3A	V	Dawson et al 2000
1 Aug 1846	Penzance	0.3	04.00	30 min duration, calm sea, 6-minute ebb and flow	1C, 2A, 3A	V	Dawson et al 2000
23 May 1847	Penzance	0.9	05.00	20 mins, squally wind, sudden rush of water	1A, 1B, 2A, 2D	V	Long 2015
7 July 1848	Bristol	1.5	04.00	Thunder	1C, 2A, 3A	V	Edmonds 1862

Date	Location	Wm (m)	Time (UTC)	Notes	ID criteria	Id Status	Reference
6 June 1855	Penzance	0.9	pm	Ebb & flow 2 to 3 times, rumbling sea, strong currents	1C, 2A, 3A	N	Dawson et al 2000
5 June 1858	Folkstone	0.9	08.00	Ebb & flow in 5 mins, ENE to WNW wind, hail, rain, seiche	1A, 1C, 2A, 2D	V	Long 2015
25 June 1859	Cornwall	0.3	Night	Abnormal sea oscillations x2, squall line, strong currents	1A, 2A, 3A	V	Dawson et al 2000
4 Oct 1859	Cornwall	4.4	07.00	3 waves, 6 minute ebb, warm air temperatures, 1 mile upriver	1C, 2A, 3A	V	Dawson et al 2000
Oct 1865	Port Talbot	-	-	2 tides in 1 h	1A, 2A, 3A	NW	www.surgewatch.org
23 Apr 1868	Lyme Regis	6	-	Swell, roar from the sea, no wind, low air pressure, calm sea	1C, 2A, 3A	V	Haslett & Bryant 2009
29 Sept 1869	Cornwall	0.9	06.00	20 min wave period	1A, 1B, 1C, 2A	V	Dawson et al 2000
13 June 1881	Shetland	-	-	3 waves in 20 min, storm, boat damage	1A, 2A	V	Long 2015
28 Aug 1883	Plymouth	0.25	09.00	Gravity pressure wave from Krakatoa volcanic eruption	1B, 2B,	V	Garrett 1970
17 Oct 1883	Severn Est	1	08.00	1 dead, SW strong wind, high tide, precipitation, 1 mile in	1A, 1C, 2A, 2D	V	Haslett & Bryant 2009
13 June 1886	Wick	0.45	16.30	Falling air pressure	1C, 2B, 3A	V	Long 2015
18 Aug 1892	Yealm	4	-	Quick ebb and flow, squall line, 3 waves, boat damage	1B, 1C, 2A, 2B	V	Haslett & Bryant 2009
16 Dec 1910	Ilfracombe	4	06.15	Swell, bore, low pressure, 100 metre inland, bedrock erosion	1B, 2B	V	Haslett & Bryant 2009
26 Dec 1912	Isle of Wight	0.9	12.00	975 mb pressure low, SW wind, rain, cold front	1A, 2A, 2B, 2D	NW	www.surgewatch.org
20 July 1929	Folkstone	6	19.30	8 waves, 180 metres inland, 5 mins period, low tide, 3 dead	1B, 1C, 2A, 2D	V	Haslett & Bryant 2009
2 Aug 1932	Aberavon	9.3	-	4 dead, wave train, cloudy, rumbling sea, strong currents	1B, 2A, 3A	V	Haslett et al 2009
5 Aug 1938	Bridlington	4	08.00	Sea receded 4.5 m, boats moved, fish left on dry land	1A, 1B, 2A	V	Haslett et al 2009
4 July 1939	Milford Haven	6	00.30	3 dead, rumbling sea, boats moved, mid tide	1B, 2A, 3A	V	Haslett & Bryant 2009
3 July 1946	Cornwall	-	PM	Ebb and flow, squall line, rumbling sea, moorings broke	1A, 2A, 2B, 3A	V	Haslett & Bryant 2009
13 July 1949	Mevagissey	-	04.00	Easterly winds, boats smashed on rocks	1A, 1C, 2A, 2D	V	Long 2015
6 July 1957	Bembridge	4	19.30	Wave train, 2 waves in 1 h, sultry, overcast, rocks moved	1A, 1C, 1C, 2A	V	Haslett & Bryant 2009
31 July 1966	Westward Ho	3	PM	Receding water, frontal trough, squall line	1A, 1B, 2A	V	Haslett & Bryant 2009
1 July 1968	Folkstone	-	-	5 mb air pressure drop in 30 mins,	1A, 2B, 3A	V	Stevenson 1969
13 Feb 1979	Bristol	0.6	07.00	Spring tide, long unbroken waves, storm surge, 10 min period	1C, 2B	V	Haslett & Bryant 2009
28 May 2008	Peterhead	3	00.30	Ebb and flow in 10 mins, 4 to 6 waves	1 A-C, 2 A-C	V	Sibley et al 2006
29 Jan 2010	Lowestoft	0.29	16.00	Open cell, S moving storm, 11 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
29 Aug 2010	Lowestoft	0.27	19.00	Open cell, S moving storm, 4 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021

Date	**Location**	**Wm (m)**	**Time (UTC)**	**Notes**	**Id criteria**	**Id Status**	**Reference**
3 Feb 2011	Ullapool	0.3	22.00	Open cell, E moving, 7 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
27 June 2011	Devonport	0.3	08.30	Non-linear, N moving, 8 tide gauges plus European tide gauges	1A-C, 2A, 3A	V	Tappin et al 2013
22 Aug 2011	Newhaven	0.3	01.00	Quasi linear, N moving, 3 tide gauges, mid latitude depression	1 A-C, 2A, 3A	V	Williams et al 2021
24 Nov 2011	Ullapool	0.26	04.30	Open cell, E moving, 8 tide gauges, mid latitude depression	1 A-C, 2A, 3A	V	Williams et al 2021
3 Jan 2012	Lowestoft	0.33	17.15	Quasi linear, SE moving, 17 tide gauges, Low pressure	1 A-C, 2A, 3A	V	Williams et al 2021
4 Feb 2013	Stornoway	0.32	07.00	Open cell, SE moving, 13 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
3 Aug 2013	Aberdeen	0.25	07.30	Non-linear cluster, NE moving, 9 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
28 Oct 2013	Devonport	0.27	03.15	Non-linear cluster, NE moving, 4 tide gauges, 1 mb/1 h drop, high	1 A-C, 2A, 3A	V	Williams et al 2021
5 Dec 2013	Kinlochbervie	0.35	16.00	Quasi linear, 19 tide gauges, 1.7 mb/1 h drop, storm surge, spring tide	1 A-C, 2A, 3A	V	Williams et al 2021
15 Dec 2013	Ullapool	0.25	18.00	Quasi linear, E moving, 6 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
18 Dec 2013	Milford Haven	0.33	19.00	Quasi linear, E moving, 24 tide gauges, 2.6 mb/ 1 h drop,	1 A-C, 2A, 3A	V	Williams et al 2021
20 Dec 2013	Kinlochbervie	0.25	19.45	Quasi linear, NE moving, 5 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
21 Dec 2013	Ullapool	0.28	10.00	Individual cell, NE moving, 4 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
3 Jan 2014	Newlyn	0.33	12.30	Quasi linear, 8 tide gauges, 1.2 mb/1 h drop, high winds, high tide	1 A-C, 2A, 3A	V	Williams et al 2021
8 Feb 2014	Weymouth	0.25	20.00	Open cell, E moving, 14 tide gauges, 1.3 mb/1 h drop at 18.30	1 A-C, 2A, 3A	V	Williams et al 2021
12 Feb 2014	Weymouth	0.26	21.45	Quasi linear, E moving, 15 tide gauges, high winds, storm at 13.00	1 A-C, 2A, 3A	V	Williams et al 2021
21 May 2014	Newhaven	0.26	23.00	Non-linear, N moving, 4 tide gauges, wave period 29 minutes	1 A-C, 2A, 3A	V	Williams et al 2021
22 May 2014	Lerwick	0.33	06.45	Quasi linear, N moving, 3 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
1 Jan 2015	Ullapool	0.26	01.30	Open cell, E moving, 9 tide gauges	1 A-C, 2A, 3A	V	Williams et al 2021
8 Jan 2015	Ullapool	0.27	01.00	Quasi linear, E moving, 10 tide gauges, wave period 15 minutes	1 A-C, 2A, 3A	V	Williams et al 2021
1 July 2015	Stonehaven	0.25	09.00	Individual cell, NE moving,	1 A-C, 2A, 3A	V	Sibley et al 2016
2 July /2015	Lerwick	0.31	23.00	Non-linear, NE moving,	1A-C, 2A, 3A	V	Williams et al 2021
10 Dec 2015	Ullapool	0.25	08.30	Open cell, E moving, 4 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
27 Jan 2016	Workington	0.3	14.00	Non-linear, NE moving,	1A-C, 2A, 3A	V	Williams et al, 2021
1 Feb 2016	Stornoway	0.27	16.30	Open cell, E moving, 11 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
23 June 2016	Newhaven	0.7	04.40	Non-linear, NE moving, 6 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021

Date	Location	Wm (m)	Time (UTC)	Notes	ID criteria	Event ID	Reference
26 Aug 2016	Devonport	0.3	22.45	Individual cell, NE moving, 7 tide gauges	1A-C, 2A, 3A	N	-
16 Nov 2016	Kinlochbervie	0.51	14.15	Open cell, E moving, 7 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
26 Dec 2016	Stornoway	0.34	08.30	Open cell, SE moving, 8 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
11 Jan 2017	Kinlochbervie	0.25	08.00	Open cell, SE moving	1A-C, 2A, 3A	V	Williams et al 2021
16 Oct 2017	Lerwick	0.35	16.00	Quasi linear, NE moving, 20 tide gauges	1A-C, 2A, 3A	V	Williams et al 2021
29 June 2019	Aberdeen	0.3	17.00	Non-linear, supercell moving from North Sea to Norway	1A-C, 2A-C	N	-
8 Feb 2020	Port Stoth	0.4	12.00	Line convection, ebb & flow, before storm Ciara, Low pressure	1A-C, 2A, 2C	NW	-
21 Aug 2020	Perranporth	0.3	21.00	Spring tide, cold front, air pressure rise of 0.5 mb/2 min, bore	1C, 2B, 2C	N	-
5 July 2021	Westward Ho	0.6	12.40	S wind, Individual cell, mid tide, air pressure rise of 0.5 mb/1h, LP	1C, 2A-C, 3A	N	-
9 Aug 2021	Totnes	0.25	11.30	S wind, Non-linear, mid tide, air pressure rise 0.5 mb/30 mins	1A, 1C, 2A-C	N	-
27 Sept 2021	Plymouth	0.32	03.00	S/SW wind, Quasi-linear, CAPE, low tide, air pressure rise 1.1 mb/20 mins	1A, 1C, 2A-D, 3A	NW	-
2 Oct 2021	Totnes	0.29	12.00	SSE wind, Non-linear, mid tide, air pressure fall 1.4 mb/1 h	1A,1C,2A,2B	NW	-
20 Oct 2021	Plymouth	0.36	05.00	SSW, Non-linear, high tide, air pressure rise 1.5 mb/10 mins, CF	1A, 1C, 2A-C	NW	-
27 Nov 2021	Totnes	0.46	04.00	S/W, CAPE, mid tide, air pressure fall 1 mb/30 mins, storm surge,	1A,1C, 2A-D	NW	-
30 Dec 2021	Totnes	0.6	00.00	S/W, non-linear, high tide, air pressure fall 0.5 mb/20 mins, Low pressure, wave period 20 minutes	1A, 1C, 2A-D, 3A	NW	-
16 Jan 2022	Port Isaac	0.3	01.00	Mid tide, air pressure fall of 1.5 mb, pressure wave from volcanic eruption	1A-C, 2B	NW	-
8 Feb 2022	Dunnet	0.3	13.15	Currents of 4 m/s, high tide, approaching cold front from north	1A,1C,2C, 3A	NW	-
18 June 2022	Newlyn	0.7	14.30	Spanish plume, 7+ locations, air pressure fall of 4 mb/10 mins	1A-C, 2B, 3A	N	-
19 July 2022	Anglesey	0.3	12.00	spring tide, air pressure fall 1 mb/35 mins, 5x ebb & flow, 9 m inland	1A-C, 2A-C, 3A	N	-
1 Nov 2022	Plymouth	0.3	09.00	Air pressure rise of 1 mb/5 mins, heavy ppt, thunder, SW wind	1A-C, 2A-D	NW	-
8 Nov 2022	Port Isaac	0.5	10.00	Air pressure rise 0.7 mb/2 mins, thunder, winds, precipitation	1A-C, 2A-D	NW	-
23 Nov 2022	Newlyn	0.7	09.00	Air pressure fall 1 mb/5 mins, cluster ppt, thunder,	1A-C, 2A-D	NW	-

4 Discussion

The aim of this paper was to introduce a revised, enhanced and current UK catalogue of meteotsunami events including a highlight of the seasonal occurrence, frequency, and spatial distribution of this hazard. This aim was set as there is no standardised identification criteria or up to date single catalogue of UK meteotsunami. This scenario has led to the mis conception that these events are non-hazardous, rare, and tend to occur more frequently in the summer months.

4.1 The updated UK meteotsunami catalogue

With the identification criteria we have laid out in this paper we have verified 98 events in UK waters since 1750 of which 38 are new events containing seven new winter events in the historical record (1750 to 2009) and 8 new winter events in the modern record (2010 to 2022).

It was found that a selection of historical events were misidentified in accounts as either abnormal coastal flooding, non-tsunami, storm surge or of unknown origin. This was extended by an analysis of current data (since 2010) which allowed us to add a total of 38 new events to the catalogue, of which 15 occurred within winter months, these are highlighted in Table 1 as new (N), new winter (NW) or verified (V) events.

The misidentified events were discovered after an attempt to highlight characteristics that match those listed in the methodology, in particular characteristics that suggested tsunami like phenomenon but with any associated storm like activity or air pressure fluctuations. If the account was found to contain a lack of evidence or information to suggest a meteotsunami it was rejected. An event occurring on 13 February 1979 was highlighted as a meteotsunami by Haslett et al. (2009a) but was contested by Thompson et al. (2020) as being a surge caused by a winter Atlantic storm due to its seasonal placement. In their 2020 paper, Thompson et al appear not to class Atlantic storms systems as sources of meteotsunami. They state that from April to October, thunderstorms generate meteotsunami and from November to March, storms generate low pressure swells and surges. Our paper has matched descriptions in historical accounts with the criteria laid out in the methodology and we agree with Haslett and Bryant (2009a/b) that the 1979 winter event was a meteotsunami. This result was determined by the similarities in the pressure profile, geographical distribution and the speed of anomaly to the known meteotsunami event of 26 June 2011.

In addition to the 1979 event, there were further events found that were previously labelled as meteotsunami to which our criteria have found them to be of alternative origin (tsunami) or to have insufficient detail or collaborative evidence to solidify a conclusion. These include the events presented in Long (2021), dated 14 October 1862 (found to be a tsunami due to an alternative source trigger), 15 August 1895 (insufficient information), 11 May 1912 (found to be a tidal bore) and another tidal bore dated 17 May 1964 presented in Haslett and Bryant, 2009a/b.

The event of the 31 March 1761 which was labelled as a tsunami by both Long (2015) and Thompson et al. (2020), was found to be a winter meteotsunami due to tsunami like waves being experienced not only along the southwest UK but also in Loch Ness in Scotland, with the mention of a calm sea before the arrival of thunderstorms.

4.2 Seasonal and geographical patterns of UK meteotsunami

The historical record (1750 to 2009) has been found to support previous studies such as Haslett and Bryant (2009a/b) that have alluded to the positive correlation between thunderstorms and meteotsunami waves with 71% of summer events displaying reports of convective activity. Our results have highlighted a summer prevalence of events with 48% of them peaking in July and August which reflects Thompson et al (2020). This prevalence has been based principally on the reliance on eyewitness reports and the volume of persons present at the shoreline during these months.

These summer events tend to be associated with heat waves and so called “Spanish plumes” as in the 27 June 2011 and the 18 June 2022 events along the southwest UK. This is where warm air moves northwards from the European continent and Iberia, during which mesoscale convective weather tends to occur. In the summer, CAPE is at its highest and overland due to warm 2 m air temperatures over landmasses (Holley et al. 2014). These types of weather event consist of single cell or clusters of small, short duration (< 1 hr) thunderstorms and squall lines with more than one convective cell (Sibley 2012 and Tappin et al. 2013).

The element of risk during the summer occurs when the meteotsunami wave can become fully disconnected from its source disturbance. This effect can be particularly apparent if the meteotsunami interacts with the continental slope where the wave can arrive hours after the original storm has dissipated or moved on. This delayed arrival of wave disturbances can surprise people who are subsequently back out on or near the water’s edge, believing the storm has passed. This scenario was experienced during the 5 July 2021 event that occurred at Westward Ho (North Devon). Where just after midday a small yet powerful wave unexpectedly progressed 50 metres up the beach inundating many beach goers.

Previous studies have suggested that winter wave anomalies such as meteotsunami are ‘less’ likely than storm waves, and surge, and winter data has not previously been interrogated for this reason. However, the present-day record (2010 to 2022) appears to contradict this with a winter prevalence of 66% of events peaking in December and January and with a tendency towards October and November in the 2021/22 winter season.

The results also show a geographical pattern to UK meteotsunami, with a large proportion of events occurring along the southwest UK and Northwest Scotland in the winter, aligning with the dominant weather direction of west to east from the Atlantic Ocean, and along the southern UK coast in the summer, aligning with Spanish Plumes bringing warm air poleward from the equator with southerly winds up and along the English Channel. The geographical pattern also reflects the influence of local bathymetry, with harbours (e.g., Penzance, Plymouth, Stornoway, and Port Talbot), bays (e.g., Kinlochbervie and Port Stoth) and river mouths (e.g., river Yealm and river Dart) containing conditions more favourable to meteotsunami initiation and amplification via resonance and seiching.

To further the concept presented in Williams et al. (2021) we selected two recent winter meteotsunami events and highlighted the meteotsunamigenic criteria. It has been indicated from the results that the combination of a mid-latitude depression, with frontal and convective weather moving across the UK may be important in the generation of this hazard. Results have shown that during these winter storms, convective elements are likely to be embedded around heavy rainfall (Figure 4a and b) and strong winds associated with the cold front leading to the potential for meteotsunami waves. This winter synoptic situation is a product of the combination of the cold maritime Arctic air being introduced to the rear side of the cold front passing over relatively warm water. The risk of flooding can be exacerbated due to surface water from precipitation as the front crosses a landmass (Masselink et al. 2015).

The results highlighted an average maximum wave height of 0.3 m which may not seem 'dangerous' but this hazard is not purely about this single factor. The key that makes meteotsunami a potential hazard is the rapid onset of the wave (sometimes referred to as a "wall of water") and the associated strong currents.

4.3 Constraints and Limitations

Identifying meteotsunami events in winter tends to be more difficult as the waves can be hidden and overshadowed by the wave characteristics of the trigger storms and may be missed unless looking specifically at the data. We strongly consider that this overshadowing means many of these winter meteotsunami do not get reported and this may have been the issue in previous research where certain winter events were identified as either storm waves or surges instead of meteotsunami. As we have seen there is a short observational record available for meteotsunami and there is evidence for severe under recording of such events. Even though the 2010 to 2022 record has shown significant improvements in recording completeness; the current 15-minute sampling interval is still too coarse. This was highlighted when certain events in the catalogue such as 2 October 2021, 20 October 2021, 27 November 2021 and 19 July 2022 were uncovered in the 1-minute tide gauge data that were not so easy to locate in the 15-minute data. This creates an issue where many events with a wave period of under 15 minutes may be potentially missed. We recommend a reduction of the sampling interval to 1 to 5 minutes to yield more data to be able to draw a complete conclusion for this hazard.

Another limitation of this study linked to the sampling frequency was the treatment of wind-driven waves which can induce infra-gravity waves of a similar wave period to meteotsunami (2 to 5 minutes). We did initially consider wind and swell peak period and wave height; however, we discovered that the detection of infra-gravity waves from low frequency tide gauge data is uncertain and was deemed to be beyond the scope of this study. To perform such an analysis and to be confident in our results we would require 1 minute / 2 Hz data for a spectral analysis. However, it may be prudent to explore this aspect in future work.

We noted that historical accounts are not optimum for identifying and analysing meteotsunami due to their anecdotal nature and as such the number of events represented here may be dramatically underestimated. Data before 2008 is not readily available and records are spatially sparse which leads to incomplete data coverage and does not allow for a robust statistical analysis.

The placement of tide gauges used to provide data also affects results. The siting of UK tide gauges tend to be biased towards populated areas with harbours and river mouths for asset protection and is ideal for the capture of the resonant component of the meteotsunami wave. However, events in less populated areas may have been missed due to this placement. We suggest potential tide gauge locations (based on the occurrence rate of previous events) could include beach or estuary locations around Devon and Cornwall such as Mevagissey or Perranporth and the North of Scotland such as Dunnet or Port Stoth.

4.4 What does this mean for the future?

As the next few decades are likely to see sea level rise push mean and extreme water levels upward which will subsequently increase the level of risk by bringing the height of the storm tide closer to the flood stage (Masselink et al. 2015). At many UK locations, flood defences are at the design threshold of current storm surge levels, they are not designed or built for a sudden, prolonged water flow as seen in meteotsunami (Lazarus et al.2021). A question that has arisen from this paper is whether the winter seasons of 2013/14 and 2021/22 are outliers or whether this clustering of storms and meteotsunami will be a commonplace scenario in the future. Currently, we can detect and forecast mid latitude depressions nine to ten days in advance (Penn State, 2019), knowing this we can incorporate a warning of potential meteotsunami activity into the forecast. However, due to the localised nature of meteotsunami, risk level in each coastal areas needs to be considered on its own merits. The risks connected with a single meteotsunami event in two different bays can be quite different. One bay may suffer from inundation and flooding where another bay may be impacted by strong currents. This paper provides a valuable insight into the frequency, seasonality and spatial distribution of what was a hidden hazard in the UK. This new data will need to be incorporated and taken into consideration when coastal management strategies and defences are adjusted for the future.

Meteotsunami may well have some role to play in coastal storm impacts, however, the relative contribution of meteotsunami to storm surge in the aftermath of a storm and the full extent of the risk remains unknown and is beyond the scope of this work. It is also difficult to determine if the frequency and intensity of either low-pressure winter storms or winter meteotsunamis are on the increase. We invite a closer and more robust scrutiny of this hazard with a year-round perspective bearing in mind that no solid conclusions can be drawn without high frequency, long term, and continuous monitoring of this of hazard.

5 Conclusions

Until recently it was thought that meteotsunami in the UK were rare and only occurred at certain times of the year, this misconception has led to a lack of provision in coastal management strategies and an under estimation of the frequency of this hazard. Motivated by coastal safety, this paper tests the hypothesis by presenting a new chronological catalogue dated from 1750 to 2022 containing 98 UK meteotsunami with highlighted seasonal and geographical aspects. Using a standardised set of identification criteria developed for this study we have verified 60 previously listed events and presented 38 new events of which 15 were found to occur in the winter (Table 1).

Results demonstrate that meteotsunami are not restricted to the summer months and are more common than initially thought. The modern record (2010 to 2022) is short and has far more winter meteotsunamis, whereas the relatively long historical record (1750 to 2009) means that the most meteotsunamis in our total have occurred in the summer which confirms the results of Thompson et al. (2020) and Haslett and Bryant (2009). During the summer months (April to September inclusive) there is a trend towards the southern UK with a 71% positive correlation between meteotsunami events and summer convective weather systems, which can occur within synoptic Spanish Plume settings as suggested by Sibley (2012). During the winter months (October to March inclusive) our results demonstrate a clustering around the southwest UK and Northwest Scotland with a positive correlation between meteotsunami and the passage of mid latitude depressions where convective elements are embedded in the associated cold fronts and low pressure troughs. Subsequently meteotsunami impacts can become hidden by being superimposed on top of the storm's impacts. The meteotsunami waves are further exacerbated by the localised nature of resonance characteristics, in particular harbours and bays which can create highly dangerous situations. The immutable nature and rapid onset of this hazard means that even a sole meteotsunami event can create changes in water level and flow velocity that has the potential to cause injury, loss of life and damage to assets.

Increased knowledge of this hazard can be made more easily accessible through a central catalogue such as the one presented in this paper and the provision of higher frequency monitoring to detect future trends. What was thought to be a 'hidden' and rare event in historical records may soon become a common hazard in the future.

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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.

References.

Bechle, A.J., Wu, C.H., Kristovich, D.A.R., Anderson, E.J., Schwab, D.J. and Rabinovich, A.B.: Meteotsunamis in the Laurentian Great Lakes. Scientific Reports 6, **(**37832). https://doi.org/10.1007/s11069-014-1193-5. 2016.

Borlase, W.: The natural history of Cornwall. Oxford. 53-4. https://archive.org/details/naturalhistoryc00borl. 1758.

British Oceanographic Data Centre: https://www.bodc.ac.uk/ Last access: 19 February 2022.

Burt, S.: Multiple airwaves crossing Britain and Ireland following the eruption of Hunga Tonga-Hunga Ha'apai on 15 January 2022. Weather. Vol 77, No 3. https://doi.org/10.1002/wea.4182. 2022.

Chatfield, C.: Landmarks of world history: A Chronology of Remarkable Natural Phenomena Eighteenth Century 1761-1770. http://www.phenomena.org.uk/page29/page38/page38.html. Last accessed 19 February 2022.

Dawson, A.G., Musson, R.M.W., Foster, I.D.L., and Brunsden, D.: Abnormal historic sea-surface fluctuations, SW England marine Geology. Vol. 170, 59-68. 10.1016/S0025-3227(00)00065-7. 2020.

Dusek, G., DiVeglio, C., Licate, L., Heilman, L., Kirk, K., Paternostro, C., & Miller, A.: A meteotsunami climatology along the U.S. East Coast. Bulletin of the American Meteorological Society,100(7), 1329–1345. https://doi.org/10.1175/BAMS-D-18-0206.1. 2019.

Edmonds, R.: On extraordinary agitations of the sea not produced by winds or tides. Transactions of the Devonshire Association. 3. 144-152. https://devonassoc.org.uk/publications/transactions/contents/. 1869.

Haigh, I., Wadey, M., Wahl, T.: Spatial and temporal analysis of extreme sea level and storm surge events around the coastline of the UK. Sci Data 3, 160107. https://doi.org/10.1038/data.2016.107 2016.

Haslett, S.K. and Bryant, E.A.: Historic tsunami in Britain since AD 1000: a review. Natural hazards and Earth Sciences. 8, 587-601. https://doi.org/10.5194/nhess-8-587-2008 2008.

Haslett, S.K. and Bryant, E.A.: Meteorological Tsunamis in Southern Britain: An Historical Review. Geographical Review. 99, 146–163. https://doi.org/10.1111/j.1931-0846.2009.tb00424.x 2009a.

Haslett, S.K., Mellor, H.E., and Bryant, E.A.: Meteo-tsunami hazard associated with summer thunderstorms in the United Kingdom. Physics and Chemistry of the Earth. 34, 1016-1022. https://doi.org/10.1016/j.pce.2009.10.005 2009b.

Holley, D.M., Dorling, S.R., Steele, C.J. and Earl, N.: A climatology of convective available potential energy in Great Britain. International Journal of Climatology. 34: 14. 3811-3824. https://doi.org/10.1002/joc.3976 2014.

Goring, D.: Meteotsunami resulting from the propagation of synoptic-scale weather systems. Physics and Chemistry of the Earth, Volume 34, Issue 17, p. 1009-1015.10.1016/j.pce.2009.10.004 2009.

Kim, M., Woo, S., Eom, H. and You, S.: Pressure-forced meteotsunami occurrences in the eastern Yellow Sea over the past decade (2010–2019): monitoring guidelines. Natural Hazards and Earth System Sciences. https://doi.org/10.5194/nhess-2021-126 2021.

Lazarus, E., Aldabet, S., Thompson, C., Hill, C., Nicholls, R., French, J., Brown, S., Tompkins, E., Haigh, I., Townend, I. and Penning-Rowsell, E.: The UK needs an open data portal dedicated to coastal flood and erosion hazard risk and resilience. Anthropocene Coasts. 4(1): 137-146. https://doi.org/10.1139/anc-2020-0023 2021.

Lightning maps: https://www.lightningmaps.org/#m=oss;t=2;s=0;o=0;b=;y=50.7086;x=-1.0547;z=4 last accessed 1 March 2023.

Linares, Á., Wu, C.H., Bechle, A.J, Anderson, E.J. and Kristovich D.A.R.: Unexpected rip currents induced by a meteotsunami. Sci Rep 9:2105. https://doi.org/10.1002/2016JC011979 2019.

Long, D.: A catalogue of tsunamis reported in the UK. British Geological Association 1R/15/043 https://nora.nerc.ac.uk/id/eprint/513298/1/IR_15_043%20%20BGS%20Tsunami%20catalogue%20update.pdf 2015.

Long, D.: Comment on: Thompson et al 2020. UK meteotsunamis: a revision and update on events and their frequency. Weather. Vol 76. No4. 137-139. https://doi.org/10.1144/sp456.10 2021.

Lynett, P.J., Borrero, J., Son, S., Wilson, R. and Miller, K.: Assessment of the tsunami induced current hazard. Geophysical Res Lett 41 (6): 2048-2055. https://doi.org/10.1002/2013GL058680 2014.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M. and Conley, D.: The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. Earth Surface Processes and Landforms, volume 41, Issue 3 378-391. https://doi.org/10.1002/esp.3836 2015.

MET Office: 5 km Resolution UK Composite Rainfall Data from the Met Office Nimrod System. https://catalogue.ceda.ac.uk/uuid/f91b2c5399c5bf689e29bb15ab45da8a 2003.

Monserrat, S., Vilibic, I. and Rabinovich, A.B.: Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band. Natural Hazards and Earth System Science. 6. 1035-1051. https://doi.org/10.5194/nhess-6-1035-2006 2006.

National Oceanography Centre: https://www.bodc.ac.uk/ Last accessed 1 March 2023.

National tide and sea level facility: Available at: https://ntslf.org/ Last accessed 19 February 2022.

Pattiaratchi, C.B. and Wijeratne, E.M.S.: Are meteotsunamis an underrated hazard? Philosophical Transactions of the Royal Society: Mathematical and Engineering Sciences 373. https://doi.org/10.1007/s11069-014-1263-8 2015.

Pellikka, H., Laurila, T.K., Boman, H., Karjalainen, A., Björkqvist, J. and Kahma, K.K. Meteotsunami occurrence in the Gulf of Finland over the past century, Natural Hazards Earth System Sciences. 0. (9). 2535-2546. https://doi.org/10.5194/nhess-20-2535-2020 2020.

Penn State.: Predictability limit: Scientists find bounds of weather forecasting. ScienceDaily. 15 April 2019. https://sciencedaily.com/releases/2019/04/190415154722.htm Last accessed 20 August 2022.

Proudman, F.R.S.: The Effects on the Sea of Changes in Atmospheric Pressure. Geophysical Journal International 2 s4. https://doi.org/10.1111/j.1365-246X.1929.tb05408.x 1929.

Reigate grammar weather station: The birth and impact of the St Jude day storm: October 2013. Available at: https://rgsweather.com/2013/10/29/st-jude-causes-and-impacts-of-the-october-storm-27-28-2013/amp/ Last accessed 19 February 2022.

Sea Level Monitoring Facility: https://ioc-sealevelmonitoring.org/ Last accessed 1 March 2023.

Šepić, J., Vilibić, I. and Mahović, N.: Northern Adriatic meteorological tsunamis: observations, link to the atmosphere, and predictability. Journal of Geophysical Research Oceans. 117(C2). https://doi.org/10.1029/2011JC007608 2012.

Šepić, J., Vilibić, I., Rabinovich, A. et al. Widespread tsunami-like waves of 23-27 June in the Mediterranean and Black Seas generated by high-altitude atmospheric forcing. Sci Rep 5, 11682. https://doi.org/10.1038/srep11682 2015.

Šepić, J., Vilibić, I., Rabinovich, A. et al. Meteotsunami (“Marrobbio”) of 25–26 June 2014 on the Southwestern Coast of Sicily, Italy. Pure Appl. Geophysics. 175, 1573–1593. https://doi.org/10.1007/s00024-018-1827-8 2018.

Sibley, A.: Thunderstorms from a Spanish Plume event on 28 June 2011. Weather. 67. No 6. 143-152. https://doi:10.1002/wea.1928 . 2012.

Sibley, A., Cox, D., Long, D., Tappin, D.R. and Horsburgh, K.J.: Meteorologically generated tsunami like waves in the North Sea on 1 July 2015 and 28 May 2008. Weather. 71. 68-74. https://doi.org/10.1002/wea.2696 2016.

Starlings roost weather: http://starlingsroost.ddns.net/weather/stats.php?type=day&field=&date=2023-03-05 Last accessed 1 March 2023.

Stevenson, C. M.: The dust fall and severe storms of 1 July 1968. Weather. 66 (5): 125–127. DOI:10.1002/WEA.780 1969.

Surge Watch database: A database of UK coastal flood events. https://www.surgewatch.org/ Last accessed 19 February 2022.

Tappin, D.R., Sibley, A., Horsburgh, K.J., Daubord, C., Cox, D. and Long, D.: The English Channel `tsunami' of 27 June 2011 - a probable meteorological source. Weather. 68. 144–152. https://doi.org/10.1002/wea.2061 2013.

Thompson, J., Renzi, E., Sibley, A. and Tappin, D.: UK meteotsunamis: a revision and update on events and their frequency. Weather. 75.9, 281–287. https://doi.org/10.1002/wea.3741 2020.

University of Wyoming: http://weather.uwyo.edu/upperair/sounding.html Last accessed 19 February 2022.

Ventusky weather: https://www.ventusky.com/?p=54.4;-5.9;4&l=radar&t=20230313/1100&w=off Last accessed 1 March 2023.

Vilibić, I. and Šepić, J.: Global mapping of non-seismic sea level oscillations at tsunami timescales. Scientific reports. 7. (1) 40818. https://doi.org/10.1038/srep40818 2017.

Vilibić, I., Šepić, J., Dunic, N., Sevault, F., Monserrat, S. and Jorda, G.: Proxy-based Assessment of Strength and Frequency of Meteotsunamis in Future Climate. Geophysical Research Letters. 45. 10501-10508. https://doi.org/10.1029/2018GL079566 2018.

Williams, D.A., Horsburgh, K.J., Schultz, D.M. and Hughes, C.W.: Examination of generation mechanisms for an English Channel Meteotsunami: Combining observations and modelling. Journal of Physical Oceanography. 49. 103-120. https://doi.org/10.1175/JPO-D-18-0161.1 2019.

Williams, D. A., Schultz, D. M., Horsburgh, K. J., & Hughes, C. W.: An 8-yr meteotsunami climatology across northwest Europe: 2010–2017. Journal of physical oceanography. 1145-1160. https://doi.org/10.1175/JPO-D-20-0175.1 2021.