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TSUNAMI: A HISTORY OF THE TERM AND OF SCIENTIFIC UNDERSTANDING OF THE PHENOMENON IN JAPANESE AND WESTERN CULTURE

by

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In the past few years we have unfortunately had several reminders of the ability of a particular type of ocean wave—a tsunami—to devastate coastal areas. The Indian Ocean tsunami of 2004, in particular, was one of the largest natural disasters of past decades in terms of the number of people killed. The name of this phenomenon, *tsunami*, is possibly the only term that has entered the physics lexicon from Japanese. We use Japanese and Western sources to document historical tsunami in Europe and Japan, the birth of the scientific understanding of tsunami, and how the Japanese term came to be adopted in English.

Keywords: tsunami; Japan; Europe; Hearn; Scidmore; Hokusai

Tsunami are the result of a large mass of water being displaced in a short time. This typically occurs with seabed earth movements from undersea earthquakes (seaquakes), volcanic eruptions or landslides in the ocean, in a sea or a large lake. A second mechanism is a large amount of material suddenly entering the water, either from a landslip onshore that ends up in the water or from a meteorite impact. In either case, the sudden displacement of a large mass of water initiates a wave, or a train of waves, that may have an extremely long wavelength of up to hundreds of kilometres. For such waves, the open sea with a depth of a few kilometres is shallow water. Shallow-water waves have rather different properties from the wind-driven deep-water waves of a few metres wavelength commonly seen on the surface of the sea. Let us rapidly consider why this should be so. The dispersion relation for water waves, $\omega^2 = gk\tanh(kD)$,[1] relates wave frequency ω and wave number k, where D is the depth of water and g is the acceleration due to gravity. In the deep-water approximation $D \gg L$, L being the wavelength, so $kD \gg 1$ and $\tanh(kD) \to 1$, and the dispersion relation becomes $\omega^2 = gk$. In the shallow-water limit, on the other hand, $D \ll L$, so $kD \ll 1$ and $\tanh(kD) \to kd$, whence the dispersion relation reduces to $\omega^2 = gk^2D$.[2] The phase velocity c is the speed at which a particular phase of the wave—the wave crest, for example—propagates. In one wave period T the crest advances one wavelength L so the phase velocity is $c = L/T = \omega/k$; in deep water, then, $c = \sqrt{(g/k)}$, whereas in shallow water $c = \sqrt{(gD)}$. Thus, in deep water, the phase velocity

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depends on the wavelength—longer waves travel faster—and deep-water waves are said to be dispersive. In shallow water, in contrast, the phase velocity is independent of the wavelength; it depends only on the depth of the water, and shallow-water waves are non-dispersive. Whereas the phase velocity is the speed of an individual part of a wave, a group of waves, and their associated energy, propagate at the group velocity given by $c_g = \mathrm{d}\omega/\mathrm{d}k$.[1] For deep-water waves the group velocity is then $\sqrt{(g/k)}/2$—that is, half the phase velocity—whereas for shallow-water waves the group velocity is $\sqrt{(gD)}$, coincident with the phase velocity and dependent on the depth. From the foregoing physics we gather that a tsunami crosses the abyssal deeps of an ocean of depth 1–10 km at a speed of about 100–300 m s^{-1}, or about 400–1000 km h^{-1}; these are aeroplane speeds, enormously greater than the velocity of deep-water waves. The form that a tsunami takes far from its source corresponds to a group of peaks and troughs. Tsunami can travel either trough first or peak first, and the first peak is not necessarily the largest, as was demonstrated by the 2004 Indian Ocean tsunami,[3] and this may be confirmed with asymptotic approximations of the wave profiles;[4] we should note that the physics of tsunami is a very active field.[5] Whereas a tsunami in the open ocean has a small amplitude compared with its wavelength and the water depth, as the water becomes shallower nearer to shore, it slows—recall that the group velocity is $\sqrt{(gD)}$—but at the same time as a result of the conservation of energy the peak builds in height. This process can cause a tsunami to appear at the shore as an extreme version of a tide. However, depending on the local conditions, if this wave-steepening process runs away, a tsunami wavefront can break into a step with a foaming front, known as a bore.[1] In either case, it is the energy that tsunami carry with them and must dissipate as they reach shore—enormously greater than the energy of a short-wavelength wind-driven wave of the same height—that has caused much tragedy throughout human history. Tsunami a few metres in height from earthquakes, volcanic eruptions, or submarine landslides inundate a coast and destroy most human structures, whereas tsunami from landslips and meteorite impacts, although much rarer, may have heights when they arrive at shore of tens and even up to hundreds of metres; some have called them megatsunami.[6]

The older English term for tsunami was ‘tidal wave’, used because the appearance of a tsunami is often like an extreme version of a tide, involving both the sea receding, like a low tide, and inundating the land to above the normal level, like a high tide. But tides are caused by the gravity of the Moon and Sun, whereas tsunami, as we have seen, have a completely different origin. So, although the expression ‘tidal wave’ is still very much alive in popular usage to denote an overwhelming phenomenon—‘a tidal wave of opinion’, and so on—in science it has been abandoned. Another term that was common for a time in technical usage was ‘seismic sea wave’, but this was too restrictive; as discussed above, earthquakes are only one of the sources of tsunami. Both of these terms were dropped in favour of the Japanese word *tsunami*, meaning waves (*nami*) breaking upon a harbour (*tsu*) (in Japanese a word is invariant in the singular and plural; in English it is either used thus, as we do here, following the custom of respecting the lexicology of loanwords in English, or else with an English plural ending in -s). There is mention of tsunami in the historical records of all the countries of eastern Asia: Japan, China, Korea and Russia. There are 15 cases reported in the history of China from 47 BC to 1978,[7] and Russia has records from the Sakhalin earthquake of 1737 onwards.[8,9] Korea has some 13 reports on unusually high tides, but only two of them seem to be referring to tsunami.[10] Japan has literature referring to tsunami back to the Hakuho Nankai earthquake of 684, which greatly affected the country of Tosa (now Kochi) on the island of Shikoku:

> 14th day [of the 10th month in the 13th year of the Temmu Emperor; that is, 26 November 684]. At the hour of the boar [10 p.m.] there was a great earthquake. Throughout the country men and women shrieked aloud, knowing not East from West. Mountains fell and rivers gushed forth; the official buildings of the provinces and districts, the barns and houses of the farmers, the pagodas and shrines were destroyed in numbers which surpass all estimate. In consequence many of the people and of domestic animals were killed or injured. The hot springs of Iyo were buried and ceased to flow. In the province of Tosa more than 500 000 shiro of cultivated land were inundated and became sea. Old men said that never before had there been such an earthquake. On this night a rumbling noise like that of drums was heard in the East. Some said that the island of Izu increased on two sides, the north and west, by more than 300 rods, and that a new island was formed; the noise like that of drums was the sound made by the gods in constructing this island. 3rd day [of the eleventh month]. The Governor of the province of Tosa reported that a great tide ['oshio'] rose and the sea water flowed in, causing many of the ships conveying tribute to sink and be lost.[11]

The word used in this report was not *tsunami* but *oshio* (large tide). The first occurrence of the word *tsunami* itself is found in a journal kept by a retainer of the shogun Tokugawa Ieyasu. On receiving the news of the Sanriku earthquake of 2 December 1611 he writes:

> Matsudaira Masamune, Lord of Mutsu, presents the first cod of the season [to Ieyasu]. On this occasion it transpired that Masamune's land by the sea was hit by towering waves and all properties were lost. 5000 died of drowning. People call it a tsunami. According to Honda, chief of Kozuke, Masamune's vassals went to the fishermen to launch the boat and catch the fish as ordered, but were rejected, on account of the strange colour of the tide and the foul weather. … In the end the vassal forced six or seven fishermen to row out for fishing, and was out in the sea for 20 or 30 cho when the sea rose and the mountainous wave struck, stupefying him. His boat was upon the waves and did not sink. When the waves subsided and he resumed his composure, he found the so-called Sengan pine tree on the mountain top where the fishermen's village was and tied the boat to the tree. Later, when the waves receded, the boat was seen to rest high up on the tree top. Still later he and the fishermen climbed down to the villages below and saw that they had been entirely washed away; not a single soul was left.[12]

Who were 'the people' calling it a *tsunami*? Were they fishermen, who might have used the term because its effects were most evident when they arrived back at harbour to find their village had been washed away? It is not clear. East met West even at the birth of the word, as this same tsunami was also recorded by a Spanish expedition led by Sebastián Vizcaíno that had arrived in Japan looking for the legendary Gold and Silver Islands—an El Dorado of the Pacific:

> On Friday [2 December 1611] we arrived at the village of Oquinay [that is, Okirai], which had another inlet of no use. Before arriving, we saw the people, both men and women, running away up the hills, deserting the village. We thought something was strange, since in other places up to now people had come to the shore to see us. Thinking they were fleeing from us, we called after them to stop, but then we saw the reason was that the sea came in to a height of more than a pica [1 pica = 3.89 m], caused by a great earthquake. It carried on for an hour with such power, inundating the village and washing away the houses and rice fields, which floated on the water, wreaking confusion. The sea water ebbed and flowed three times in this interval, and the inhabitants could not save their properties, nor many their lives. … This occurred at five in the afternoon, and during this time we were at sea, where we felt its great flows. The sea waves met and rose, and we thought we were going to sink. Two boats behind us were hit by the waves in the offing, and went down.[13]

As the report of the Hakuho Nankai earthquake suggests, it was widely recognized in Japan that tsunami were associated with earthquakes. Various other terms such as *onami*

(large wave), *shikai namisu* (waves rise in all directions), *takanami* (high wave), *takashio* (high tide) and *kaisho* (roaring and resounding sea) were at times employed in Japanese; just as in English, there was sometimes confusion in Japanese between tsunami and other phenomena producing large waves and flooding. Even the word *tsunami* itself does not escape; tsunami seem to have been confused with storm waves in some old texts, not only figuratively but literally. However, the abundance of tsunami in Japan alongside their clear association with earthquakes probably accounts for the recognition of tsunami as a distinct phenomenon there. As an island country on the boundary of the Eurasian tectonic plate with the Pacific plate, the geographical situation of Japan exposes it to earthquake and volcanic activity with accompanying locally produced tsunami: the earthquake itself is felt and is seen to be followed by a tsunami. In parts of the world where tsunami are less frequent, or originate from sources farther off, their cause is less immediately obvious and they may be mistaken for storm surges. Although Japan lies at one edge of the Pacific, the largest ocean, and so also finds itself affected by tsunami that cross the ocean from more distant sources, this is a rather rarer occurrence than locally produced tsunami.[14]

The word *tsunami* was first brought to the attention of English speakers by two foreigners, both journalists and authors but with very different literary styles. The first was the American travel writer Eliza Ruhamah Scidmore, who repeatedly sojourned in Japan from 1884 onwards, visiting her brother George, who was first a consular clerk in Yokohama and later consul general and a lecturer at what is now Chuo University in Tokyo. Eliza herself was based in Washington and joined the National Geographic Society, where she became its first female director, took an active part in planting the cherry trees along the Potomac River, and wrote several books on Japan and the East.[15] She reported to *National Geographic Magazine* on a very destructive tsunami that struck Sanriku, Japan, on 15 June 1896:

> On the evening of June 15, 1896, the north-east coast of Hondo, the main island of Japan, was struck by a great earthquake wave (tsunami), which was more destructive of life and property than any earthquake convulsion of this century in that empire. The whole coastline of the San-Riku, the three provinces of Rikuren [that is, Rikuzen], Rikuchu, and Rikuoka [that is, Mutsu], from the island of Kinkwazan [that is, Kinkazan], 38° 20′ north, northward for 175 miles, was laid waste by a great wave moving from the east and south, that varied in recorded height from 10 to 50 feet. A few survivors, who saw it advancing in the darkness, report its height as 80 to 100 feet. With a difference of but thirty minutes in time between the southern and northern points, it struck the San-Riku coast and in a trice obliterated towns and villages, killed 26,975 people out of the original population, and grievously wounded the 5,390 survivors.[16]

This same tsunami prompted a rather less scientific, more florid report in *The Atlantic Monthly*:

> From immemorial time the shores of Japan have been swept, at irregular intervals of centuries, by enormous tidal waves,—tidal waves caused by earthquakes or by submarine volcanic action. These awful sudden risings of the sea are called by the Japanese tsunami. … Through the twilight eastward all looked, and saw at the edge of the dusky horizon a long, lean, dim line like the shadowing of a coast where no coast ever was,—a line that thickened as they gazed, that broadened as a coast-line broadens to the eyes of one approaching it, yet incomparably more quickly. For that long darkness was the returning sea, towering like a cliff, and coursing more swiftly than the kite flies. '*Tsunami!*' shrieked the people; and then all shrieks and all sounds and all power to hear sounds were annihilated by a nameless shock heavier than any thunder, as the colossal swell smote the shore with a weight that sent a shudder through the hills.[17]

Its author was Lafcadio Hearn, a journalist and writer born to Irish and Greek parents, who was among the foreigners who went to live in Japan after it reopened its doors to the world; between Vizcaíno's time and the mid 1850s it had been a country closed to the West for two centuries. Hearn was settled in Japan and naturalized as Koizumi Yakumo, married to the daughter of a samurai, and, like Scidmore, dedicated himself to describing the exotic—to a westerner—Japan of the turn of the twentieth century.[18] He used the recent tsunami to introduce the story of a real occurrence related to an earlier tsunami: a village chief who set fire to his rice harvest after the 1854 Nankai earthquake to warn the villagers of the impending inundation.[14] The story, published in book form the following year, was then translated back into Japanese and later included in a textbook for Japanese schoolchildren.[19] It is worth remarking that three British scientists, James Ewing, Thomas Gray and John Milne, were from 1876 working in seismology while living in Japan; they perfected the seismograph and founded the Seismological Society of Japan; Ewing and Milne were to become Fellows of the Royal Society.[20] Clearly, they must have known the word *tsunami*, but we cannot find any mention of it in their writings, in which they used the term *seismic sea wave*. After Scidmore and Hearn, the word *tsunami* begins to crop up in scientific reports in English. *Nature* magazine, for example, contains a number of items from Japan in the first decades of the twentieth century that use the term. The earliest, from 1905, notes under the heading *Seismology in Japan* that 'out of forty-seven destructive earthquakes which originated beneath the Pacific, twenty-three were accompanied by *tsunami* or sea waves'.[21] The use of the term in English was reinforced by a major tsunami that hit Hawaii on 1 April 1946, known as the April Fool's Day tsunami; after this event in 1949 the Pacific Tsunami Warning Center was established in Hawaii. During the second half of the twentieth century, the term became firmly established in the scientific literature in English.

A famous print by the Japanese artist Katsushika Hokusai, *Great wave off Kanagawa*, has often been held to be the depiction of a tsunami. The Hokusai image is one of a beautiful series of views of Mount Fuji from different viewpoints. In this image, the viewpoint is out at sea; we see Fuji in the background, while in the foreground several boats battle through large waves. The print is reproduced in many places, in books, on the Internet; even printed on T-shirts, as an example of a tsunami.[22] However, the text on the image, which states 'behind the wave off Kanagawa', gives us no reason to suppose that Hokusai wished to represent anything other than storm waves. Moreover, as we have discussed, a tsunami out at sea does not have this aspect but is a generally unnoticeable swell with a small amplitude and a very long wavelength. Only rather rarely might a tsunami produce the type of breaking wave depicted by Hokusai. Instead of a tsunami, the print more probably depicts a large storm wave; the wave is so abnormally large compared with typical storm waves in Tokyo Bay, the indicated location of the image, that it must be considered an example of a freak or rogue wave.[23] So are there in fact depictions of tsunami in Japanese art? There are drawings by less well known artists (for example figure 1), but nothing to compare with the power of Hokusai's image. The popular Japanese art movement of that time, ukiyo-e, depicted a 'floating world' (ukiyo) in which to forget about the real world, thus restricted to painting ornamental themes such as courtesans, actors, erotica and, occasionally, romantic landscapes; there was nothing to suggest the misery of this world. There were hundreds of city fires in the Edo period (1603–1868), but these were hardly painted. Another popular artist, Hiroshige, depicted the altered shape of the volcanic cone of Mount Fuji after its 1707 eruption, which is possibly the only acknowledgement of geological processes in Japanese art of the period. There is nothing depicting directly traces of an earthquake. There was, however, a popular craze for 'namazu-e' pictures showing a giant

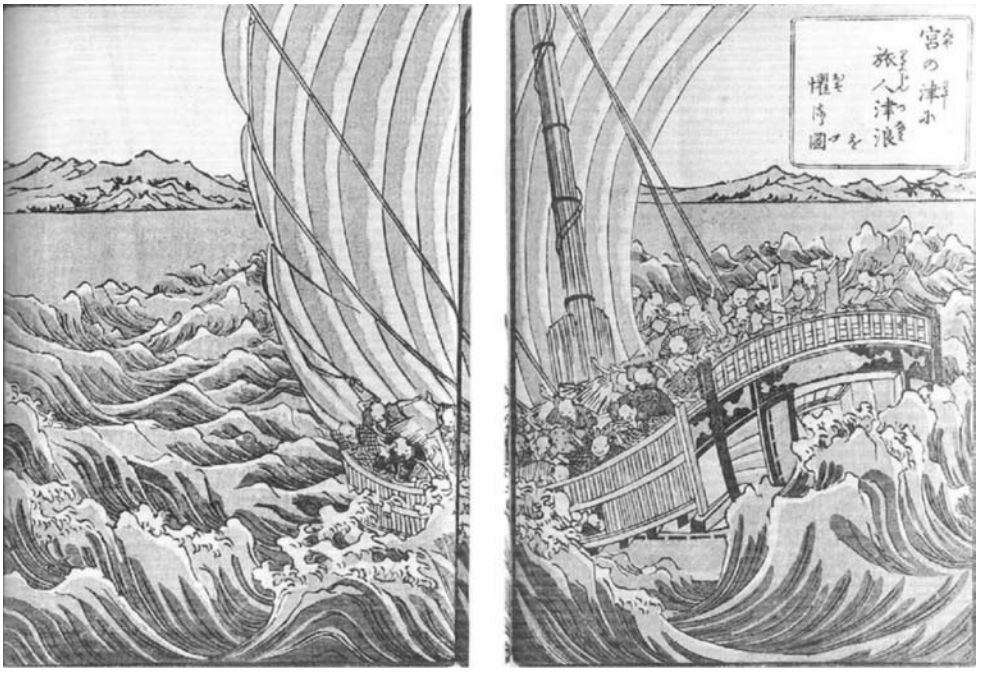

Figure 1. Book illustration to *Ansei Kenmonroku* recording the tsunami that accompanied the 1854 Ansei Nankai earthquake, which gave rise to Hearn's story. The caption reads: 'Travellers fear the tsunami while crossing at Miya.' The book describes how the weather was fair with no wind, and the land shook before the tsunami occurred.[57] The Ansei Nankei earthquake had been preceded 32 hours earlier by the Ansei Tokai earthquake, the tsunami from which was the first to be recorded by a tide gauge installed in San Diego and was presented to the American Association for the Advancement of Science as the successful detection of a submarine earthquake. Commodore Perry of the US Navy, who was in Japan negotiating the treaty to reopen the country, sent reports back to the USA that the earthquake had in fact occurred 5000 miles away, in Japan.[58] These earthquakes and tsunami were followed a year later by the Ansei Edo earthquake of 1855, which finally pushed Japan to open the then-closed country and produced the craze for catfish prints (figure 2).

catfish (namazu) attempting through its movements to cause earthquakes (figure 2)![24] In earlier eras, the subject of art was even more limited to landscapes and portraits, or else Buddhist paintings of heaven and hell, and later periods produced Western-influenced art with still lives and abstract paintings. Traditionally death and the other world were not treated in the Japanese native religion of Shintoism, and secular Japanese painters likewise rarely depicted them. The Buddhist teaching of *teinen* (resignation) led many people in Japan to accept the aftermath of earthquakes without enquiring into their causes. Thus, phenomena accompanying earthquakes such as tsunami were empirically known but were explained non-scientifically. The theory still current when Japan reopened to the West in the mid 1850s was the Chinese idea of earthquakes based on the principle of Yin and Yang, in which the Earth floating on water is shaken in accordance with activities of the other two elements, fire and wind.[24] As for Japanese literary works, the same tendency not to treat disasters prevails. When they are depicted, it is to teach the readers *teinen*, as in Kamono Chomei's essay *Hojoki* (1212), in which he makes a reference to the Kyoto earthquake of 1185:

> In about the same year [the second year of Genryaku], there was a great earthquake. It was totally out of the usual state of things. The mountain crumbled and buried the river, the sea leaned and soaked the land. The ground gaped open and the water gushed forth, the rock cleaved and fell onto the valley, the rowing boat at the shore drifted among the waves, the

Figure 2. Namazu-e: a giant catfish is attacked by people in Japan for causing earthquakes (1855).

> galloping horse knew not where to land its feet. … Thus the living is tough, and one's life and dwelling are ephemeral and vain. … The gist of Buddha's teaching is that one should not linger on any particular thing.[25]

If we look now to Europe, we find that Europeans had written of tsunami before the Japanese, only subsequently to forget about them for centuries, so that by the time that westerners such as Vizcaíno encountered tsunami while in Japan, the phenomenon was virtually unknown to people in Europe. Yet tsunami had had an important role in European history. The first European civilization, the flourishing Minoan culture on Crete, was brought to its knees by the explosive eruption in *ca.* 1600 BC of the nearby island of Thera and the associated tsunami.[26–29] The legend of Atlantis, which, as recounted in Plato's *Timaeus* (*ca.* 360 BC), sank under the sea, might possibly be a distant and distorted recollection of this event:

> This great island [Atlantis] lay over against the Pillars of Heracles, in extent greater than Libya and Asia put together, and was the passage to other islands and to a great ocean of which the Mediterranean sea was only the harbour; and within the Pillars the empire of Atlantis reached in Europe to Tyrrhenia and in Libya to Egypt. This mighty power was arrayed against Egypt and Hellas and all the countries bordering on the Mediterranean. … A little while afterwards [Atlantis lost the war] there were great earthquakes and floods … and the great island of Atlantis … disappeared in the sea. This is the explanation of the shallows which are found in that part of the Atlantic ocean.[30]

Another possible reference to this disaster is in Hesiod's *Theogony* (*ca.* 700 BC) depicting the war between the Olympians and the Titans, especially Zeus' victory over Typhoeus:

> And truly a thing past help would have happened on that day, and he [Typhoeus] would have come to reign over mortals and immortals, had not the father of men and gods been quick to perceive it. But he [Zeus] thundered hard and mightily: and the earth around

> resounded terribly and the wide heaven above, and the sea and Ocean's streams and the nether parts of the earth. … And through the two of them heat took hold on the dark-blue sea, through the thunder and lightning, and through the fire from the monster, and the scorching winds and blazing thunderbolt. The whole earth seethed, and sky and sea: and the long waves raged along the beaches round and about, at the rush of the deathless gods: and there arose an endless shaking. … But when Zeus had conquered … Typhoeus … the huge earth groaned. And flame shot forth from the thunder-stricken lord in the dim rugged glens of the mount, when he was smitten. A great part of huge earth was scorched by the terrible vapour and melted as tin melts when heated by men's art in channelled crucibles; or as iron, which is hardest of all things, is softened by glowing fire in mountain glens and melts in the divine earth through the strength of Hephaestus. Even so, then, the earth melted in the glow of the blazing fire. And in the bitterness of his anger Zeus cast him into wide Tartarus.[31]

In Homer's *Odyssey* (800–600 BC), the depiction of 'shining Charybdis' also seems to recall a volcanic tsunami:

> On one side was Skylla, and on the other side was shining Charybdis, who made her terrible ebb and flow of the sea's water. When she vomited it up, like a caldron over a strong fire, the whole sea would boil up in turbulence, and the foam flying spattered the pinnacles of the rocks in either direction; but when in turn again she sucked down the sea's salt water, the turbulence showed all the inner sea, and the rock around it groaned terribly, and the ground showed at the sea's bottom, black with sand.[32]

The Græco-Roman world experienced various important tsunami,[33,34] and they seem to have been a phenomenon known to educated people. A tsunami in 479 BC at Potidaia, Chalcidike, in northern Greece is probably the earliest for which there is coeval documentation.[33] Herodotus writes in his *Histories* (440 BC):

> When Artabazus had besieged Potidaea for three months, there was a great ebb-tide in the sea which lasted for a long while, and when the foreigners saw that the sea was turned to a marsh, they prepared to pass over it into Pallene. When they had made their way over two-fifths of it, however, and three yet remained to cross before they could be in Pallene, there came a great flood-tide, higher, as the people of the place say, than any one of the many that had been before.[35]

In the first century BC Virgil referred to tsunami in verse. In *Georgics*[36] (29 BC) he writes of the 'quaking of earth' and the 'heave' of deep seas, and in the *Aeneid* (29–19 BC) of a 'boiling deep', suggestive of undersea volcanic activities, amid the violent northern wind of Boreas:

> Thus while the pious prince his fate bewails,
> Fierce Boreas drove against his flying sails,
> And rent the sheets; the raging billows rise,
> And mount the tossing vessels to the skies:
> Nor can the shiv'ring oars sustain the blow;
> The galley gives her side, and turns her prow;
> While those astern, descending down the steep,
> Thro' gaping waves behold the boiling deep.[37]

Ovid, in *Metamorphoses* (*ca.* AD 2–8), depicts a devastating earthquake tsunami as Neptune's anger:

> And Neptune with his trident smote the Earth, which trembling with unwonted throes heaved up the sources of her waters bare; and through her open plains the rapid rivers rushed resistless, onward bearing the waving grain, the budding groves, the houses, sheep and men,—and holy temples, and their sacred urns. The mansions that remained, resisting

> vast and total ruin, deepening waves concealed and whelmed their tottering turrets in the flood and whirling gulf. And now one vast expanse, the land and sea were mingled in the waste of endless waves—a sea without a shore.[38]

Pliny the Elder, who died observing the eruption of Vesuvius in AD 79,[39] wrote in his *Natural History* (*ca*. AD 77) of what may well be tsunami:[40] '[the sea] has seized on 30,000 paces, which were suddenly torn off, with many persons on them', and the first scientific observation of a tsunami comes to us from his nephew Pliny the Younger, who described the tsunami following the eruption in AD 79:

> The sea seemed to roll back upon itself, and to be driven from its banks by the convulsive motion of the earth; it is certain at least the shore was considerably enlarged, and several sea animals were left upon it.[41]

Beyond the classical period, there seems to be no mention of tsunami in European literature before the eighteenth century. Of course, tsunami continued to occur, and they are noted in historical records,[34,42,43] but nascent scientific thinking had yet to comprehend their causes; they were experienced by people but were not observed with a scientific mind. In stormy northern Europe, moreover, it was easy to confuse a tsunami with an Atlantic storm surge. For example, on 20 January 1607 flooding in the Bristol Channel and Severn Estuary in England[44] took 2000 lives and caused huge damage to houses along the coast, and a 60-ton ship was washed inland in Appledore. A parish clerk, Robert Langdon of Barnstaple, wrote of the 'storm' and 'tempest' coming from the river. This has been seen as a possible tsunami, because for a storm to push a ship like this inland, the wind needs to reach hurricane force. Such a hurricane would have done much damage across England, but reports mention only the rise of water as the cause of damage to houses and there is no record of rain, although a high spring tide and strong wind are recorded in the local chronicles.[45] It is possible that Shakespeare might have had these events in mind when shortly afterwards he wrote *The Tempest* (*ca*. 1611).

A firmer candidate for the earliest reference to a tsunami in English literature is Daniel Defoe's *Robinson Crusoe*, published in 1719. The following passage has an earthquake followed by a storm in which the sea floods the shore. Crusoe relates in his journal:

> it was a terrible earthquake, for the ground I stood on shook three times at about eight minutes' distance, with three such shocks as would have overturned the strongest building that could be supposed to have stood on the earth, and a great piece of the top of a rock, which stood about half a mile from me next the sea, fell down with such a terrible noise, as I never heard in all my life. I perceived also, the very sea was put into violent motion by it; and I believe the shocks were stronger under the water than on the island. … After the third shock was over, and I felt no more for some time, I began to take courage. … While I sat thus, I found the air overcast, and grow cloudy, as if it would rain; soon after that the wind arose by little and little, so that, in less than half an hour, it blew a most dreadful hurricane: the sea was all on a sudden covered over with foam and froth, the shore was covered with the breach of the water, the trees were torn up by the roots, and a terrible storm it was; and this held about three hours, and then began to abate, and in two hours more it was stark calm, and began to rain very hard. All this while I sat upon the ground very much terrified and dejected, when on a sudden it came into my thoughts, that these winds and rain being the consequences of the earthquake, the earthquake itself was spent and over, and I might venture into my cave again.[46]

This description of a great storm as a consequence of an earthquake reads like a confused description of a tsunami. Alexander Selkirk, the sailor on whom Crusoe was modelled, was

marooned on the island of Más a Tierra off the Chilean coast from 1704 to 1707. An earthquake with epicentre in Peru affected the area in 1705 and caused a tsunami with 8 m of runup on the South American mainland.[47] This earthquake and tsunami would almost certainly have been noted by Selkirk, who might have passed a garbled account of the events to Defoe.

Enlightenment thinking woke up to the existence of tsunami with that caused by the Lisbon earthquake of 1 November 1755 (figure 3).[48] Voltaire's *Candide* of 1759 includes one of the earliest literary descriptions of this tsunami, which he heard first hand from a Portuguese witness. The earthquake occurs soon after a 'tempest' wrecks the ship that Candide and his mentor Pangloss were aboard, off the port of Lisbon:

> While he [Pangloss] reasoned, the sky darkened, the winds blew from the four quarters, and the ship was assailed by a most terrible tempest within sight of the port of Lisbon. … Scarcely had they [Candide and Pangloss] reached the city, lamenting the death of their benefactor, when they felt the earth tremble under their feet. The sea swelled and foamed in the harbour, and beat to pieces the vessels riding at anchor. Whirlwinds of fire and ashes covered the streets and public places; houses fell, roofs were flung upon the pavements, and the pavements were scattered. Thirty thousand inhabitants of all ages and sexes were crushed under the ruins. … 'What can be the sufficient reason of this phenomenon?' … 'This concussion of the earth is no new thing.' … 'The city of Lima, in America, experienced the same convulsions last year; the same cause, the same effects; there is certainly a train of sulphur under ground from Lima to Lisbon.'[49]

The Royal Society did not yet exist at the time of the Bristol Channel and Severn Estuary floods of 1607, but now in 1755 it was well equipped to act as a scientific clearing-house. The first reports that arrived in London were printed in a couple of collections of letters in *Philosophical Transactions* soon after the earthquake. The first collection[50] contains accounts from around the British Isles and beyond on unusual changes in water levels at the coast (the tsunami itself) and in lakes, ponds, and so on (seiches) on the day of the earthquake; it seems that people in the UK, and in northern Europe in general, did not feel the ground move (only one report mentions an earth tremor) but noted peculiar motions of bodies of water. Henry Mills gave the following account from London:

> As I am informed, that an account of what I observed in the Thames, Nov. 1 would not be unacceptable to you, the fact was briefly this. Being in one of my barges, unloading some timber, between eleven and twelve a clock, both myself and servants were surprised by a sudden heaving up of the barge from a swell of the water, not unlike what happens when a ship is launched from any of the builders yards in the neighbourhood. But the state of the tide did not then suit with the launching of ships, and I am since certain, that no ship was launched at that time. After the barge had alternately rose and sunk three or four times with a motion gradually decreasing, the water became quiet again.

And William Borlase recounted from Mountbay, near Penzance, Cornwall:

> A little after two o'clock in the afternoon, the weather fair and calm, barometer at the highest, thermometer at 54, the little wind there was being at north-east, about half an hour after ebb, the sea was observed at the Mount-pier to advance suddenly from the eastward. It continued to swell and rise for the space of ten minutes; it then began to retire, running to the west, and south-west, with a rapidity equal to that of a mill-stream descending to an undershot-wheel; it ran so for about ten minutes, till the water was six feet lower than when it began to retire. The sea then began to return, and in ten minutes it was at the before-mentioned extraordinary height; in ten minutes more it was sunk as before, and so it continued alternately to rise and fall between five and fix feet, in the same space of time. The first and second fluxes and refluxes were not so violent at the Mount-pier as the third

Figure 3. The Lisbon tsunami of 1755 as seen from a contemporary print.

> and fourth, when the sea was rapid beyond expression, and the alterations continued in their full fury for two hours: they then grew fainter gradually, and the whole commotion ceased about low water, five hours and an half after it began.

The other collection of accounts[51] concentrates on the earthquake itself, but also includes observations of the tsunami; J. Latham reported from Lisbon:

> From the high grounds we could see the sea at about a mile's distance come rushing in like a torrent, tho' against wind and tide. A fine new stone quay in Lisbon, where the merchants land their goods, where at that time about three thousand people were got out for safety, was turned bottom upwards, and every one lost.

Benjamin Berwick wrote from Cadiz:

> An hour after [the earthquake], looking out to sea, saw a wave coming at eight miles off, which was at least sixty feet higher than common. Every body began to tremble; the centinels left their posts, and well they did. It came against the west part of the town, which is very rocky: the rocks abated a great deal of its force. At last it came upon the walls, and beat in the breast-work, and carried pieces of eight or ten tun weight, forty and fifty yards from the wall, and carried away the sand and walls, but left the houses standing, so that only two or three persons were drown'd. Every one now thought the town would be swallowed up; for although this was run off, yet with glasses we saw more coming. The people were in the utmost consternation, and ran some one way, some another. The governor ordered the gates to be shut, that people might not go out of town, as the land was lower than the town; by which means he saved the lives of thousands, who wanted to fly, they did not know where. When the wave was gone, some parts, that are deep at low water, were quite dry, for the water retired with the same violence it came with. These waves came in this manner four or

> five times, but with less force each time; and about one the sea grew more calm, but was still in a boiling motion.

Also present in Cadiz was Antonio de Ulloa. One of the discoverers of platinum,[52] de Ulloa also made contributions to astronomy during an expedition to South America. On the return voyage from this expedition in 1745, the ship in which he was travelling was detained by the British, and he was taken captive as a prisoner of war; he held the rank of lieutenant in the Spanish navy, and Britain and Spain were at war. On arriving in Britain, however, the Royal Society interested itself in him; he was elected FRS, and the authorities permitted him to return to Spain.[53] He set up an astronomical observatory in Cadiz in 1753. He reported:

> we had here an earthquake, … It happened in very fine weather, at three minutes after nine in the morning … The inhabitants had scarce begun to recover from their first terror, when they saw themselves plunged into new alarms. At ten minutes after eleven they saw rolling towards the city a tide of the sea, which passed over the parapet of sixty feet above the ordinary level of the water. At thirty minutes after eleven came a second tide; and these two were followed by four others of the same kind, at eleven o'clock fifty minutes; twelve o'clock thirty minutes; one o'clock ten minutes; and one o'clock fifty minutes. The tides continued, with some intervals, till the evening, but lessening. They have ruin'd 100 toises of the ramparts part of which of three toises length, and of their intire thickness, were carried by the torrent above fifty paces.

And Thomas Heberden wrote from Madeira:

> About an hour and half after the shock had ceased, the sea, which was quite calm (it being a fine day, and no wind stirring) was observed to retire suddenly some paces, and, arising with a great swell, without the least noise, as suddenly advancing, overflowed the shore, and entered into the city. It arose full fifteen feet perpendicular above high water mark, although the tide, which ebbs and flows here seven feet, was then at half ebb. The water immediately receded again, and, after having fluctuated four or five times between high water and low water mark, the undulations continually decreasing (not unlike the vibrations of a pendulum) it subsided, and the sea remained calm as before this phenomenon had appeared.

In the following months, further observations of both earthquakes and tsunami were published in *Philosophical Transactions*. As well as more observations of the 1 November 1755 events from further afield—there were reports of the tsunami from Antigua—in February 1756 there was another tsunami noted in the UK produced by an earthquake located in the North Sea. After these observations, in a *Philosophical Transactions* article of 1760, John Michell[54] synthesized the data into a theory of how earthquakes, and the tsunami that follow them, might be produced by 'subterraneous fires'. Michell and others of his time saw that seismic and volcanic activity were both manifestations of geothermal energy (hence Voltaire's 'train of sulphur' in *Candide*). He gave a schema of the genesis of a volcanic tsunami:

> as soon as some part of the roof falls in, the cold water contained in the fissures of it, mixing with the steam, will immediately produce a vacuum, in the same manner as the water injected into the cylinder of a steam engine, and the earth subsiding, and leaving a hollow place above, the waters will flow every way towards it, and cause a retreat of the sea on all the shores round about: then presently, the waters being again converted by the contact of the fire into vapour, together with all the additional quantity, which has now an open communication with it, the earth will be raised, and the waters over it will be made to flow every way, and produce a great wave immediately succeeding the previous retreat.

Some of the tsunami observations were very quantitative, whereas others omitted details important to a scientist, and there were mutual contradictions on timing (notable, for example, in the two reports from Cadiz); undoubtedly it was felt that it was important to publish all the available data of whatever quality. These imprecisions must nevertheless have frustrated Michell; he constructed a table of the tsunami travel time from observations of the interval between the earthquake and the tsunami and notes in the accompanying text:

> The times themselves also are often so carelessly observed, as well as vaguely related, that they are many of them subject to considerable error.

Despite these anomalies, he was able to conclude that tsunami travel at different speeds through different depths of water:

> the [tsunami arrival] time will be found to be proportionably shorter or longer, as the water through which the wave passed was deeper or shallower.

Michell's paper, which is now seen as one of the foundation stones of seismology, led to his election as a Fellow of the Royal Society;[55] apart from this work, he is best known for his 1783 prediction of the existence of black holes.[56] In publishing the accounts that Michell used to construct his theory, followed by his paper itself, the Royal Society undoubtedly had an important role in tsunami science.

From this time on, through the work of Michell and others, the Western scientific mind became receptive to reports of tsunami and began to associate them with geological causes. It is interesting from our comfortable position of hindsight to revisit the earlier views. The storm after the earthquake in *Robinson Crusoe* strongly resembles the accounts given by Langdon and others of the 1607 Bristol Channel floods; Voltaire also refers to a tempest in *Candide*, where it is set not after, but before, the earthquake; and even some of the reports of the Lisbon earthquake in *Philosophical Transactions* were confusing to Michell as he tried to build a coherent picture of the phenomenon. Human psychology is such that memories can become distorted, especially after stressful events such as earthquakes and tsunami, and this—to us contrariwise—telling of the events is in accordance with the tradition that a great happening should be preceded by an omen. Equally interesting is the fact that tsunami were known to the Græco-Roman world but had been forgotten about in intellectual terms in Europe when the huge Lisbon earthquake and tsunami forced people to pay attention to the phenomenon. A not dissimilar process of political reawakening to the importance of tsunami occurred recently after the 2004 Indian Ocean tsunami. We conclude with the hope that this historical review may have some utility for those working on tsunami; as Dionysius of Halicarnassus quotes of Thucydides, 'history is philosophy teaching by examples'.

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