METEOROLOGICAL TSUNAMIS IN SOUTHERN BRITAIN: AN HISTORICAL REVIEW*

SIMON K. HASLETT and EDWARD A. BRYANT

ABSTRACT. Meteorological tsunamis, or meteo-tsunamis, are long-period waves that possess tsunami characteristics but are meteorological in origin, although they are not storm surges. In this article we investigate the coast of southern Britain—the English Channel, the Bristol Channel, and the Severn Estuary—for the occurrence of tsunami-like waves that, in the absence of associated seismic activity, we recognize as meteo-tsunamis. The passage of squall lines over the sea apparently generated three of these events, and two seem to have been far-traveled, long-period waves from mid–North Atlantic atmospheric low-pressure systems. The remaining three wave events appear to have been associated with storms that, among possible explanations, may have induced large-amplitude standing waves—such as seiches—or created long-period waves through the opposition of onshore gale-force winds and swells with high ebb tidal current velocities. This coastal hazard has resulted in damage and loss of life and should be considered in future coastal defense strategies and in beach-user risk assessments. *Keywords: coastal hazards, meteo-tsunamis, Great Britain, storms, weather.*

Meteorological tsunamis, or meteo-tsunamis, are waves that possess tsunami characteristics but have a meteorological origin (Defant 1961; Rabinovich and Monserrat 1996, 1998; Bryant 2001; González, Farreras, and Ochoa 2001). Tsunamis are characterized by their long wavelength and long-period nature; that is, the distance and time, respectively, between consecutive wave crests, often measured in kilometers and tens of minutes rather than in meters and seconds, as with most wind-generated waves, characteristics that enable shoaling tsunamis to grow in height at the shore and to penetrate relatively far inland. Various local names around the world describe meteorological tsunamis, such as *rissaga* in the Spain's Balearic Islands (Monserrat, Ibbetson, and Thorpe 1991), *abiki* in Japan's Nagasaki Bay (Hibiya and Kajiura 1982), *marrobbio* in Sicily (Candela and others 1999), *Seebär* in the Baltic Sea, and also, perhaps, "freak waves" (White and Fornberg 1998; Wu and Yao 2004).

Meteo-tsunamis have the same periods, spatial scales, physical properties, and destructive impacts as seismically generated tsunamis have when they refract and shoal along coasts (Bryant 2001; Monserrat, Vilibi, and Rabinovich 2006). Rogue waves are large meteorological waves that are infamous for sinking ships in the open sea and thus differ from tsunamis, which are of low amplitude in the open

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FIG. 1—The aftermath of the "Great Tidal Wave" that struck Ilfracombe, Devon, England, on 16 December 1910. The wave progressed from left to right, ripping up concrete and knocking over lampposts and other street furniture (see also Figure 4). (Photograph reproduced courtesy of Ilfracombe Museum)

ocean, but rogue waves formed in coastal waters may be considered meteo-tsunamis if they take on tsunami-like characteristics (Kharif and Pelinovsky 2003).

A number of mechanisms can result in a meteo-tsunami. These include the passage of cyclones or hurricanes, frontal squalls, atmospheric pressure jumps (sudden changes in atmospheric pressure associated with thunderstorms), atmospheric gravity waves (vertical oscillations of air cells), tide-generated internal waves (Giese and others 1982), wave superposition (addition of overlapping wave-crest heights), interaction of wind and current, and atmospheric shock waves from volcanic activity (Rabinovich and Monserrat 1996; Lowe and de Lange 2000; Bryant 2001). These processes can generate tsunami-like waves if the disturbance propagates at the same speed as any surface ocean wave being generated (Monserrat, Vilibi, and Rabinovich 2006). Meteo-tsunamis are also very sensitive to resonance generated by local coastal geometry and topography, which, in enclosed inlets, bays, and harbors, can induce high-amplitude seiches; that is, standing waves that slosh back and forth across enclosed water bodies (Rabinovich and Stephenson 2004).

Coastal managers do not currently consider the coast of the British Isles to be at risk from meteo-tsunamis, but a review of historical large waves in southern Britain leads us to believe that the phenomenon does occur. This is particularly so within the enclosed basins of the Bristol Channel and the English Channel, sometimes with catastrophic consequences (Figure 1). Some authors have criticized the current coastal hazard planning in the United Kingdom for its lack of integration: It operates at the

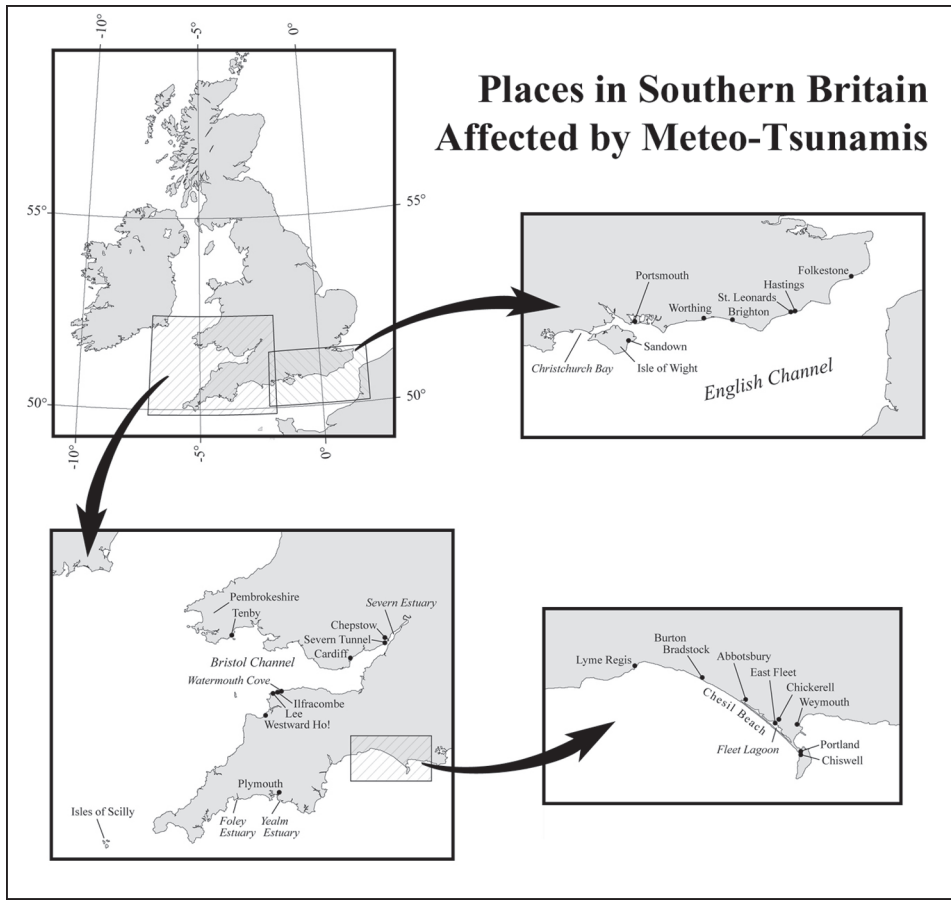

Fig. 2—Places in southern Britain mentioned in the text. (Cartography by the authors)

local or regional level and is usually conducted by local government authorities (Ballinger and others 2000). Coastal planners in the United Kingdom are more concerned with long-term, predictable hazards, such as coastal flooding, erosion, and sea-level rise, than with meteo-tsunamis, but evidence suggests that meteo-tsunamis should also be included in any coastal hazard assessment of these areas.

Meteo–Tsunami Occurrences

Events included in this study share a key trait: one or more large waves that resemble a tsunami with no known associated seismic activity but with a possible meteorological explanation. However, the possibility exists, even with a meteorological explanation, that some of these events may be due to distant seismic activity or a submarine landslide. The locations of places mentioned in this article are shown in Figure 2, and Table I summarizes the characteristics of meteo-tsunamis they experienced. We identified events through a survey of scientific and popular literature and of newspaper reports. Although the latter can provide valuable information,

TABLE I—SUMMARY OF METEO–TSUNAMI OCCURRENCES IN SOUTHERN BRITAIN

DATE	AREAS EFFECTED	ORIGIN	IMPACTS
23 November 1824	Chesil Beach and The Fleet	Local gale/ hurricane	Large wave overtopped a gravel barrier and penetrated inland, destroying houses and a church and causing up to sixty deaths
23 April 1868	Burton Bradstock and Lyme Regis	Unknown, but not associated with a local storm	Villages inundated, waves up to 9 meters high
17 October 1883	Severn Estuary	Unknown, but linked to a local storm	Large wave overtopped sea defenses and flooded lowlands
18 August 1892	Yealm and Fowey Estuaries	Linked to a thunderstorm/ squall in the English Channel	A series of large waves damaged boats
16 December 1910	Ilfracombe and the surrounding area	Local gale	Wave up to 9 meters high struck Ilfracombe and penetrated inland, causing damage
20 July 1929	Folkestone to Brighton	Squall line in the English Channel	Large wave struck beaches, killing two people
31 July 1966	Westward Ho! and Pembrokeshire	Probably a squall line in the Bristol Channel	Large wave struck, bowling people over up the beach at Westward Ho! and causing damage along the Pembroke coast
13 February 1979	Bristol Channel and the western English Channel coasts	Distant Atlantic storm	A series of large, long-period waves overtopped Chesil Beach and sea defenses

especially eye-witness statements, each report requires careful reading to avoid attributing credibility to statements that may be exaggerated or fabricated.

CHESIL BEACH AND THE FLEET (DORSET)

A storm on 23 November 1824 was marked by gale- or hurricane-force winds, according to some reports. One or more large waves with tsunami characteristics accompanied the storm and caused much damage and loss of life. Gordon Le Pard (1999) and Ian West (2008a, 2008b) provide accounts of the event that form the basis of the evidence we present. The Fleet is a lagoon sheltered behind the southwest-facing Chesil Beach gravel barrier (May 2003). During the 1824 storm a single giant wave overtopped, rather than breached, the gravel barrier from Chesil in the east, where it destroyed many fishermen's cottages and apparently killed fifty to sixty people. In Abbotsbury, to the west, the wave inundated back-barrier meadows to a depth of approximately 6.9 meters. Commemorative information regarding

this event is on display at these locations and at the nearby coastal town of Weymouth, where the event badly damaged the seafront (Figure 3).

The most detailed accounts of the wave come from the village of East Fleet, in a small valley midway along the length of The Fleet lagoon (see Figure 3). What has been described as a tidal wave struck Fleet Church—also known as "Moonfleet Church"—where a boy,

> at six o'clock in the morning . . . was standing, with other boys, by the gate near the cattle pound when he saw, rushing up the valley, the tidal wave, driven by the hurricane and bearing on its crest a whole haystack, and debris from the fields below. They ran for their lives to Chickerell, and when they returned they found that five houses had been swept away and the church was in ruins,[.] . . . The sea began to break over the beach at 5 a.m., [and] the water came up as fast as a horse could gallop. James watched as long as he dared, and then, terrified, ran for his life to Chickerell. (Le Pard 1999, 26)

Only the chancel remained of Fleet Church, which now contains a notice that states "in 1824 a great tidal wave washed over the ridge of the Chesil Beach and over the Fleet Water and passed onwards, the water reaching a depth of about 30 feet [approximately 9 meters] at this point." With reference to a nearby Ordnance Survey benchmark we surveyed (using a Leica 400 Total Station), the church floor stands at 4.05 meters Ordnance Datum (OD Newlyn, approximately mean sea level), so the wave run-up must have been a minimum of approximately 13 meters above sea level at this point. According to West, "the original lower village of Fleet, normally sheltered by the Chesil Bank, was devastated by [a] wave resembling a tsunami. Just why there was a sudden appearance of [a] giant wave which came over the Chesil Beach and the Fleet Lagoon is not clear" (2008b).

A surge was clearly linked with the storm, because at Lyme Regis a customs officer reported that "the tide was flowing [coming in] at one a.m. . . . though it ought not by the tide table, to have been low water until an hour after the time!" and that subsequently "it came up to high water mark during neap tides at three o'clock which was five hours before the time of high water [spring tide predicted at 7:39 a.m.]! Before four, the sea had risen to a great height[,] . . . which soon afterwards broke over the [sea] walls" (Le Pard 1999, 23); however, large, long-period waves may have superposed on the storm surge sometime after 7:00 a.m., when an initial inundation "made a clean breach" through the ground floor of an alehouse; then, ten minutes later, a second wave "broke in the roof" that had collapsed, followed by a "third wave [that] carried the whole away" (p. 24).

THE SEVERN ESTUARY (MONMOUTHSHIRE)

During the construction of the Severn Tunnel, a railway tunnel under the Severn Estuary, "a great tidal-wave burst over the whole of the low-lying ground . . . as a solid wall of water 5 or 6 feet [1.52–1.83 meters] high" on 17 October 1883 (T. A. Walker [1891] 1990, 172). During a nighttime gale, the 19 October *Times* reported, "between 8 and 9 o'clock a huge tidal wave, rolling in from the [Bristol] channel at

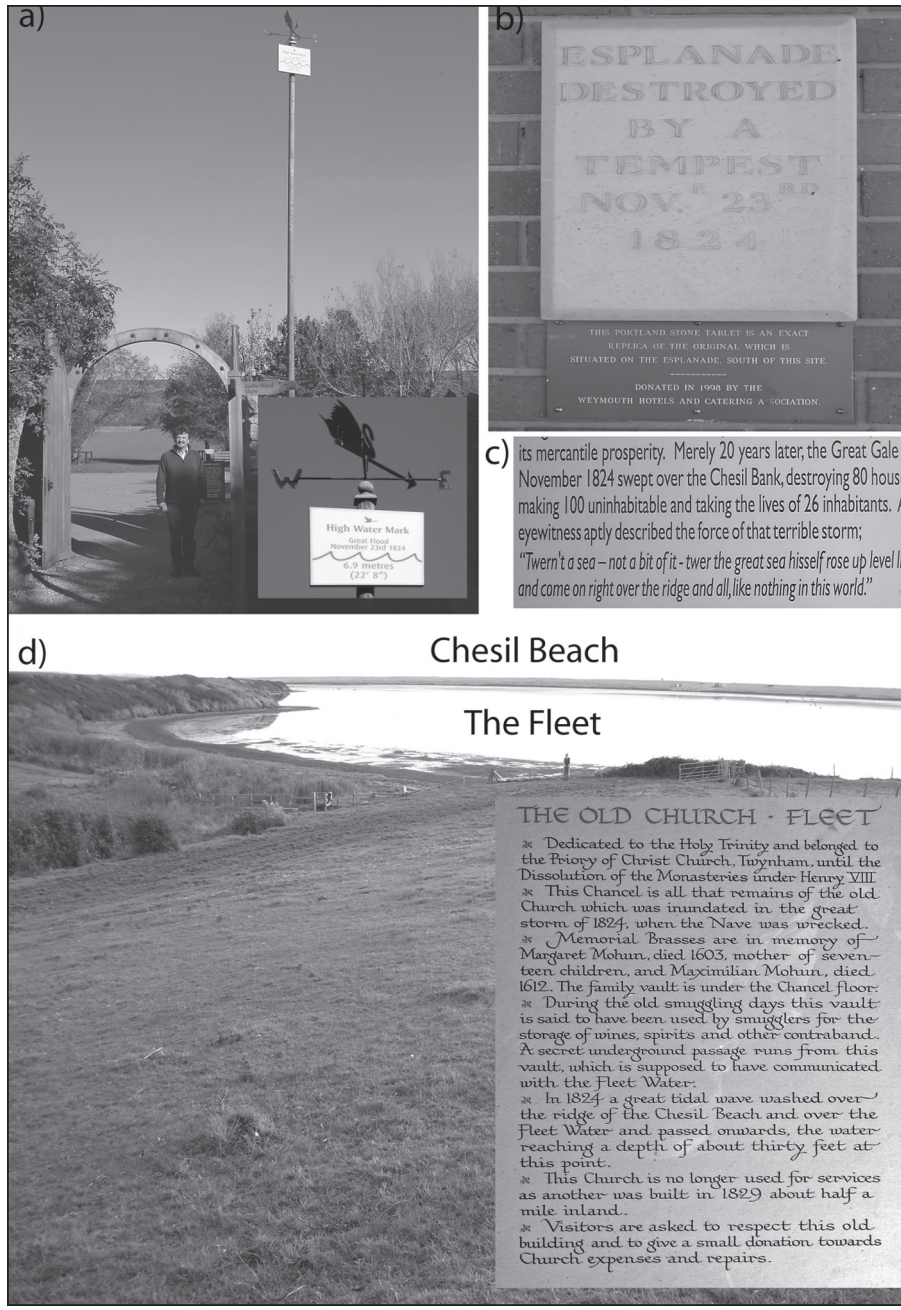

Fig. 3—Locations in Dorset, England affected by the 1824 wave: a) the 6.9-meter flood depth (see the inset) at Abbotsbury is recorded by this vertical flood marker; b) a plaque commemorating the destruction of the esplanade at Weymouth; c) an extract from a public information board at Chesil; d) a view of the valley at East Fleet, where the wave is reported to have overtopped Chesil Beach and traveled across The Fleet to inundate the valley and submerge the church at the valley head, behind the photographer (the inset shows the commemorative plaque at the church). (Photographs by the authors, October 2007)

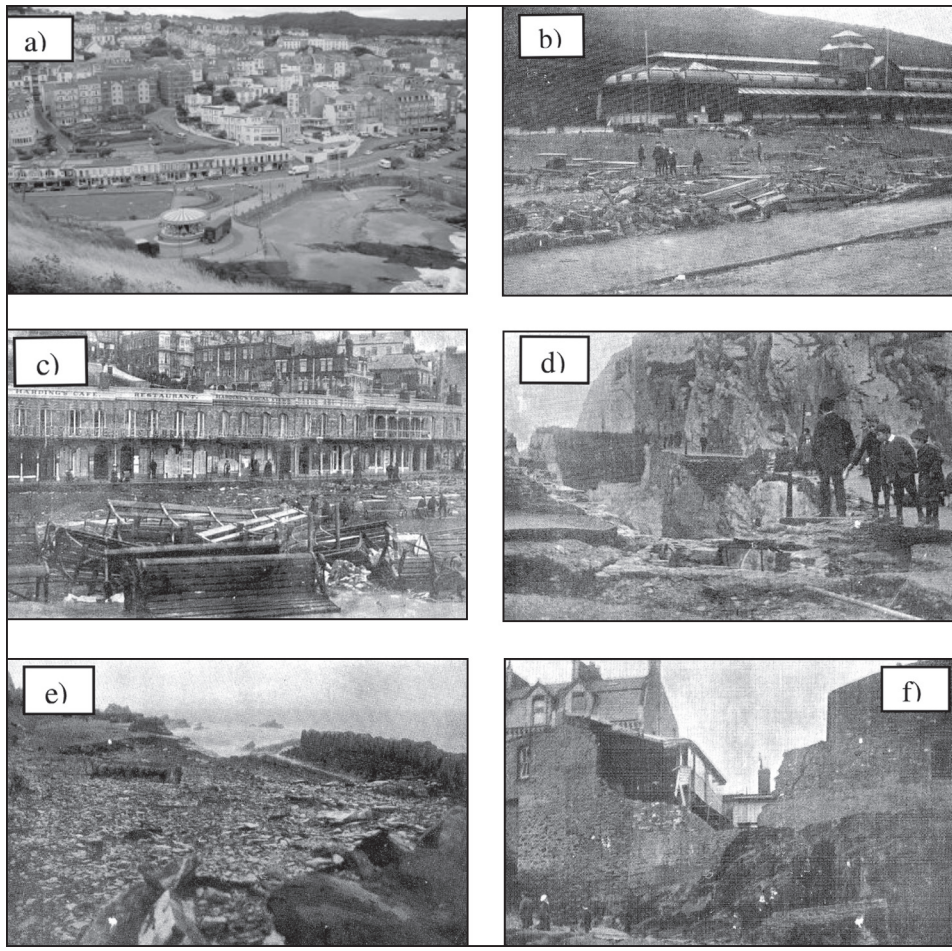

Fig. 4—Recent and 1910 views of Ilfracombe, Devon, England: a) view in July 2005 of the Promenade from the Capstone; b) "Ropery Meadow, from the Promenade," after the 1910 wave hit; c) "The Promenade Shops Barricaded after the Storm" in 1910; d) "Asphalt Torn up, and Part of the Parapet Demolished on the Parade," after the 1910 wave hit; e) "Ilfracombe Hotel Grounds, Ploughed up by the Waves" in 1910; f) "Breach in Sea wall. Cheyne Beach, Showing Mr Knill's Wrecked Garage," after the 1910 wave hit. (Photograph 4a by Simon Haslett, July 2005; photographs 4b–4f reproduced courtesy of Ilfracombe Museum)

high tide, covered all the low-lying land." The wave flooded the tunnel, and one construction worker drowned. The time of the high spring tide was 7:48 p.m., so the wave arrived as the tide was ebbing. The inundation was clearly linked to poor weather and flooding along the South Wales coast, affecting the shore from Cardiff to Chepstow (Zong and Tooley 2003).

THE YEALM (DEVON) AND FOWEY ESTUARIES (CORNWALL)

Newspapers reported that "a series of tidal waves" occurred along the western English Channel coast in the estuary of the River Yealm, where "a good deal of damage

was done to boats moored in the river" on 18 August 1892 (Penny Illustrated 1892). The 19 August *Times* also reported this event, stating that "there was a rapid rise in the River Fowey as a great tidal wave, but this immediately subsided." Although these waves coincided with an earthquake that had occurred in the Bristol Channel, to which the newspapers connected them, they are more likely to have been related to squalls. *The Times* reported thunderstorms in the English Channel that day (1892b), and Charles Davison believed that the storms generated the large waves (1924).

ILFRACOMBE AND THE SURROUNDING AREA (DEVON)

A storm occurred on 16 December 1910, accompanied by gale-force winds and both coastal and river flooding over a wide area of southern Britain (The Times 1910a). Much damage was caused to sea defenses by storm surge and wave action at a number of locations during the day (see, for example, Cundy and others 2002); but Ilfracombe in North Devon, on the Bristol Channel coast, was hit by a unique large wave (Figure 4a). The local *Ilfracombe Gazette and Observer* carried the headlines "The Tidal Wave. Terrible Havoc. Enormous Damage!" (IGO 1910b). High tide at Ilfracombe occurred at 5:24 p.m., and the wave reportedly struck between 6:10 and 6:15 p.m. The U.K. synoptic chart for that day, published in *The Times* on 17 December, indicated that by 6:00 p.m. the 979-millibar storm depression lay over northeast England and the North Sea, that pressure over southwest England had increased to 992 millibars, with the "bar rising steadily," and that a westerly gale maintained "rough" seas. A wind record for 6:00 p.m. at Bristol on 16 December, from the National Meteorological Archive, indicated a Force 7 (13.9–17.1 meters per second on the Beaufort Scale) southwesterly, with pressure at approximately 986 millibars.

Because storm surges tend to occur below an atmospheric depression, these data suggest that the wave at Ilfracombe is unlikely to have been surge related, for it hit sometime after the depression had passed. Moreover, eyewitness reports suggested that the wave had characteristics of a tsunami. Indeed, the local residents were so astounded by the occurrence that the *Ilfracombe Gazette and Observer* produced a souvenir pamphlet containing eyewitness reports and photographs (IGO 1910a) (Figure 4b-4f; see also Figure 1). A pair of artists' impressions of the "Great Tidal Wave" also appeared at the time (Figure 5).

At Ilfracombe, according to the souvenir pamphlet,

> a tremendous tidal wave swept over the Capstone Parade, and the Ropery Meadow, breaking upon the Promenade shops with terrific force. . . . Practically the whole of the damage was done by a huge tidal wave. . . . It is a rather remarkable fact that although this was nearly an hour after high tide comparatively little damage was done till then. The huge wave broke upon the shore with almost incredible force. It carried everything before it. The lampposts on the Parade were about the first to go. These were snapped off like fragile reeds. Heavy seats and big blocks of masonry were carried upon the crest of the wave, which swept over Ropery Meadow at a height estimated at from 15 to even 30 feet [approximately 4–9 meters] high, leaving

> ruin and wreckage in its path. The wall of Ropery Meadow yielded before it, and the masonry and the Parade seats were hurled with tremendous force against the Promenade shops. The Promenade was immediately a rushing torrent. Several people narrowly escaped injury. On seeing the huge wave approaching they turned and fled for their lives. Two or three were unable to reach a place of safety before the wave reached them, and were knocked over like ninepins. Others fell in their hurry to get out of danger. It seems remarkable that no one sustained serious injury. (IGO 1910a, 1–2)

One observer said that "the great wave came in straight across the Preacher's Rock, and struck the Bandstand with full force. . . . It was like a tidal wave" (IGO 1910a, 5). An interesting account came from a gentleman who "saw two cross waves meet . . . and rose like a mountain. . . . The most remarkable thing was that scarcely any wind was blowing in shore at the time. I have seen rougher seas scores of times," he added, "but it was one wave that did the damage. . . . I should think that the whole of the damage along the coast, practically speaking, was done by that single wave" (pp. 5–6).

The wave produced geomorphological effects, including erosion, where "large ruts, three feet [nearly 1 meter] deep, were dug out of the concrete" by the wave (IGO 1910a, 3), and cavities appeared in the north side of the pier (IC 1910), cavities that resembled the erosion of bedrock by tsunamis described elsewhere (Bryant and Young 1996). Also, at Lee "the sea wall adjoining the road was simply lifted from its foundation, and laid intact on its side [by the wave]. This wall is 36 feet [almost 11 meters] long, four feet [1.2 meters] high, and two feet [0.6 meters] wide" (IGO 1910a, 4). Deposition also occurred when "the previously green turf of the Meadow was covered with mud, shingle and wreckage" (p. 4), and "the Ropery Meadow was strewn with huge boulders, broken seats, iron railings" (p. 3).

A report in the 16 December *Ilfracombe Gazette and Observer* suggested that two waves struck several minutes apart, but most other accounts mentioned only one wave. The 21 December *Ilfracombe Chronicle* described how the wave broke upon the shore, stating that

> the huge wave came up to the level of the Parade, and then erecting itself fell with terrific force on the low wall surmounted with an iron railing, that stands between the Parade and the Ropery Meadow. This obstruction was swept out for most of its length as cleanly as if scooped out by a spoon. The wave next attacked the wall by the road, a large part of which as also swept away. Huge pieces of walling were driven across the road, and considerable damage done. (IC 1910)

The same account detailed how "the huge wave made the pleasant terrace [the Esplanade] a desert, strewn with boulders and blocks of stone, with great holes [eroded potholes] here and there" and how "great slabs of concrete [were] heaped up in confusion" (IC 1910).

Although no records of seismic activity exist, the Ilfracombe wave appears to have possessed the characteristics of a long-period tsunami wave because it rose abruptly as it reached the shore to an anomalously large height and then progressed

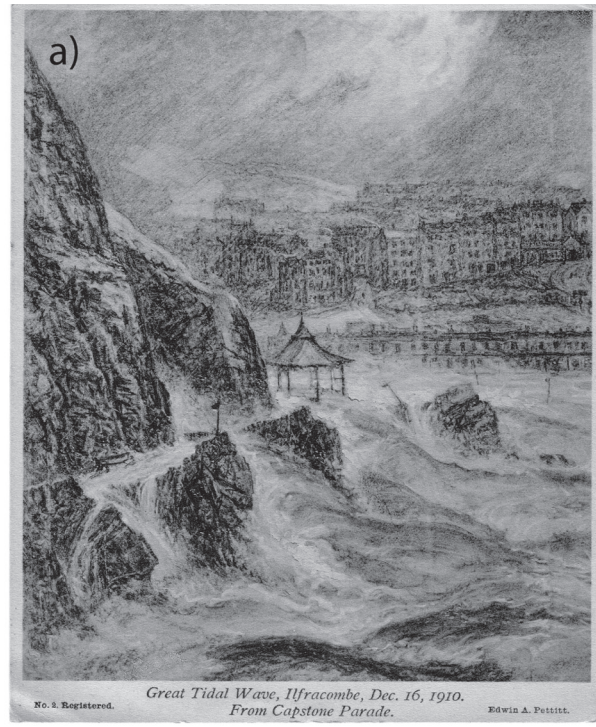

Fig. 5—Artists' impressions of the 1910 wave at Ilfracombe, Devon, England: a) "Great Tidal Wave, Ilfracombe, Dec. 16, 1910. From Capstone Parade"; b) "Great Tidal Wave, Ilfacombe, Dec. 16, 1910. From the Ilfracombe Hotel." (Illustrations reproduced courtesy of Ilfracombe Museum)

across a distance of approximately 100 meters, through buildings and up the footslopes of the hills behind. The nature and scale of erosion, sediment transport, and deposition are also reminiscent of tsunamis (Bryant 2001). Indeed, one eyewitness, recollecting the event many years later, had forgotten about the storm associated with the wave:

> I had been around Capstone about fifteen minutes before the great sea disaster that so shattered the sea walls along the North Devon coast. Our Parade, Pavillion and shops on the front were damaged and flooded, also St. James Place and the Quay and many boats were smashed. It was not a gale that caused the sea to rise up and crush everything in its way—something must have happened out in the [Bristol] Channel, a small earthquake or something similar, as no damage was caused to the town excepting the sea front. At Watermouth, which is a sheltered harbour, big boats were washed up into fields. No one seemed to have known of anything like it before. It did not last very long but was very severe while it lasted. (Wilson 1976, 64)

Elsewhere in the surrounding area, local newspapers report that the same "tidal wave" occurred at Lynmouth (Devon) and at Minehead and Porlock (Somerset), where the wave overtopped a gravel barrier and flooded a golf course (Bray and Duane, 2002).

FOLKESTONE (KENT) TO BRIGHTON (SUSSEX)

At around 7:30 p.m. (about an hour and a quarter after low tide) on 20 July 1929 a large, tsunami-like wave struck the Kent and Sussex coasts, busy with tourists, and drowned two people. The 22 July *Times* described the event at a number of locations: At Brighton and Worthing sudden downpours of rain and high winds accompanied the wave, but at Folkestone and Hastings, where one person drowned at each site, the weather was clear, and estimates projected the unexpected wave at approximately 3.5 and 6 meters high, respectively. Uniquely, at Folkestone, observers reported eight large waves entering the harbor, picking up motorboats lying on sand flats, exposed close to low tide, and transporting them more than 180 meters along the length of the inner harbor. The wave washed away a sixteen-year-old boy who was fishing from the breakwater, his body never to be recovered. If this event had coincided with the high tide, then the number of casualties would probably have been much greater and damage more extensive. C. M. K. Douglas suggested that a squall line traveling up the English Channel, coincident with rain and wind, generated the wave, so it may be referred to as a "meteorological tsunami" (1929).

Further details from *The Times* give a fuller picture of the event (1929, 14). At Brighton "a line of foam rushed towards the beach, while pleasure boats raced for safety. Almost before the crowds realized what was happening torrential rains poured down and the wave rushed far up the beach, carrying away chairs and bathers' clothes." At Folkestone

> a number of bathers and people paddling were caught by the tide and were in danger of being drowned. Mrs Ruth Kirby . . . and her five and six year old daughters . . .

> were injured by being cast on the rocks and had to be taken to hospital for treatment. The mother was only able to catch her two children as they were submerged by the sea, but was fortunately able to retain her hold on them. Mrs Elizabeth Hill . . . and two Folkestone boys named Whiting and Pryor were also injured by being thrown on the rocks. . . . A small boat with two men in it was lifted up on to the rocks at East Cliff and left high and dry.

At Hastings "Mrs Lillian Pollard . . . was drowned when the boat in which she was a passenger capsized. . . . The wave overturned the boat and all its occupants went under. . . . At St. Leonard's two boats were capsized by the wave and all the occupants were thrown into the sea." On the east side of the Isle of Wight "a bank of sand swept along the sea front with considerable force. Many boats were overturned on Sandown beach." Finally, at Worthing "the sea was churned up into a wave quite 6 ft. [1.8 meters] high, which came sweeping towards the shore at an alarming pace. It extended as far as the eye could see and within five minutes the sea had risen from low to half full tide. The people on the front and those who were bathing or paddling ran for shelter."

WESTWARD HO! (DEVON) AND PEMBROKESHIRE

According to an eyewitness account,

> On the beach at Westward Ho! in North Devon in August 1966, as far as I can now ascertain the date[,] . . . I was in the water with my small surf board, "catching" waves to bring me into shore. Suddenly, with my back to the sea[,] . . . I found [that] the water had dropped from waist level to around my ankles. I turned to look out to sea and saw a huge wave coming in. . . . When it arrived, I had the surf board ripped from my hands, and I was bowled over and over in the foaming water. The wave ran up the beach, soaking everyone who had not seen it coming, and stealing all possessions. . . on the stones there. . . . I remember thinking I would surely drown in this giant wave, but found myself still alive, but pretty battered. . . . I remember looking over my shoulder when the wave was very close, and realising, with horror, that it was enormous. I am 5 feet 4 inches [1.63 meters] tall, and I would estimate the wave to have been something in the region of eight to ten feet [2.44–3.05 meters] in height. . . . If it had been hitting the coast of Devon in any other place than Westward Ho!, then the results could have been quite devastating. The huge stones and sea defences behind probably dissipated the force of the vast amount of water. (Murray 2005)

Although one cannot be certain, an examination of weather events in the outer Bristol Channel region around August 1966 reveals a candidate for the event that took place during the afternoon and early evening of 31 July. The front page of the 1 August *Times* ran the headline "40 Yachts Hit by Freak Squall" and describes how a damaging squall with wind speeds up to 45 meters per second struck the Pembrokeshire coastline across the Bristol Channel from Westward Ho! Rescue services searched for hours for people missing as yachts were blown away from their moorings and in some instances were washed out to sea and/or overturned; eventually everyone was accounted for. If this link between the Pembrokeshire squall and the

Westward Ho! wave is correct, this event constitutes a second instance in which the passage of a frontal squall in southern Britain generated a meteo-tsunami. Indeed, this wave appears to have been similar to one that hit Kent and Sussex in July 1929, where the wave unexpectedly struck coasts in areas where the meteorological effects—heavy rain and strong winds—were absent.

Fig. 6—Locations affected by far-traveled, long-period waves in Dorset, England: a) the village of Chesil (Chiswell), located behind Chesil Beach, with the Isle of Portland in the distance, which was inundated in 1979 (and also in 1824); b) a gap in the cliffs at Burton Bradstock through which a large wave passed in 1868 and traveled inland up the c) narrow valley to inundate the village of Burton Bradstock. (Photographs by the authors, October 2007)

An alternative, or contributory, factor in this event may have been the position of Hurricane Dorothy in the mid–North Atlantic on 30 and 31 July (Erickson 1967; Sugg 1967), which may have generated far-traveling, long-period waves. We believe that this is unlikely, however, given the occurrence of a local squall, but nevertheless possible, as the next example demonstrates.

THE COASTS OF THE BRISTOL AND WESTERN ENGLISH CHANNELS

A series of long-period waves arrived unexpectedly in southwest Britain on the morning of Tuesday, 13 February 1979. The waves entered the Bristol and English Channels, and also occurred along the Atlantic seaboard of Europe as far south as Portugal. Laurence Draper and T. M. Bownass briefly reported the damage inflicted by the waves in southern Britain (1983), including the Isles of Scilly, Plymouth Harbour and Sound (where a wave broke over the 19-meter-high breakwater light), Seaton, Portland, Tenby in South Wales, Christchurch Bay (2-meter wave heights), and even as far east as Hayling Island near Portsmouth (1.5-meter wave height). They also stated that a wave recorder offshore of Lisbon recorded a maximum wave

height of 17.2 meters at 3:40 a.m. on 13 February. The arrival of the waves in the English Channel coincided with a surge of 0.6 meters at Plymouth, probably associated with an area of low pressure over the western Channel at the time, and with high tide at Portland at 7:40 a.m. It was here that the most dramatic overtopping of the 12-meter-high eastern end of Chesil Beach occurred, enhanced by refraction and wave set-up, inundating the village of Chesil (Chiswell) with water and gravel (Figure 6a).

Draper and Bownass examined the origin of the waves and showed that the local wind was a 10-knots (5 meters per second) easterly and not able to produce the affects observed (1983). They concluded that a deep (952-millibar) depression in the Atlantic Ocean generated the waves. During the preceding forty-eight hours the depression had "moved with roughly the same speed (30 kn [15 m/sec]) and in the same direction as that of the wave components of about 18–20 seconds [period; c. 500–625 m wavelength] which it had generated, and so continued to input energy preferentially into this longer-period part of the wave spectrum for a considerable time, creating high and unusually-long-period sea waves" (p. 348). Then, "after the source depression died out[,] the waves continued to travel across the ocean at a speed of about 15 m/s" (J. M. Walker 1991, 66). In addition, the wave train appears to have contained an even longer-period wave set, because the tide gauge of St. Mary's on the Scilly Isles for that morning indicated "considerable disturbances," with a wave period of approximately ten minutes (Draper and Bownass 1983, 349).

Interestingly, Alastair Dawson and his coauthors recounted a similar flood event that occurred nearby at the western end of Chesil Beach, at Burton Bradstock (Figure 6b, 6c), on 23 April 1868, when the village "was inundated by a rush of water from the sea. . . . The sea was calm" (Dawson and others 2000, 66). At Lyme Regis, waves up to approximately 9 meters high also appeared on that day. The authors cited a similarity of this event with the February 1979 waves and reported that it had been described as a "ghost storm."

Causes of Meteo–Tsunamis in Southern Britain

The coast of southern Britain has clearly experienced large waves that possess characteristics of tsunamis but that appear to be linked to meteorological phenomena and that, in the absence of any known seismic activity, may best be described as "meteotsunamis." Of these seven occurrences, three—1892, 1929, and 1966—appear to have been linked to the passage of frontal squall lines over the sea, in the same way in which similar waves have been generated elsewhere (see, for example, Platzman 1958; Sallenger and others 1995), where a squall line generates a large-amplitude wave that subsequently moves at a speed in phase with the squall. The squall may dissipate, but the wave continues to progress to shore, where it shoals and may refract, enhancing wave heights locally. Two other events—1868 and 1979—are likely to be far-traveled, long-period waves generated a considerable distance from the coast (that is, in the mid–North Atlantic), in the manner described by Draper and Bownass (1983), producing what have been called "ghost storms" (Dawson and others 2000).

The remaining three large wave occurrences—1824, 1883, and 1910—appear to have coincided with major storms and their associated storm surges; however, the characteristics of the waves suggest tsunami-like phenomena rather than storm-surge inundation. A possible explanation for the generation of meteo-tsunamis under such conditions is the excitation of large-amplitude seiches in semienclosed water bodies, such as the Bristol and English Channels, where seiching may be related to the resonance characteristics of the local coastal configuration. Alexander Rabinovich and Fred Stephenson examined the passage of a storm (960 millibars of pressure, wind velocity of 39 meters per second) over the coast of British Columbia and noted a storm surge of approximately 1 meter above the predicted tide (2004). Seiching occurred in a number of the inlets and harbors investigated, superimposed on the surge height, with a maximum seiche height of 15 centimeters and periods between two and fifteen minutes. Seiching at other locations, due to local topography, can attain heights in excess of 4 meters (Rabinovich and Monserrat 1998), so this process has the potential to explain some of the large waves described in this article.

Seiching in southern Britain is not well known, particularly in the Bristol Channel. Recently, however, a tidal barrage was constructed across Cardiff Bay, and a new tide-gauge station associated with the barrage now provides high-resolution tide-level data. During a southwesterly gale in the Bristol Channel on 3 December 2006, a 1.5-meter surge occurred. As high tide approached, seiching developed, with a ten-minute period and maximum heights of 30 centimeters above the surge level. These data demonstrate that seiching does occur within the Bristol Channel and, under more severe meteorological conditions, may give rise to large meteo-tsunamis. This may have been the contributor to the 1824 Dorset event, when at least three large waves superposed on elevated surge levels at approximately ten-minute intervals.

An alternative explanation may involve the near-coastal generation of single, large freak waves. Modeling, observational, and laboratory studies have provided clear evidence that single large waves may be generated where wind, sea swell, and opposing current superposition occur (Smith 1976; Lavrenov 1998; Wu and Yao 2004). These phenomena are common offshore of South Africa, where wind speeds of approximately 15 meters per second generate fast-moving swells that oppose currents of around 2 meters per second (Torrance 1995; Lavrenov 1998).

In laboratory experiments Chin Wu and Aifeng Yao showed that strong currents opposing wind and swell directions can elevate the steepness and asymmetry of freak waves, producing a high wave height fronted by a deep trough (2004). This process, therefore, both amplifies the wave height and slows down the advancing wave. Offshore of South Africa, waves up to 6 meters high can be produced in this way and are a hazard to shipping. Similar conditions were present during the 1883 and 1910 events described above. At Ilfracombe, in 1910, the storm depression occurred some hours before the wave struck, but a westerly gale continued to blow onshore. Significantly, the wave occurred forty-five minutes to an hour after high

tide, a period in which ebb tidal flow can attain velocities up to 2 meters per second (Severn Tidal Power Group 1989). However, this wave, too, could have been due to the passage of a frontal squall associated with the storm or, taking into account the eyewitness who stated that he "saw two cross waves meet" (IGO 1910a, 5), to superposition of two separate large waves, or to the convergence of a single refracting large wave (see Haslett 2008).

Whatever the mechanism for the generation of these storm-associated meteo-tsunamis, they may have relevance in understanding older historical events within the region. For example, a debate is currently taking place over the cause of a catastrophic flood in the Bristol Channel and Severn Estuary in 1607 that appears to have resulted in around 2,000 fatalities. Eyewitness accounts have led some authors to propose that a tsunami caused the flood (Bryant and Haslett 2003, 2007; Haslett and Bryant 2005, 2007a, 2007b, 2008), because some accounts suggested that the weather was fine and described wave-inundation characteristic of tsunamis, whereas other authors have maintained that the flood resulted when a storm surge overtopped the sea defenses (Horsburgh and Horritt 2006). Our recognition that meteo-tsunamis can occur in the region provides a third possible explanation. Although it is unlikely that this alternative could account for all the observations linked to this event, it is interesting to note that the 1607 Somerset flood occurred more than thirty minutes after high tide, when ebb tidal currents may have attained sufficient velocity to enhance the height of any tsunami-like wave that was progressing up the channel.

Meteo–Tsunami Study

Our historical review strongly indicates that further research, especially modeling, is required on the causal mechanisms of meteo-tsunamis in the coastal waters of southern Britain, because these large waves are not presently accounted for in the coastal defense strategies of the region. Sea walls are typically constructed up to the height of known historical storm surges, but allowance is not made for large, superposed waves. As a result, such waves present a potential hazard, one that was associated with considerable damage and loss of life in the past. It is usually possible to predict storm surges hours if not days before they hit, but the arrival of meteo-tsunamis has always been unexpected and, from the accounts we reviewed, has always taken people by surprise. Thus the distinction between storm surge and meteo-tsunamis as hazards is clear. In particular, beach users should be made aware of the dangers associated with the passage of frontal squalls, for on two occasions in the past meteo-tsunamis associated with squalls occurred unexpectedly on summer days, when beaches had many recreational users. Awareness could be achieved partly through information boards that warn the public to be on the lookout for large waves if they observe a thunderstorm at sea. Coastal hazard planners, therefore, should also consider implementing more sophisticated warning systems, so that beaches can be evacuated if threatened by a meteo-tsunami. This could be achieved by evaluating existing local tsunami warning systems elsewhere (Darienzo and others 2005).

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