



Editorial

Meteorological tsunamis: Atmospherically induced destructive ocean waves in the tsunami frequency band

Vela Luka is a small town hidden in a bay on Korčula Island in the Adriatic Sea. In the early morning of 21 June 1978, the sea suddenly began to rise in the town, overtopping the piers and surging into the streets. The rumble of the incoming water awakened inhabitants who witnessed a series of destructive ocean waves, flooding much of the city and causing devastation and widespread damage. Tsunami-like waves with trough-to-crest heights of up to 6 m and periods of about 18 min appeared without any warning, resulting in the greatest natural disaster in the modern history of Vela Luka. Subsequent scientific investigations indicated that the waves were not related to a seismic event or submarine landslide but to atmospheric processes, identifying this as a meteorological tsunami event (Hodžić, 1979/1980; Orlić, 1980).

Tsunamis are the main cause of destructive seiches observed in the World Ocean. However, long waves generated by atmospheric forcing (atmospheric gravity waves, pressure jumps, frontal passages, and squalls) can also be responsible for significant, even devastating, long waves which have the same temporal and spatial scales as typical tsunami waves. These waves are similar to ordinary tsunami waves and can affect coasts in a similar way, although their catastrophic effects are normally observed only in a limited number of specific bays and inlets. Nomitsu (1935), Defant (1961) and Rabinovich and Monserrat (1996, 1998) suggested the term 'meteorological tsunamis' ('meteotsunamis') for such waves.

At certain places in the World Ocean, hazardous atmospherically-induced waves occur regularly and have specific local names: 'rissaga' in the Balearic Islands, 'marubbio' ('marrobio') in Sicily, 'šćiga' on the Croatian coast of the East Adriatic, 'milghuba' in Malta, 'abiki' and 'yota' in Japan, 'Seebär' in the Baltic Sea, 'death waves' in Western Ireland, and 'inchas' and 'lavadiads' in the Azores and Madeira islands. These waves have also been documented for the Yellow and Aegean seas, the Great Lakes, the northwestern Atlantic, for coastal areas of Argentina and New Zealand, and in some specific ports such as Port Rotterdam (cf. Honda et al., 1908; Defant, 1961; Hibiya and Kajiura, 1982; Rabinovich and Monserrat, 1996, 1998; de Jong and Battjes, 2004; Vilibić et al., 2004, 2008; Monserrat et al., 2006; Rabinovich, 2009). Because of the pronounced similarity between 'meteotsunamis' and seismically-generated tsunamis (cf. Monserrat et al., 2006; Thomson et al., 2007), it is often difficult to recognize one form of wave from another. Catalogues of tsunamis normally contain references to 'tsunami-like' events of 'unknown origin' that could, in fact, be atmospherically generated ocean waves.

The best known location where meteorological tsunamis occur on a regular basis is Ciutadella Harbour on the western coast of Menorca Island (Balearic Islands, Spain). The harbour is located at the head of an inlet which is about 1 km long, 100 m wide and 5 m deep. The fundamental period of the inlet (the Helmholtz

mode) is approximately 10.5 min. Due to its particular geometry, Ciutadella Inlet has a high Q-factor which results in significant resonant amplification of long waves arriving from the open sea. Seiche oscillations with durations ranging from a few hours to several days and wave heights exceeding 0.5 m occur in Ciutadella every summer. However, rissaga events (large-amplitude seiches) having wave heights of more than 3–4 m, and which have dramatic consequences for the harbour, usually take place once every 5–6 years. During the rissaga of 21 June 1984, about 300 boats were destroyed or severely damaged (Rabinovich and Monserrat, 1996). More recently, on 15 June 2006, Ciutadella Harbour was affected by the most dramatic rissaga event of the last 20 years, when nearly 6-m waves occurred in the harbour and led to an economic loss totalling several tens of millions euros (Monserrat et al., 2006; Vilibić et al., 2008).

Extreme seiche oscillations (meteotsunamis) in Ciutadella Harbour, and at other ports and harbours of the Balearic Islands and Catalan coast of the Iberian Peninsula, are known locally as 'rissaga', a Catalan word that means 'drying', similar to the Spanish word 'resaca'. Because these are probably the best known examples of meteorological tsunamis, the term 'rissaga' also began to be used for extreme atmospherically induced seiches in other regions of the ocean (cf. Goring, 2005).

In the past, little attention has been paid to tsunamis of meteorological origin in comparison to seismically-, volcanically-, or landslide-generated tsunamis. The situation began to change drastically after the devastating megathrust 2004 Sumatra tsunami that killed roughly 228 thousand people (cf. Bernard et al., 2006; Bernard and Robinson, 2009). Firstly, this extreme catastrophic event attracted high public and scientific interest toward tsunamis and other marine natural hazards in general. Secondly, this event initiated a major upgrade of existing tide gauge networks around the globe. The new digital instruments were designed to continuously measure sea level variations with high precision and to store the sea level records once every 1–2 min. The newly upgraded coastal tide gauges enabled scientists to measure relatively high-frequency local seiches in regions previously inaccessible to such investigations. Moreover, at certain sites, the sea level measurements were accompanied by simultaneous precise observations of atmospheric pressure fluctuations. As a result, high-quality records of meteorological tsunamis now exist for many areas of the World Ocean. Also stimulating interest in this problem are the several recent destructive events which occurred in the vicinity of the Balearic Islands (Monserrat et al., 2006; Vilibić et al., 2008) and in the East Adriatic (Vilibić et al., 2004; Belušić et al., 2007; Šepić et al., 2009).

Modern data on meteotsunamis, together with new computing facilities and numerical procedures, greatly accelerated interna-

tional research on this phenomenon. On 19–21 June 2008, on the 30th anniversary of the Great Flood in Vela Luka (Croatia), the *First International Symposium on Meteotsunamis: "30th Anniversary of the Great Flood of Vela Luka (21 June 1978)"* was organised in Vela Luka. The symposium attracted scientists from Spain, Italy, Russia, Malta, and New Zealand, as well as many atmospheric and ocean scientists, specialists, managers and authorities from Croatia. Various aspects of meteorological tsunamis were discussed, including their atmospheric source and generation mechanism, risk assessment and mitigation, and the establishment of an effective warning system in the Mediterranean to forecast meteotsunamis. The symposium was organised jointly by local authorities and research institutions, establishing a relationship that is a prerequisite for any effective action in mitigating the impacts during hazard situations.

The suggestion to prepare a special collection of papers on meteotsunamis was presented at the Symposium and, a year and half later, came to fruition as this topical issue of the journal of *Physics and Chemistry of the Earth*. The *raison d'être* of this issue was to assemble papers not only from the participants of the symposium but also from other scientists around the world who are interested in the problem, and to cover various aspects of meteorological tsunamis, beginning with the extraction of satellite images of meteorological features favourable for meteotsunami generation, through the documentation of meteotsunamis at different ocean basins of the World Ocean, to the creation and testing of the meteotsunami detection algorithms that may be used in future warning systems. Altogether, 12 papers have been submitted to this issue with the authors representing 12 countries: Argentina, Australia, Brazil, Canada, Croatia, France, Italy, Malta, New Zealand, Russia, Spain and the United Kingdom.

The Great Adriatic flood of 21 June 1978 has been documented by Vučetić et al. in a paper that contains detailed eyewitness descriptions of the event, its outreach along both the eastern (Croatian) and western (Italian) coasts of the Adriatic Sea, and the aftermath and recovery activities in Vela Luka (Korčula Island) where a maximum wave height of 6 m was reported. All available records have been collected and analysed to detect the source and the generating mechanism of the observed extreme tsunami-like seiches. An eastward travelling atmospheric disturbance was detected and assumed to be responsible for the flood event.

An overview paper on Adriatic meteotsunamis is presented by Vilibić and Šepić who assessed meteotsunami events documented in the Adriatic Sea over the last several decades using available eyewitness reports, documented literature, and atmospheric sounding and meteorological reanalysis data available on the web. The paper encompasses all aspects of Adriatic meteotsunamis, from characterization of the synoptic conditions observed during the events, through the ground-based meteorological observations that captured the travelling atmospheric disturbance, to the generation of long ocean waves through a resonant mechanism, and ending with the coastal inundation and amplification of the ocean waves through harbour resonance.

Belušić and Strelec Mahović have analysed the four strongest meteorological tsunamis over the past 30 years in the Adriatic Sea and assumed that the convective systems that were present during all events were responsible for the air pressure disturbances, which subsequently caused formation of the meteorological tsunamis. Because convective cells can be recognized in satellite images and their movement followed using the nowcasting tools based on satellite data, the approach can be used for short-term prediction of meteotsunamis in the Adriatic.

The appearance of concurrent, or subsequent, meteotsunamis in the vicinity of the Balearic Islands and the Adriatic Sea is examined by Šepić, Vilibić and Monserrat. Waves from such events are a consequence of either the simultaneous presence of a favourable syn-

optic pattern above the two areas or from a pattern propagation from one area to another. Upper level instabilities are recognized as the most important synoptic feature for the occurrence of meteotsunamis. These instabilities help trap the atmospheric energy at lower levels and generate atmospheric gravity waves which then lead to the generation of meteotsunamis.

Marcos et al. examine sea level records for four coastal sites on Mallorca and Menorca islands (Balearic Islands, Spain), showing that the forcing characteristics reconstructed for different events are significantly different, but similar for the same event, even for sites located far away from each other. Pronounced similarities were found for two specific sites, Ciutadella (Menorca Island) and Cala Ratjada (Mallorca Island). The findings can be used to create an efficient meteotsunami warning system for the most vulnerable sites, such as Ciutadella Harbour, based on sea level measurements along the Mallorca coast. This, in turn, allows for the determination of potentially destructive ocean waves approximately 40 min before they reach the Menorca coast.

A comprehensive analysis of high-frequency sea level measurements for the Maltese Islands has been undertaken by Drago, focusing on extreme seiche oscillations (locally known as '*milghuba*') observed and extracted from time series collected from 1993 to 1996. These seiches occur in numerous embayments on the northern coastline of the islands and are accompanied by strong alternating currents. Although important for the mixing and exchange of water between the embayments and the adjoining open sea, the currents can be a nuisance to navigation, especially at the harbour entrances.

The first in-depth examination of meteorological tsunamis recorded by tide gauges located at offshore, as well as sheltered, sites along the coasts of British Columbia (Canada) and Washington State (USA) has been provided by Thomson et al. The event of 9 December 2005 was sufficiently strong to trigger an automatic tsunami alarm, while other events generated oscillations in several ports that were potentially strong enough to cause damage to marine craft and harbour infrastructure. Analysis of coincident 1-min sea level data and high-frequency atmospheric pressure data confirms that the events originated with atmospheric pressure jumps and trains of atmospheric gravity waves with amplitudes of 1.5–3 hPa. The pronounced events of 13 July 2007 and 26 February 2008 are examined in detail. Findings reveal that the first atmospheric pressure event had a propagation speed of 24.7 m/s and an azimuth of 352°; the second event had a speed of 30.6 m/s and an azimuth of 60°. These speeds and directions are in close agreement with high-altitude geostrophic winds (the jet stream).

Rogerio Candella examined a four-year, high-resolution (1-min) tide gauge record for Arraial do Cabo, RJ (Brazil) to identify intense high-frequency sea level oscillations and to relate these oscillations to possible forcing mechanisms. The dominant period of the oscillations is close to the fundamental (Helmholtz) mode of about 20 min for the bay. Although the waves had an average height of only 20 cm, some waves exceeded 30 cm and, in an extreme event associated with an atmospheric pressure jump of 10 hPa in 2 h, reached a height of 60 cm, which is comparable to the highest low-frequency variation (periods greater than 36 h) measured in the region between 1999 and 2008.

Dragani et al. consider four energetic seiche events recorded on the coast of Argentina in 1982. Focus is mainly on oscillations observed at Quequén. Results show that large-amplitude sea level oscillations occur at this station first and then move north to Mar del Plata, Pinamar, and Mar de Ajó. Maximum amplitudes detected for each event at these different locations are very similar. Energetic events at Quequén have spectral peaks concentrated between 0.8 and 4.0 cph (15–75 min) and, based on wavelet analysis, are highly intermittent. Findings support the assumption that intense atmospherically-induced sea level oscillations are formed along

the broad Patagonian continental shelf, enter the port of Quequén through its narrow mouth, and then propagate northward towards other stations.

Derek Goring has analysed high-frequency sea level oscillations on the eastern coast of New Zealand. From time to time, significant long waves up to 1 m high and with periods of a few minutes occur on this coast. These waves create a threat to navigation because they cause set-down in vessels navigating to berth, thus reducing their under-keel clearance. The events are strongly correlated with low-pressure systems that originate in the tropics and propagate southwards 1000 km or more to the east coast of New Zealand. The speed of propagation of the weather systems is generally of the order of 20 km/h, which is well below the long wave speed of 800 km/h, but is close to the group velocity of swell waves in deep water which are assumed to be the main source of the observed waves.

Haslett et al. examine numerous historical reports on high long waves recorded on the coast of the United Kingdom (UK). A recent analysis has suggested that these waves have an atmospheric origin and may be considered as meteorological tsunamis. They are apparently generated by various source mechanisms, such as seicheing in enclosed basins related to storm activity, the arrival of large far-travelled waves generated in the open ocean, and by the local generation of large waves near the coast by thunderstorms and squalls. Fatalities have occurred during meteotsunami events in the UK, including people on beaches killed by meteotsunamis arriving unexpectedly at the coast during summer months. Of the nine major meteotsunami events that have occurred in the period 1892–1966, up to five resulted in fatalities. The risk related to such events is discussed and the authors recommend that some measures be taken to educate beachgoers to the meteotsunami hazard associated with offshore thunderstorms.

Finally, Šepić, Denis and Vilibić provide an algorithm which was developed and tested to detect meteotsunami events in the Mediterranean. The algorithm is based on real-time measurements of air pressure at a number of high-resolution microbarographs. Two different methods are proposed to estimate air pressure disturbance speed and direction. Both methods are generally able to identify potentially dangerous air pressure disturbances and can be used in any future meteotsunami warning system in the Mediterranean.

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