UK meteotsunamis: a revision and update on events and their frequency

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Introduction

A tsunami is a series of waves caused by the displacement of water. The displacement may result from 'bottom-up' seabed movement, such as that caused by earthquakes, landslides and volcanic eruptions or 'top-down' movement, from pressure perturbations in the atmosphere. These 'top-down' events are termed meteotsunamis. Meteotsunamis frequently occur in the Mediterranean, the Baltic Sea, the east coast and Great Lakes of North America, and Japan, so they are not exclusive to the United Kingdom (UK). The most recent meteotsunami near the UK coast was in May 2017, when waves around 2m in elevation, generated by a storm passing over the UK, struck the coast of the Netherlands. Historical documents covering the past 150 years describe many meteotsunamis from UK coastal waters (Haslett *et al.*, 2009; Haslett and Bryant, 2009; Tappin *et al.*, 2013; Vilibić *et al.*, 2015; O'Brien *et al.*, 2018). Some of these events have resulted in fatalities, involving beach users who were struck by unexpected sea waves.

Meteotsunamis commonly strike the coasts of the UK, damaging harbours, boats and very rarely, causing fatalities. In the UK, they were usually detected by analysis after the event, unless witnessed first-hand. This post-event analysis is particularly necessary in the UK because the data provided by the tide gauge system, operated by the Environment Agency, only records at 15-minute intervals, not in real time as in the rest of Europe. The periods of meteotsunamis are in the range of minutes to tens of minutes (Pattiaratchi and Wijeratne, 2015). A frequency of tens of minutes is similar to a typical frequency expected from a meteotsunami that would have an amplified response from harbour or bay resonance (Tappin *et al.*, 2013). Therefore, those occurring in UK waters are not often recorded with the present tide gauge settings and as a consequence, cannot be analysed effectively.

Meteotsunami mechanisms

Meteotsunamis are 'tsunami-like' waves with a meteorological origin. Initially, they are generated by atmospheric pressure perturbations, which may result from squalls and internal gravity waves. These pressure perturbations cause waves on the surface of the ocean, either by 'pulling up' the sea surface in the case of low-pressure areas, or 'pushing down' in the case of high pressure. The perturbations on their own are not large enough to generate significant meteotsunami waves, which may be centimetres in elevation, so amplification by other mechanisms is required. One such mechanism is Proudman resonance, whereby a traveling pressure perturbation adds energy to, and increases in size, a wave moving with the same trajectory and speed. Other effects that contribute to the growth of meteotsunami waves include:

(i) Shelf amplification, whereby a meteotsunami traveling over a continental shelf, from deeper to shallower water, increases in size due to the change in water depth,
(ii) Basin or harbour resonance, whereby the meteotsunami has a similar frequency to that of the resonant frequency of the basin or harbour that it is traveling through, and
(iii) Greenspan resonance, whereby the speed of waves travelling along the coast, after meteotsunami generation, is close to the speed of the pressure perturbation travelling in the same direction.

Meteotsunamis are generated over very short (minutes) timescales, which makes them less predictable than storm surges, which develop over longer timescales (days), from low-pressure weather systems moving from the deep ocean to the coast. Storm surges, initially, can be identified up to 15 days in advance (Met Office, 2015) and with increasing confidence, closer to the coast as the low-pressure system develops. Further differences between meteotsunamis and storm surges are that (i) meteotsunami waves can travel faster than the convective storm that caused them and (ii) they can continue after the storm has decayed in strength. In addition, with storm surges, the wavelengths generally are longer and more closely associated with the locality of the driving low-pressure system.

Meteotsunamis, therefore, can strike without warning, often when weather conditions at the coast are clear, with a calm sea and blue skies (e.g. Pattiaratchi and Wijeratne, 2015; Sallenger, *et al.*, 1995). Without forewarning, and effective response and mitigation, the damage to harbours, boats and beaches, and the potential for the loss of human lives, is much greater (Monserrat *et al.*, 2006; Tappin *et al.*, 2013; Vilibić *et al.*, 2015). Protecting the coastline from meteotsunamis through improved forecasting, therefore, is of both economic and social benefit.

UK Meteotsunamis – history and impact

Meteotsunamis in the UK have been investigated only recently, with systematic research into high-frequency sea level variations taking place only during the last decade. This research reveals that meteotsunamis are more common than previously recognised (Haslett and Bryant, 2009). For example, during the period 2000–2013, in the Solent, there were eight rapid sea level changes with an average height of 1.2m attributed to meteotsunamis (Pattiaratchi and Wijeratne, 2015). More recently, in July 2015, at Stonehaven Harbour, Scotland, a strong convective weather system generated a 1.25m meteotsunami, which damaged boats and caused a serious injury to a crewman (Sibley et al., 2016).

Although a 1-m meteotsunami is much less destructive than a 5-m storm surge,

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it should be noted that the difference between a 1-in-10 and a 1-in-200 sea level return period in UK coastal waters can be as low as 30cm (Pattiaratchi and Wijeratne, 2015). Mean sea levels are predicted to rise by this amount over the next 80 years according to the UKCP18 Marine report: for example, at Cardiff between 0.27m and 0.69m under the lower RCP2.6 scenario (their table 3.1.2). The report states as a key finding: "… that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline." (Palmer *et al.*, 2018). Therefore, not including meteotsunamis in short-term wave statistics can produce significant distortions in estimating sea level return periods. In turn, inaccurate return period predictions compromise the design of safe and reliable coastal structures.

Despite this potentially worrying scenario, the precise causal mechanisms and propagation dynamics of meteotsunamis in UK coastal waters have not yet been determined (Haslett and Bryant, 2009; Tappin *et al.*, 2013). Meteotsunamis, therefore, remain an *entirely neglected hazard in the UK* (Haslett *et al.*, 2009). Some countries that are historically prone to meteotsunamis, such as Japan, Croatia, Spain and the United States of America, have recently promoted research efforts to better understand this phenomenon and mitigate this hazard. For example, in 2011 the US National Oceanic and Atmospheric Administration (NOAA) funded the research project: Towards a Meteotsunami Warning System along the US Coastline (TMEWS).

At present, in the UK, there is no central repository of verified meteotsunamis, nor is there a formal governmental commitment for their mitigation through monitoring and prediction, although the joint Environment Agency/Met Office, Flood Forecasting Centre has responsibility for forecasting coastal flooding. Although reports of possible meteotsunamis date back to 1759, the concept of tsunamis generated by weather patterns is relatively new. Some nineteenth century reports (e.g. Roberts, 1849; Edmonds, 1862), observed that there were thunderstorms associated with episodes of unusual waves and tidal action, but causal mechanisms were not clearly identified, understood or formulated. Indeed, the first recognitions of meteotsunamis (although not named as such) are Proudman (1929) and Douglas (1929).

Haslett *et al.* (2009) include in their list of meteotsunamis some events where a combination of long period, swell waves and storm surges resulted in wave overtopping of coastal defences. However, these events are not included here because they are not strictly classified as meteotsunamis, but result from Atlantic storm systems. For example, Draper and Bowness (1982) consider the long period, high-amplitude waves and surges of February 1979 to have been generated by a wintertime Atlantic storm system. We consider meteotsunamis generated near thunderstorms are more likely in the spring, summer and early autumn months (April to October); whereas long period swell waves and surges primarily occur during winter months (November to March). The following section will focus upon meteotsunamis generated near thunderstorms around the coast of the UK (Gray and Marshall, 1998; Hand *et al.*, 2004) (Figures 1 and 2).

UK Meteotsunamis – historical events

Presented here are descriptions and references for anomalous UK wave events, which from report details and corroborating accounts, we confidently interpret as meteotsunamis. The events, and their confidence level, are provided in Table 1 and their locations in Figure 3.

Lyme Regis 1759

On the 31 May 1759 Perrey (1849) reported that the sea … *flowed in and out three times during an hour….* This is consistent with a

Figure 1. Screen shot of the video of the Yealm meteotsunami from figure 8 in Tappin et al. (2013). (Photo provided by Simon Fitch.)

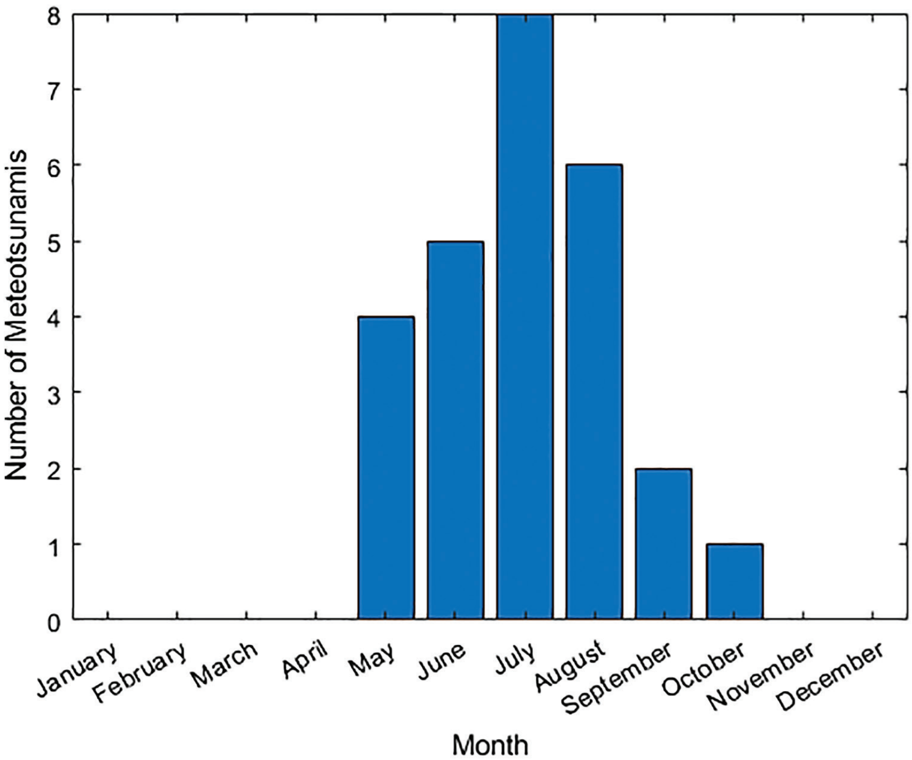

Figure 2. Number of confirmed meteotsunamis by month.

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Table 1

Meteotsunami candidates on the coast of the United Kingdom with most likely cause.

Date of occurrence	*Location*	*Most likely cause*	*Sources*	*Reliability*	*Map key*
31 May 1759	Lyme Regis	Meteotsunami	Dawson *et al.* (2000); Edmonds (1862)	Probable	M1
31 March 1761	Mounts Bay (Cornwall)	Earthquake tsunami	Edmonds (1862); Long (2018)	No	
18 August 1797	Lyme Regis	Meteotsunami	Dawson *et al.* (2000); Perrey (1849)	Possible	M2
23 November 1824	English Channel impacting at Chesil beach	Storm surge	Haslett and Bryant (2009); le Pard (1999); Observer (1824)	No	
05 July 1846	Cornwall	Meteotsunami	Dawson *et al.* (2000); Edmonds (1862)	Probable	M3
1 August 1846	Penzance	Meteotsunami	Dawson *et al.* (2000); Edmonds (1862)	Possible	M4
23 May 1847	Cornwall	Meteotsunami	Long (2018), Long (2007)	Possible	M5
7 July 1848	English Channel/Bristol Channel	Meteotsunami	Edmonds (1862); Roberts (1849)	Probable	M6
6 June 1855	Penzance	Unknown	Dawson *et al.* (2000); Edmonds (1856)	Possible	M7
5 June 1858	English Channel	Meteotsunami	Long (2018); Newig and Kelletat (2011)	Probable	M8
25 June 1859	Cornwall and Scilly Isles	Meteotsunami	Dawson *et al.* (2000); Edmonds (1862)	Probable	M9
4 October 1859	Not known ± SW England	Meteotsunami	Dawson *et al.* (2000); Edmonds (1862)	Probable	M10
23 April 1868	English Channel	Long period swell waves	DCC (1868); Haslett and Bryant (2009); West (2019)	No	
29 September 1869	Not known ± Cornwall	Unknown	Dawson *et al.* (2000); Perrey (1872)	Probable	M11
17 October 1883	Severn Estuary – Severn tunnel construction	Storm surge	Guardian (1883); Haslett and Bryant (2009); Walker (1969)	No	
18 August 1892	Cornwall Estuaries	Meteotsunami or earthquake tsunami	Haslett and Bryant (2009); Penny Illustrated (1892)	Possible	M12
16 December 1910	Bristol Channel	Unknown	Haslett and Bryant (2009); IGO (1910a, 1910b)	No	
20 July 1929	English Channel	Meteotsunami	Douglas (1929); Haslett *et al.* (2009); The Times (1929)	Confirm	M13
2 August 1932	Aberavon (South Wales)	Meteotsunami	Haslett *et al.* (2009); The Times (1932)	Possible	M14
5 August 1938	Bridlington	Meteotsunami	Haslett *et al.* (2009); The Times (1938)	Probable	M15
5 July 1939	Weymouth	Meteotsunami	Haslett *et al.* (2009); The Times (1939a,b)	Probable	M16
6 July 1957	Isle of Wight	Meteotsunami	Haslett *et al.* (2009); Isle of Wight County Press (1957)	Probable	M17
17 May 1964	Arnside	Tidal bore	Haslett *et al.* (2009); The Times (1964)	No	
31 July 1966	North Devon coast	Meteotsunami	Haslett *et al.* (2009); The Times (1966)	Probable	M18
1 July 1968	English Channel	Meteotsunami	Stevenson (1969)	Probable	M19
13 February 1979	Southwest UK	Long period swell waves and storm surge	Draper and Bownass (1983); The Guardian (1979); Haslett *et al.* (2009); Daily Mail (1979)	No	
28 May 2008	Peterhead, Scotland	Meteotsunami	Sibley *et al.* (2016)	Confirm	M20
27 June 2011	English Channel	Meteotsunami	Tappin *et al.* (2013); West *et al.* (2011)	Confirm	M21
1 July 2015	North Sea	Meteotsunami	Sibley *et al.* (2016)	Confirm	M22
23 June 2016	English Channel	Meteotsunami	Williams *et al.* (2018)	Confirm	M23

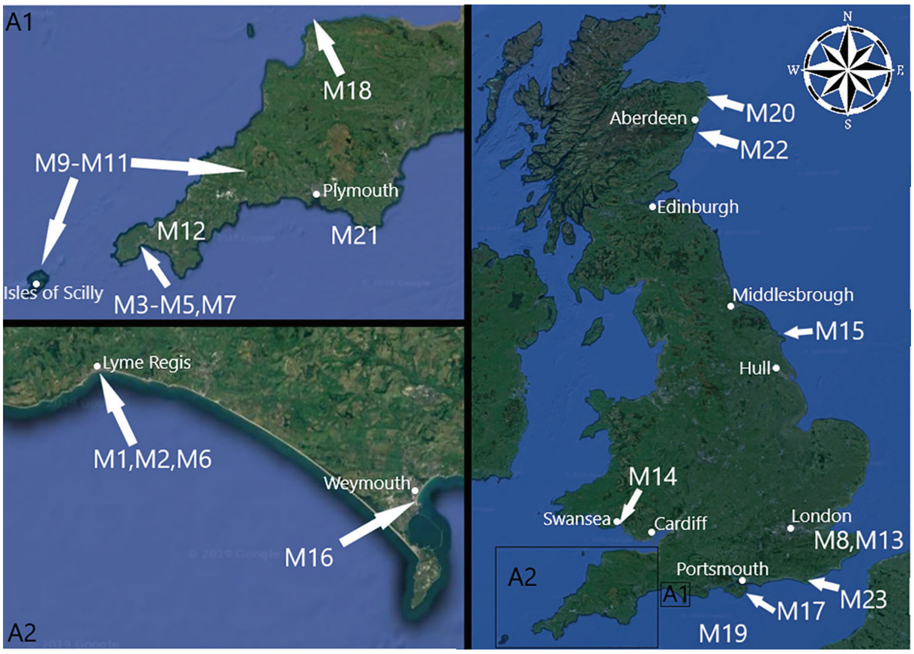

Figure 3. Location of known meteotsunamis around the UK.

typical period of a meteotsunami, but in the absence of any corroborating evidence, there is still uncertainty about this event.

Lyme Regis 1797

Perrey (1872) is the single source that reports an unusual sea disturbance on 18 August 1797 – *sea flowed 3 times in one hour, attended by lightening [sic]*. This is consistent with a meteotsunami, but in the absence of additional evidence, we can only conclude that this is a 'possible' meteotsunami.

Cornwall 1846

On the morning of the 5 July 1846, there was *An episode of unusual coastal flooding* (Edmonds, 1862). There is also a mention of a severe storm around the time of the disturbance, suggesting it was likely a meteotsunami.

Penzance 1846

On the 1 August 1846 Edmonds (1862) writes …*the sea in Penzance pier at 0400h being very calm … suddenly rose between 1 and 2 ft.*. John Bull (1864) mentions "most destructive storms that has occurred within the memory of man" with the origin of these storms being from the southwest of London. These storms may have caused the meteotsunami that hit Penzance.

Cornwall 1847

On the 23 May 1847, there was a 0.9m to 1.5m rise and fall observed all day at Mounts Bay. One cause could have been the slight tremor that was felt at the Scilly Isles, Penzance and Mounts Bay. Edmonds (1862) reports nearby thunderstorms, but also the occurrence of an earthquake in Scilly and Cornwall. The cause of this tsunami is uncertain, so it could possibly be a meteotsunami or an earthquake tsunami.

Bristol Channel 1848

The description of the event occurring on the 7 July 1848 given by Roberts (1849) is a very detailed, second-hand, account with references to the weather and the sea state. However, from the description, the cause of the wave generation is unclear.

Penzance 1855

On the 6 June 1855 Edmonds (1856) noted …*an extraordinary oscillation of the sea occurred in the tidal harbour of Penzance, with the sea rushing in and out several times like a very strong tide, ultimately floating and leaving dry boats which drew three feet of water*. This is a good description of a tsunami, but it does not give us any clues as to the cause of the waves. This is possibly a meteotsunami, but the amount of evidence leaves doubt as to the waves' origin.

English Channel 1858

A series of waves hit the east coast of Kent at around 0900h on the morning of the 5 June 1858. Newig and Kelletat (2011) presents the Ramsgate harbourmasters report, which mentions an *undulation of the tidal column*. Reports, also presented by Newig and Kelletat (2011), mention waves impacting the north coast of France, Belgium and the Netherlands, and the east coast of Denmark. The conclusions made by Newig and Kelletat (2011) are that the most likely explanation is a meteotsunami with an origin near the coast of France, Spain or Portugal.

Cornwall and Scilly Isles 1859

On the 25 June 1859, there was *an exceptional episode of coastal flooding* along the coast of Cornwall as described by Dawson *et al*. (2000) referencing Edmonds' (1856) report in the Edinburgh New Philosophical Journal. Edmonds (1862) reports considerable oscillations, together with thunderstorms with violent squalls, which suggests that it was most likely a meteotsunami.

South West England 1859

On the 4 October 1859 Edmonds (1862) describes several waves arriving at the Isles of Scilly with a maximum height of 14ft 7in (~4.44m). This was most probably a meteotsunami associated with the warm weather and thunderstorms as reported by Edmonds (1862).

Cornwall and Scilly Isles 1869

At Penzance and the Isles of Scilly, unusually high waves arrived between 0600h and 1000h on the morning of the 29 September 1869. The period of these waves was 20 minutes with a wave amplitude of about 5ft (~1.5m). Dawson *et al.* (2000) mentions that …*there is at present no satisfactory explanation for these coastal changes*. The weather report in *The Times* (1869) states that there was a thunderstorm at Portsmouth at 1800h on the 29th, which could have caused a meteotsunami earlier in the day before reaching Portsmouth. The Times (1869) also reports that *The sea is disturbed at the entrance to the English Channel*. It is uncertain what caused this disturbance, with only distant thunderstorms reported. Therefore, it appears most likely to be seiching, but what caused this is not clear.

Cornwall Estuaries 1892

On the 18 August 1892, there was a rapid rise in sea level at the mouth of the River Yealm, which quickly subsided. This does seem to have parallels with meteotsunamis in Menorca and a similar event in the Yealm Estuary (Tappin *et al.*, 2013), but may be related to a Pembrokeshire earthquake at the time, which led to small water disturbances in southwest Wales (Davison, 1924). However, Davison (1924) suggests that unusual wave activity in the Channel was unrelated to the earthquake.

English Channel 1929

The waves that hit Folkestone on 20 July 1929 were likely from a meteotsunami. A tsunami-like wave struck the Kent and Sussex coasts, busy with tourists, and two people were drowned (Haslett *et al*., 2009). Eight waves hit Folkestone harbour and a storm hit Brighton on the same day (The Times, 1929). C. M. K. Douglas (1929) suggested that a squall line traveling up the English Channel, coincident with rain and wind, generated the waves.

Aberavon (South Wales) 1932

At this incident, at Aberavon on the south coast of Wales, several boys aged 14 to 16 years of age were drowned, *…washed out to sea by a sudden tidal wave…*, (The Times, 1932). There are no reports of wave height, nor whether, after the initial wave, further waves struck the beach. The weather report for the day in question mentions several thunderstorms throughout the UK, and the weather at Aberavon, was noted as being 'cloudy' and 'unsettled' by The Times (1932). Most likely a meteotsunami although lacking strong evidence.

Bridlington 1938

Haslett *et al*. (2009) describe what they call *…undoubtedly a meteotsunami…*, which occurred at Bridlington on the coast of Yorkshire. They reference the The Times (1938) article which mentions the sea receding *…15 ft., leaving vessels high and dry…*, later *…refloat other craft farther up the harbour*, which is consistent with a meteotsunami. There were thunderstorms on the same day, which appear linked to the event; so again supporting a meteotsunami.

Weymouth 1939

The description given by Haslett *et al*. (2009) on the tsunami impacting Weymouth on the 5 July 1939 suggests that the origin of the tsunami were the 'violent storms' (The Times, 1939a) which swept the UK at the time, but *The Times* article also mentions an 'earth tremor' in the early hours of the morning in South Wales. This earthquake was unlikely to be the direct cause of the tsunami that hit Weymouth, since it was too far west. Hence, it still seems more likely that it was a meteotsunami.

Isle of Wight 1957

On the 6 July 1957, a series of waves hit Bembridge on the east coast of the Isle of Wight. The Isle of Wight County Press (1957) described the weather as *sultry and overcast…*, *…with heavy thunderstorms over the sea off the east end of the Island*. Haslett and Bryant (2009) do not explicitly make any connection between the waves and the thunderstorms, but the absence of any other explanation, such as an earthquake and the presence of the thunderstorms, point to it being a meteotsunami.

North Devon coast 1966

On the 31 July 1966 at Westward Ho!, water receded, before a large wave (2.5–3m) hit, as written in Haslett and Bryant (2009). The event was further analysed in Haslett *et al*. (2009), who mention a connection between the event at Westward Ho! and a squall front in the southern United Kingdom, which appeared to be associated with a frontal trough. It looks like a meteotsunami based on this information.

English Channel 1968

Although the events of 1 July 1968 described by Stevenson (2011) do not mention the impact of any tsunami-like events on any particular coast, they do say that there was *a fluctuation imposed upon the tidal motion* and *pressure fluctuations at ground level, sometimes by as much as 5 mb in 30 minutes*. This, qualitatively, is how we expect the pressure to behave to generate a meteotsunami.

Peterhead, Scotland 2008

On the 28 May 2008, according to the harbourmaster of Peterhead's report, there was *a sudden outflow of water from the harbour, followed by a sudden return about 10 min later*. There was also a similar phenomenon reported at Fraserburgh and in the Faeroe Islands. The cause of this event appears to be a pressure anomaly moving northward over the North Sea, as presented by Sibley *et al*. (2016), which confirms this to be a meteotsunami.

English Channel 2011

The tsunami of the 27 June 2011 is well documented, with first-hand accounts, weather radar imagery, tide gauge data and a video from the Yealm Estuary. Together with the meteorological data presented by Tappin et al. (2013), this event is the meteotsunami we know most about from generation to impact. The conclusion of Tappin *et al*. (2013) was that the tsunami resulted from *thundery cells located off the Bay of Biscay off Brittany, with earlier contributions from convective cells located over Portugal and later in the English Channel*.

North Sea 2015

On the 1 July 2015, waves impacted the east coast of Scotland after a 1.25m drop in the sea level at Stonehaven Harbour. The conclusions of Sibley *et al*. (2016) were that the event was a meteotsunami caused by the associated *convective systems and surface pressure anomalies*.

English Channel 2016

On the 23 June 2016, a wave of ~13cm struck Newhaven in East Sussex. A wave, with a maximum height of ~43cm also struck the north coast of France. The tide gauge reading for Newhaven should be read, with the proviso that the frequency of tide gauge measurements was 15 minutes. Therefore, meteotsunami waves in the period range of 10 minutes would not have been recorded. Without additional observations, therefore, the event is hard to assess. In addition, the Newhaven tide gauge is sheltered by a breakwater, which protects the opening of the harbour from incoming waves. The conclusions of Williams *et al*. (2018) were that this event was a meteotsunami caused by a convective weather system in the English Channel, with pressure forcing generating the initial wave.

Other possible meteotsunamis

In addition to the meteotsunamis reported above, for which there is supportive evidence on their origins, there are other reports in Edmonds (1862) from Cornwall, and Roberts (1849), from Lyme Regis, of anomalous coastal waves. These reports, however, lack sufficient detail and corroborating evidence to draw strong conclusions as to their mechanisms, but for completeness, they have been included here only as possible meteotsunamis.

On the 25 July 1761, the sea rose 6ft in Mounts Bay. Edmonds (1862) noted *thunder at times all day*. On the 5 July 1843, Edmonds (1862) reports tidal fluctuations associated with violent thunderstorms moving from Cornwall northwards and eastwards around the time of disturbances on the sea. On the 30 October 1843 Edmonds (1862) reports a northeast wind with rain, with a disturbance on the sea. On the 31 May 1811 Edmonds (1862) mentions *Rain, thunder & lightning*. with a disturbance of the sea. On the 8 June 1811 Edmonds (1862) mentions *…during a severe thunder-storm…*, there was a disturbance of the sea.

From Lyme Regis, Roberts (1849) mentions: on the 31 May 1759, *the sea flowed three times in one hour*. On the 18 August 1797, *the sea flowed three times in 1 h, attended by lightning*. On the 26 January 1799, *the sea [flowed] as above about 4 o'clock a.m.* During the summer of 1813, *Upon a summer's day about 1813 something similar (to the above) took place*.

Tsunamis and anomalous waves from other mechanisms

In published reports and publications, some wave events are interpreted as meteotsunamis, but after further research we conclude that for these, (i) insufficient data exists to draw a firm conclusion on their origin, and/or (ii) there is an alternative explanation.

Mounts Bay (Cornwall) 31 March 1761

At about 1230h on 31 March 1761, at Penzance, there was a rapid ebb and flow of the tide up to 4ft deep, five times in an hour. The weather was windy and cloudy, with a north-northeasterly prevailing wind. Also of note in Borlase (Borlase, 1762), is that Loch Ness in Scotland rose and fell 2ft on the same day at about two in the afternoon. There was, *A perfect calm for several hours before and after*. Davison (1924), referencing Glyn, (1761), reports that there was an earthquake of unspecified scale near Cork in Ireland on the 31st of March. Long (2018) reports a 7.5 magnitude earthquake centred near 34.5°N 13°W, off the coast of Portugal. From these reports, we suggest that the tsunamis at Penzance and Loch Ness were most likely caused by one of the two earthquakes, although there is not enough evidence to rule out a meteotsunami.

Chesil beach 1824

On the 23 November 1824, a large storm in the English Channel stuck Chesil Beach. Le Pard (1999) and West (2019), report that a storm surge overtopped the cobble bank, which acts as a sea defence and, shortly afterward, a wave superimposed upon the swell flooded the coastline behind the bank. This is clearly a wintertime storm with a storm surge, storm waves and long period, swell waves. Waves breached the Chesil bank, but also a tidal surge could have come through the eastern entrance.

English Channel 1868

Described as a 'ghost storm' as the sea was calm with no prevailing wind. At Lyme Regis, waves of up to 9m appeared that day also. These were most likely long period swell waves.

Bristol Channel 1910

On the 16 December 1910, a wave struck Ilfracombe in the Bristol Channel, causing large ruts to be 'dug out' of concrete, which resembled coastal erosion by tsunamis elsewhere. The wave struck after a storm depression passed over, so this is unlikely to be a storm surge or a meteotsunami. The newspaper reports differ on whether there was a single wave or a few waves. All of this makes it doubtful that the wave was a meteotsunami, but more likely a long period swell.

Arnside 1964

From Haslett and Bryant (2009), there is little information about this event, only a short paragraph in The Times (1964) which mentions *a father and son being swept away by a tidal wave in the Kent estuary*. There were scattered thunderstorms at the time but as Haslett *et al*. (2009) mention, *the Kent estuary… does experience tidal bores, which presents an alternative explanation*.

Southwest United Kingdom 1979

On the morning of the 13 February 1979, a series of waves hit the southwest coast of the UK. Waves also struck mainland Europe as far south as the coast of Portugal, and as far north as Tenby in South Wales. Haslett and Bryant (2009) references Draper and Bownass (1983) describing the pressure profile over the Atlantic Ocean, which started with a deep depression, that *moved with roughly the same speed (30 kn [15 ms^{-1}]) and the same direction as that of the wave components*. These, however, given the type of weather system, were more likely long period swell waves.

Discussion and Conclusions

From our analysis of the evidence available between 1759 and 2017 for UK anomalous wave events, we confidently identify 23, which we attribute to meteotsunamis. In Figure 2, we present by month the confirmed UK events. The evidence suggests that UK meteotsunamis are more likely to occur in the spring, summer and early autumn months. Both Gray and Marshall (1998) and Hand *et al*. (2004), present the frequency of UK convective systems, showing that most convective systems around the UK occur between May and September. This suggests a positive correlation between meteotsunamis and convective weather systems, which prevail during this period.

From our evidence, covering a period of 258 years, there is a meteotsunami return period of about a decade. If, however, we consider only the last 10 years, when there were six meteotsunamis, the frequency is much higher, with four meteotsunamis since 2008, before which, the last one was in 1968. The increase in event frequency may be real, or apparent and attributable to a raised awareness of geological tsunamis taking place over the past 20 years. For example, there was a major increase in tsunami awareness following the devastating Indian Ocean tsunami in 2004 when, not only were there over 220 000 fatalities, but of these, perhaps over 1000 were western Europeans, 150 of whom were British. It is also notable that, from our list, there were eight reports of meteotsunamis between 1846 and 1859, possibly also a period of heightened interest and awareness.

The evidence we present here supports our conclusion that the anomalous wave events we interpret as meteotsunamis were generated by atmospheric weather systems. Further, that these are convective systems, which predominantly take place during the spring, summer and early autumn. This conclusion agrees with that of Pellikka *et al*. (2015) who studied meteotsunamis in Finland and Bechle *et al*. (2016), who studied events in the Great Lakes of North America.

Tappin *et al*. (2013), discuss the possibility that, with global warming, there could be an increased likelihood of meteotsunamis striking the UK. In addition to the events presented in this paper, in May 2017 a well-publicised meteotsunami struck the Netherlands, with waves around 2m recorded (Assink *et al*., 2018). The video of the event demonstrated its destructive power.[1] The tsunami struck a popular holiday beach; fortunately, it was at 0600h in the morning, so the beach was empty. One aspect of this tsunami was that there was high-frequency radar technology available to identify and mitigate the impact.[2]

With the evidence presented here, the increased frequency of meteotsunami events may be related to awareness, but such events are predicted to become more hazardous with sea level rise. In the context of global warming, rising sea levels and the possibility of more severe storms (Palmer *et al*., 2018), it is relevant to consider how we might better record, model and predict meteotsunamis: for example, tide-gauges operated by other European countries, record in real time and at higher frequencies. The UK has highly developed, operational storm surge/tide forecast models and coupling these (at appropriate coastal resolution) to high-resolution (1.5km) weather forecast models may enable us to understand better the key physical processes of meteotsunamis. In the future, we need to explore how this might be carried out.

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[1]https://www.youtube.com/watch?v=CjQk_xt_WU0.

[2]https://www.hydro-international.com/content/article/mini-tsunami-detected-using-wave-radar?output=pdf.

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