The Mediterranean and Black Sea meteotsunamis: An overview

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Abstract

This paper presents the first comprehensive review of the Mediterranean and Black Sea meteorological tsunamis or meteotsunamis (atmospherically induced destructive long ocean waves in the tsunami frequency band) based on the available literature, tools and services. The Mediterranean and Black Seas are micro-tidal basins; therefore, rapid sea level changes in the tsunami frequency band may strongly affect coastal regions and infrastructures and endanger human lives. The review also includes a succinct bibliography of Mediterranean and Black Sea meteotsunami papers and evaluates their structure in respect to geographical extent, the type of tools used (observations versus modelling), and source processes in the atmosphere versus ocean manifestations. This review continues with a presentation of major meteotsunami events and a discussion about their sources, the resonant transfer of energy towards the sea, their propagation towards shore and their interactions with bathymetry. Meteotsunami monitoring and forecasting systems are overviewed with respect to available observations, deterministic and stochastic modelling tools and operational early warning networks. This review includes an important assessment of operational and research gaps and ideas for improving research tools and understanding of various aspects of meteotsunamis. The authors believe and hope that this review will help researchers and services to increase or improve their capacities and skills for conducting better research on meteotsunamis, not just in the Mediterranean and Black Seas, but in all ocean basins around the world affected by this destructive and dangerous phenomenon.

Key words: Meteotsunamis; Review; Mediterranean; Black Sea

1. Introduction

Since ancient times, meteorological tsunamis or meteotsunamis – atmospherically induced destructive long ocean waves in the tsunami frequency band – have been known to impact coastal communities (Monserrat et al. 2006; Pattiaratchi and Wijeratne 2015; Vilibić et al. 2016; Rabinovich 2020). In several cases, memorable events even gave birth to local legends, for example, that of Vrboska Bay (Hvar Island, Adriatic Sea). There, after a procession was hit by a meteotsunami (Šepić and Orlić 2020), the coastal communities united. The Arabs landed in Mazarra del Vallo (southwestern Sicily coast) in the 9th century and named the local river Mazaro ("possessed") due to the propagation of a meteotsunami bore (Šepić et al. 2018a). Since then, impacts by meteotsunamis have been recorded in a large number of coastal communities in all continents of the world except Antarctica. In addition, a variety of local names have been used for the phenomenon: *rissaga* in the Balearic Islands (Ramis and Jansà 1983; Monserrat et al. 1991a 1991b), *marrobbio* (*marrubbio*) in the Strait of Sicily (Colucci and Michelato 1976; Candela et al. 1999), *milghuba* in the Maltese Islands (Drago 2009), *šćiga* (*štiga*) in the Adriatic Sea (Hodžić 1979/1980, Orlić, 1980), *abiki* in Japan (Honda et al. 1908; Nakano and Unoki 1962; Hibiya and Kajiura 1982), and *Seebär* in the Baltic Sea (Defant 1961; Metzner et al. 2000; Pellikka et al. 2014). In addition to locations with existing local names for meteotsunamis, which presumably reflect the destructiveness of the past meteotsunami events, there are a great number of additional places where severe meteotsunami events occurred: the English Channel and UK coast (Proudman 1929; Haslett et al. 2009; Williams et al. 2019), the Great Lakes (Ewing et al. 1954; Bechle et al. 2016), the East US Coast, from Florida to Maine (Churchill et al. 1995; Šepić and Rabinovich 2014; Vilibić et al. 2014c; Wertman et al. 2014), the US and Canadian West Coast (Thomson et al. 2009), the Patagonian Shelf (Dragani et al. 2014), the South African coast (Okal et al. 2014), the Australian shelf (Pattiaratchi and Wijeratne 2014) and many other locations.

Occasionally, meteotsunamis are characterized by sea level oscillations of several metres with periods from several minutes to an hour. Furthermore, meteotsunami events can cause human losses and injuries (e.g., the 1954 and 2003 events in the Great Lakes – Ewing et al. 1954; Linares et al. 2019; the 1979 Nagasaki Bay abiki – Hibiya and Kajiura 1982; the 2017 Dayyer meteotsunami in the Persian Gulf – Salaree et al. 2018; and the 2014 Odessa meteotsunami – Šepić et al. 2018b) in addition to frequent, and sometime substantial, coastal infrastructure damage (Pattiaratchi and Wijeratne 2015). Still, the destruction and property damage caused by meteotsunamis has been restricted to certain hot spots (harbours, bays, beaches) and is much lower than that resulting from destructive seismic tsunamis due to the smaller wave heights and spatial extent of meteotsunamis as compared to largest tsunamis. In addition, human casualties from meteotsunamis are rare and occur during the most extreme meteotsunami events, while such casualties can be substantial during strong seismic tsunamis, in particular in those generating ocean-wide impacts (Gusiakov et al. 2019).

Because of the destructive nature of meteotsunamis, which can occur without warning even during 'calm' weather, researchers have studied the physics of such events and their generation and propagation/growth towards the shore. The most intriguing question, related to how energy is transferred from the atmosphere to the meteotsunami waves, was explained in 1929 as a resonance mechanism: the so-called *Proudman resonance* (Proudman 1929). Namely, atmospheric disturbances with high-frequency (from minutes to hours) energy, which can sometime be seen on old barogram records, may travel over shelf areas at the speed of tsunami waves (i.e., $U \approx (gH)^{1/2}$, where U is the speed of the atmospheric disturbance, H is the water depth and g is gravity). If such conditions persist, the amplification of the wave that is generated is multiplied (Rabinovich 2009). However, in real shelf areas, the varying bathymetry, tides and currents are known to affect the strength of the resonance (Williams et al. 2020), which can differ from the theoretical conditions described for flat bathymetries. Travelling atmospheric disturbances may generate edge waves on sloping bathymetries near a shore (so-called Greenspan resonance, Greenspan 1956) or may generate shelf waves directly on shelves of limited size (Rabinovich 1993). Compared to tsunami waves, meteotsunami waves are constantly modified by the force of the atmosphere during their travel towards the shoreline (e.g., Hibiya and Kajiura 1982), while the bathymetry simultaneously changes their properties. The waves can reach destructive levels along open sea beaches, such as was observed during the Daytona Beach meteotsunami of 3 July 1992, when wave heights reached 3 m above tide (Churchill et al. 1995). If the waves impact bays or harbours, they can be further amplified through the harbour resonance (Wilson 1972; Rabinovich 2009) and reach heights of up to 6 m, such as occurred during the Great Vela Luka flood of 21 June 1978 (Vučetić et al. 2009; Orlić et al. 2010).

Specific atmospheric conditions that lead to intense, long-lived and fast atmospheric disturbances have also been investigated as mechanism of generating meteotsunami events.

Physical mechanisms responsible for keeping energy near the sea surface over hundreds or more kilometres are needed to reach a substantial amplification of the meteotsunami waves. There are several atmospheric processes found to satisfy these conditions. Wave ducting of internal gravity waves appears to commonly accompany meteotsunamis in the Mediterranean and other mid-latitude locations (Monserrat and Thorpe 1996; Tanaka 2010; Šepić et al. 2015a). Other processes in the world oceans include wave-CISK (Convective Instability of the Second Kind, Belušić et al. 2007), squall lines and derechos (Ewing et al. 1954; Churchill et al. 1995; Paxton and Sobien 1998; Šepić and Rabinovich 2014), mesoscale convective storms (Linares et al. 2019; Williams et al. 2020), and rain bands in tropical cyclones (Shi et al. 2020). However, the capacity to reproduce the generation and propagation of meteotsunamigenic atmospheric instabilities, including their interaction with orography, are at the edge of the state-of-the-art atmospheric numerical model capacities (Renault et al. 2011; Horvath and Vilibić 2014; Denamiel et al. 2019a) due to both the physics implemented and the coarse resolution.

In recent decades, through the increased availability of high-frequency (1 min) sea level and meteorological data and the development of numerical tools accompanied by the increase in high-performance computing resources, the physics of meteotsunami waves and their atmospheric sources have been increasingly researched (Vilibić et al. 2016).

Meteotsunamis are a worldwide phenomenon; however, literature reviews show that they have been traditionally studied much more in the Mediterranean than in the rest of the world. This can be explained by the micro-tidal nature of the Mediterranean Sea where tidal amplitudes (a few tens of centimetres except in the Gulf of Gabes and the northern Adriatic Sea, Tsimplis et al. 1995; Medvedev et al 2020) are an order of magnitude smaller than the amplitudes of meteotsunamis. In consequence, coastal infrastructure along the Mediterranean coast is generally not adapted to accommodate rapid sea level changes, resulting in much greater damage and flooding during meteotsunami events than what occurs along macro-tidal coasts of the world (Fig. 1).

The first theoretical explanation for Mediterranean meteotsunamis was provided at the beginning of the 20th century for the Balearic/Catalan region where Fontserè (1934) noticed the coincidence between rapid changes in the air pressure and seiches in the Barcelona harbour. Almost simultaneously, Caloi (1938) investigated air pressure and sea level records in the northern Adriatic and associated the recorded seiches with propagating atmospheric disturbances. Subsequently, in late 1970s and early 1980s, research on rissaga (i.e., meteotsunami) events occurring in Ciutadella (Balearic Islands) demonstrated their relationship with specific synoptic conditions (Ramis and Jansà 1983). These observations were the basis for the subsequent rissaga synoptic forecasting system, which tracked (i) ground and low (below 850 hPa) level atmosphere conditions in which a weak cyclone was present during rissaga events, (ii) south-westerly flow of dry and warm African air at levels corresponding to approximately 850 hPa, which are situated over a relatively cold surface air and give rise to a characteristic temperature inversion, (iii) the strong south-westerly air flow over the Western Mediterranean that occurs at 500 hPa, and (iv) a jet stream between the Balearic Islands and the Iberian Peninsula, which occurs at 300 hPa.

In the Adriatic Sea, the Great Flood of Vela Luka on 21 June 1978 (Vučetić et al. 2009) triggered extensive research on the origin of this event. Several active theories to explain the observed waves were developed: (i) a tsunami triggered by the 6.4 Mw Aegean earthquake, which took place the day before (Zore-Armanda, 1979; however, no correspondence between the observed and theoretical arrival times of tsunami waves has been found, and the distance between the epicentre and Vela Luka is far too large; (ii) a tsunami triggered by a landslide along the Italian side of the Middle Adriatic Pit (Bedosti 1980); however, no waves were reported close to the source, which would be expected for landslide tsunamis; (iii) cyclonic-waves generated by a cyclone in the open sea that propagated as free waves toward the affected bays (Hodžić 1979/1980); however, no energy transfer mechanism has been proposed; and (iv) a resonant transfer of energy from intense air pressure disturbances that propagated north-eastward at a speed of 22 m/s in addition to long ocean waves generated through the Proudman resonance (Orlić 1980); the latter was confirmed by recent investigations (Orlić et al. 2010), although a mismatch concerning the speed of the air disturbance and the effect of the Proudman resonance versus other effects driven by bathymetry, was found.

Since these early studies, the science of the Mediterranean meteotsunamis has substantially progressed; this progress was initiated by major meteotsunami events for which observations were available: those that occurred in the 1980s and 1990s in the Balearic Islands (Tintoré et al. 1988) and in the 2000s in the Adriatic Sea (Vilibić and Šepić 2009). An extensive application of numerical modelling tools followed these observations, peaking in the 2010s with the development of high-performing computing facilities (Orlić et al. 2010; Renault et al.

2011). Investigations of atmospheric sources, energy transfer towards the sea, and the propagation and amplification of meteotsunami waves have been the main topics of these investigations. A comprehensive and systematic overview of the knowledge acquired in these papers is the primary motivation for this study, which is the first such study dedicated to the Mediterranean Sea (including the Black Sea). Section 2 introduces the topic through an overview of the media coverage and societal behaviour that occurred after major meteotsunami events, including the reaction of society, which is different in various countries. Section 3 contains a basic map of the Mediterranean and Black Sea meteotsunami papers cited by the Web of Science database, which includes the geographical coverage, tools used in the research and the atmosphere or ocean meteotsunami source. Section 4 gives and overview of meteotsunami research, from that pertaining to the mechanism of atmospheric generation to the genesis and amplification of meteotsunami waves in coastal regions. Existing meteotsunami monitoring and forecast systems in the Mediterranean and Black Seas, including observations, deterministic models, stochastic approaches, and hazard assessments are presented in Section 5. Section 6 describes the major bottlenecks that exist in Mediterranean and Black Sea meteotsunami research, followed by perspectives on future research and research directions and conclusions described in Section 7.

2. Description, media coverage and societal behaviour after major meteotsunami events

In recent decades, major meteotsunami events associated with structural damage in coastal regions that have impacted local populations have often attracted local and national media attention. In this section, three examples of media coverage and societal behaviour during and after Mediterranean and Black Sea meteotsunamis will be briefly overviewed.

2.1. The Great Vela Luka Flood of 21 June 1978

This event, characterized by wave heights up to 6-m in the city of Vela Luka (Korčula Island, Croatia), impacted the whole middle Adriatic from the Italian to the Croatian coasts and is often referred to in the literature as the most devastating and memorable meteotsunami in the Adriatic. The Vela Luka Bay is funnel shaped and has been known by local inhabitants to have persistent eigen oscillations that normally reach less than a metre or two in height and can be easily handled by the city harbour without suffering inundation or structural damage (Orlić 2015). This destructive event was described in detail by Vučetić et al. (2009), while a collection of newspaper articles and other relevant material was documented by Vučetić and Barčot (2008). The event attracted a large amount of media attention, while scientists tried to explain the physical mechanisms.

The first meteotsunami waves were observed in the early morning, on 21 June 1978 at 4:15 UTC (local time 5:15), overtopping the piers and quays and flooding houses at the waterfront. Intuitively, the electricity service switched off the power for the whole city to prevent any human losses and damage caused by electric shocks. Telephone connections were also disabled during and after the event. The sea oscillated every 15-20 min, peaking at 7:00 UTC, when a 6-m wave was observed at the top of the harbour (in fact, several media sources reported wave heights of 8 to 11 m, as no data were available to quantify the trough of the meteotsunami wave that emptied the harbour). The sea returned to calm at approximately 10:00 UTC, leaving a great amount of household goods floating within the bay, between sunk boats and ships, with heavy furniture (e.g., refrigerators) removed from several houses and a health centre destroyed at the top of the bay.

The media reported the event the very first day, providing basic facts and impact assessments (Vučetić and Barčot 2008): "*Life in Vela Luka is paralyzed. People were not on their jobs today. All of Vela Luka is on its feet this morning from five o'clock. The Vis ferry did not dock at all, but carried forward towards Split. The city was run out of food and telephone connections. The gasoline station was also destroyed. It is unknown at this time how many boats, ships and cars were damaged. The level of destruction is enormous and it is impossible to talk about it now … Military units from the island area also came to the rescue, and police is having a great trouble regulating traffic that is completely paralyzed*."

Simultaneously, after the first impact, the local authorities started to organize cleaning of the bay and announced rules of behaviour via a public proclamation on the day after the event (Fig. 2). These rules, designed to mitigate damage and prevent uncontrolled behaviour of the population, included: (i) the treatment of water, in particular the potable water, (ii) the treatment of the food stored in houses, (iii) the treatment of vegetables in gardens, (iv) the recovery of flooded basements and houses, (v) the control of personal hygiene and the management of pre-existing health conditions, and (vi) rules for bathing and swimming. Three days later, the authorities engaged local populations in voluntary sanitation and cleaning of the Vela Luka area, after which the city become safe for living and working. At that time, the final estimation of the damage caused by the meteotsunami was approximately 7 million US dollars, which was approximately a quarter of the annual income of the whole Korčula Island.

In the following month, several researchers, such as Tonko Tabain, who is quoted hereafter, were interviewed by the media to provide a theoretical background of the event to the general public: "…*the second hypothesis, by which sea pressure waves are the causative cause of šćiga (o.a. meteotsunami), provides an answer to the questions asked … sea pressure waves are generated by atmospheric pressure waves, and these arise when two air masses of different density (temperature) move at different speeds relative to each other*." After the first interviews, more research was carried out and papers on the event by Hodžić (1979/1980) and Orlić (1980) were published. Unfortunately, a comprehensive research program developed in the following two years by the Academy of Science and Arts in Zagreb, which consisted of the installation of a monitoring network and a meteotsunami hazard assessment via numerical models in the Vela Luka area, was never implemented. Interestingly, during this event, reflected waves were far less destructive than those that hit the Croatian coastline, which were also observed with a few hour time lag along the Italian coast (Orlić et al. 2010). As the two shorelines were part of the different political systems (socialism in Yugoslavia versus capitalism in Italy), the explanation for the observed waves was dramatically different: Bedosti (1980) hypothesized that the waves were the result of a submarine landslide along the western flank of the Middle Adriatic Pit. Indeed, such a hypothesis did not include any of the observations available along the Croatian coastline, presumably due to a lack of information available to the Italian researchers. More than 30 years were thus needed to gather all available Italian and Croatian observations and provide reasonable explanations and quantifications of the physical mechanism of the event (Vučetić et al. 2009; Orlić et al. 2010).

2.2. The destructive rissaga event of 21 June 1984

Meteotsunamis in the Balearic Islands are historically known by the local name of rissaga. The first references of the hazardous effects of rissaga events in Ciutadella (the eastern coast of Menorca island) are found in documents dating to the XV century. The phenomenon is also described in detail by Riudavets as early as 1885 in his book: History of Menorca Island. From then on, many references in local newspapers exist but there are only very few mentions in the scientific literature (Fontseré 1934). Rissaga was not extensively considered by the scientific community until the early eighties, when several works were published in Spanish by Agustí Jansà and Clemente Ramis (Ramis and Jansà 1983; Jansà 1986 1987). Several of the pioneering publications were motivated by the extreme event observed in 1984.

On 21 June 1984, a singular rissaga event struck Ciutadella harbour. Local eyewitnesses reported that several minutes after four o'clock in the morning (local time) the harbour, located at the end of Ciutadella inlet, suddenly became dry. Shortly after, when water re-entered the inlet, it washed up towards the harbour end most of the boats that previously had broken their mooring ropes, hit each other and caused great damage (Fig. 3). After the initial "big wave", large sea level oscillations (of more than one metre), with a period coinciding with an inlet seiche (approximately 10 min), remained for several hours. Total damage was tremendous: of the 117 boats moored at the port at that time, 81 were affected and 35 were sunk. Most of the local fishing float became inoperative during the following months. Fortunately, no personal injuries were reported, but economic damage was quantified to be over two and a half million euros.

Abnormal sea level oscillations, although of much less of a consideration than in Ciutadella, were also observed in other Menorca inlets, such as adjacent Platja Gran. Similar large amplitude sea level oscillations that caused moderate damage were also reported in other harbours on the nearby Mallorca island, such as those in Porto Colom or Porto Cristo.

The next day, local newspapers related several witness accounts of how a sudden blow of wind woke them up in the middle of the night. When a short time later they looked towards the port, they were surprised to find the port empty of water. Then, a great wave entered the port and washed away everything in its path. Although rissaga were not a rare phenomenon in Ciutadella, everyone agreed this particular event was one of the more destructive ever experienced at this location.

No sea level records were available at the time, but the largest oscillations in Ciutadella were estimated to reach more than 4 m of through-to-crest amplitude. A detailed analysis of this event, including the examination of the atmospheric synoptic situation, vertical structure of the wind and pressure and the available records of surface winds and atmospheric pressure at several stations were provided by Jansà (1986). Most of the generation mechanisms suggested in that work remain valid to this day.

2.3. The Odessa meteotsunami of 27 June 2014

This destructive event has been documented as a chain of meteotsunamis that hit the coasts of the Mediterranean and Black Seas and was described in detail and investigated by Šepić et al. (2018b). To summarize, sudden tsunami waves with wave heights of more than 1 m (up to 2.5 m as claimed by several eyewitnesses) hit two beaches near Odessa (Ukraine), which were inundated to a distance of 50 m, and resulted in 15 people injured. This extreme event was unprecedented as it occurred during calm weather in a region located far from major earthquake zones (Yalçiner et al. 2004) where seismic tsunamis are not frequent.

In addition to the injuries, the meteotsunami generated a wave of panic within the local population, amplified by the unstable political situation during the Ukrainian crisis (https://en.wikipedia.org/wiki/2014_Odessa_clashes), which, less than two months before, left 48 people dead (the highest toll since The Great War) during clashes in Odessa. In this context of terror, several maladaptive hypotheses to explain the generation of such extreme waves circulated among the population and were even promoted by the media (e.g., https://dumskaya.net/news/nevedomaya-hujnya-037089): "*Meanwhile, scientists continue to put forward more and more versions of what happened. Most adhere to a version of the anthropogenic or technogenic nature of what happened, they assume that the wave appeared as a result of human activity … At the same time, eyewitnesses refute the assumption that a large vessel (at least 50 thousand tons displacement) could travel at high speed (more than 30 knots) in the immediate vicinity of the coast, which could only cause such a wave. Also unlikely are the versions that the wave was the result of dredging, although today, indeed, a dredger was seen near the Black Sea. Another hypothesis was put forward by the hydrologist Anatoly Petrachenko. He suggested that the cause could be, for example, the explosion of a small boat with ammunition that sank during the Great Patriotic War near Lustdorf … Firstly, such an explosion would undoubtedly be recorded by seismologists, whose station is 15 km from Chernomorka. Secondly, there were no stunned fish and victims of water hammer at the scene, which puts an end to all the "explosive" versions … In turn, the inhabitants of Chernomorka argue that such large waves in these places occur every few years and are the result of a complex interaction of warm and cold currents. This time, such a wave was stronger than usual.*"

To prove that the observed waves were indeed meteotsunamis, Šepić et al. (2018b) collected all available observations and carried out several numerical experiments. Although the magnitudes of the waves were underestimated, presumably due to insufficient resolution of the atmospheric forcing and the bathymetry at the shelf edge and in coastal regions used in the study, the authors reproduced the spatial extent of the event and indicated that it was caused by remote generation of long ocean waves that are topographically directed towards the affected beaches.

3. Succinct analysis of the Mediterranean meteotsunami bibliography

The bibliography of the Mediterranean and Black Sea meteotsunamis (presented in Fig. 4a) is composed of 55 research papers, as archived by the Web of Science (WoS) database from 1955 to 2019. The bibliography encompasses both well-researched hot spots for meteotsunamis for which many papers have been published, such as the Balearic Islands or the Adriatic Sea, as well as sites that contain a single meteotsunami observation, such as the Black Sea sites. The first article on the list, by Tintoré et al. (1988), was preceded by a great number of non-WoS papers that mostly described different aspects of the Balearic and Adriatic meteotsunamis (Fontseré 1934; Caloi 1938; Colucci and Michelato 1976; Hodžić 1979/1980; Orlić 1980; Ramis and Jansà 1983; Jansà 1986 1987).

The number of WoS meteotsunami papers per year increased from 0 to 2 in the late 1980s and early 1990s to more than 2 per year after the mid-2000s (except 2013, Fig. 4b). Interestingly, the peak of the papers was largely connected to special issues of several journals: (i) Physics and Chemistry of the Earth in 2009 (Rabinovich et al. 2009) included 8 meteotsunami papers, and (ii) Pure and Applied Geophysics in 2018 (Vilibić et al. 2018a) included 5 meteotsunami papers, while (iii) the third special issue on meteotsunamis, in journal Natural Hazards in 2014 (Vilibić et al. 2014b), was driven by an US project and therefore containing just one paper covering Mediterranean and Black Sea meteotsunamis. While the first special issue in 2009 was dedicated to only meteotsunami research, the second in 2018 covered a variety of Mediterranean and Black Sea meteorology and climatology topics, including meteotsunamis. In total, 10 papers were published between 1990 and 1999, 20 between 2000 and 2009 and 24 between 2010 and 2019. Most of these papers have been geographically limited to the Balearic (22) and Adriatic (21) regions (Fig. 5a), while other meteotsunami hot spots (e.g., Strait of Sicily and Maltese Islands) have been only sporadically researched. In addition, 5 papers covered more than one Mediterranean and Black Sea sub-basin or even the whole Mediterranean and/or Black Sea and include research on meteotsunami teleconnections, multi-meteotsunami events or an analysis of high-frequency sea level data. Additionally, all but one paper published prior to 2000 focused on Balearic meteotsunamis, while 11 of the 24 papers between 2000 and 2019 document Adriatic meteotsunamis and the 13 remaining papers cover all regions known for meteotsunami occurrence.

Approximately half of the meteotsunami research papers in the Mediterranean and Black Seas are exclusively based on oceanic and atmospheric observations; 10 papers only rely on numerical models, while another 10 papers combine observations and numerical investigations (Fig. 5b). The use of numerical models in Mediterranean and Black Sea meteotsunami research started in 1999, while half of the meteotsunami articles published between 2010 and 2019 included numerical modelling. Eight standalone or combined observation and numerical experiment papers contain analytical solutions used to theoretically derive various meteotsunami processes, particularly for the Balearic Islands. Most of papers investigated both atmospheric and oceanic aspects of meteotsunamis (Fig. 5c), with oceanographic studies more concentrated in the Balearic region in which several observational campaigns have been carried out (e.g., LAST-97 experiment, Monserrat et al. 1998; Liu et al. 2002).

4. Meteotsunami properties

4.1. The source processes and meteotsunamigenic disturbances

Several aspects related to the source of meteotsunamis are presented: (i) the resemblance of synoptic patterns related to meteotsunami occurrences and high-frequency sea level oscillations in general, (ii) the mesoscale processes responsible for generation and maintenance of meteotsunamigenic disturbances, and (iii) the manifestation of atmospheric disturbances as high-frequency air pressure or wind oscillations.

4.1.1. Synoptic patterns connected to meteotsunamis

Atmospheric gravity waves, probably the most frequent source of meteotsunamigenic disturbances, are generated by intense mesoscale processes (such as jets, fronts, convection) related to specific synoptic conditions (Plougonven and Zhang 2014). The relationship between specific synoptic conditions and Balearic meteotsunamis was established in the early 1980s (Ramis and Jansà 1983) and has been confirmed in subsequent studies that were mostly focused on specific meteotsunami events (Tintoré et al. 1988; Monserrat et al. 1991a 1991b; Jansà et al. 2007). Šepić et al. (2009a) further analysed this relation and documented that 23 out of 32 meteotsunamis (i.e., 72%) in Ciutadella (Balearic Islands) were associated with specific synoptic conditions including: (i) inflow of warm and dry air masses from North Africa at low levels of approximately 850 hPa, (ii) strong winds in the mid-troposphere, higher than 20 m/s between 3 and 8 km, and (iii) an instable layer in the mid-troposphere with a Richardson number lower than 0.25. They found that the correspondence between synoptic conditions and meteotsunami events increased to 88% for the strongest meteotsunamis. The connection between Ciutadella meteotsunamis and specific meteotsunamigenic synoptic patterns has been formally quantified by Šepić et al. (2016a), who constructed a synoptic atmospheric index that increases as the synoptic conditions better match the ideal suggested framework. This research has shown that there exists a threshold below which intense meteotsunami never occur. Still, favourable synoptic conditions for meteotsunamis (high index) are necessary but insufficient, as the exceedance of the threshold is associated with only a 20% probability for meteotsunamis.

The connection between synoptic patterns and meteotsunamis in the Balearic Islands preceded the research on Adriatic meteotsunamis, which – aside from early papers – was initiated in mid-2000s and was systematically established for Adriatic events occurring in the 2000s and 2010s. The first indication of a similar link between meteotsunamis and synoptic patterns in the Adriatic Sea was derived from the analysis of extreme Bakar Bay seiches (Šepić et al. 2008), which revealed that extreme events are associated with strong south-westerly flow at 700 hPa. Later, several studies documented conducive synoptic conditions observed during the meteotsunami events occurring on 22 August 2007 in Ist, on 15 August 2008 in Mali Lošinj and, retrospectively, on 21 June 1978 in Vela Luka (Belušić and Strelec Mahović 2009; Vilibić and Šepić 2009). However, the middle Adriatic meteotsunami of 27 June 2003 was an exception for which the west-north-western flow was present in most of the atmosphere

(Belušić et al. 2007). Systematic investigations of the northern Adriatic meteotsunamis (Šepić et al. 2012) mapped the following favourable synoptic conditions for 16 meteotsunami events observed at the Rovinj tide gauge between 1955 and 2010: (i) a cyclone associated with an approximately 10 hPa drop of air pressure in its centre compared to the climatological mean and stretching north-west from the affected area; (ii) a sharp thermal front at 850 hPa stretching from Algiers over Corsica to the northern Adriatic in the WSW-ENE direction and associated with temperature anomalies of up to 5°C and -4°C southeast and northwest from the front, respectively; and (iii) an anomalously strong mid-troposphere jet at 500 hPa with up to 15 m/s higher velocities than climatological means in the northern Adriatic and northern Italy, just over the affected area and WSW from it.

Links to synoptic conditions exist in other parts of the Mediterranean. For example, the events of 27 June 2014 in Odessa (Šepić et al. 2018b) and of 25 June 2014 in Sicily (Šepić et al. 2018a) were studied; these events occurred, along with the Adriatic multi-events (Šepić et al. 2016b), as a sequence of meteotsunamis that hit the Mediterranean and Black Seas, from the Balearic Islands to the northern Black Sea. A systematic investigation of high-frequency sea level events that were measured at 29 tide gauge stations located mostly in the Western and Central Mediterranean was provided by Šepić et al. (2015c), who documented 36 events with strong high-frequency sea level oscillations. The events observed at the Balearic Islands, southern Sardinia, Strait of Sicily and southwestern Greece were mostly linked to the same meteotsunamigenic synoptic patterns as those documented for destructive Adriatic and Balearic meteotsunamis (Fig. 6).

4.1.2. Meteotsunamigenic mesoscale atmospheric processes

Although specific synoptic atmospheric patterns are definitely associated with meteotsunami events in the Mediterranean and Black Seas, mesoscale processes are key to the generation and propagation of long-lived meteotsunamigenic disturbances. Monserrat et al. (1991a) and Monserrat and Thorpe (1992), first for the Balearic Islands, observed these disturbances in a set of microbarograph measurements and suggested an initial theoretical background based on the wave-duct theory introduced by Lindzen and Tung (1976). Later, Monserrat and Thorpe (1996) fully applied the theory and found that the observed vertical structures of wind and temperature in the lower atmosphere resemble those that allow theoretical modes to propagate long distances in the lower troposphere without a significant loss of energy. These conditions include an unstable layer in the mid or upper troposphere that overtops stable conditions, which are maintained by a dry and warm air. An important prerequisite for wave ducting over long distances is a quasi-linear increase in the wind speed from the ground to the unstable layer, which is normally placed in the mid-troposphere. This unstable layer acts as a reflecting wall that is able to keep the energy related to the atmospheric disturbance in the lower atmosphere. The theory also establishes the relationship between the wind speed at the reflectance mid-troposphere layer with the propagation speed of the atmospheric disturbances (i.e., existence of a critical level within the unstable layer at which these two speeds should be equal).

Similar to synoptic patterns, the mesoscale properties of the Adriatic meteotsunamis were found to be associated with the same physical mechanisms as the Balearic events. Several observational studies reproduced the atmospheric conditions favourable for wave ducting, related to the 2007 Ist meteotsunami (Šepić et al. 2009b) and the 2014 middle Adriatic meteotsunami (Horvath et al. 2018), although the latter has also been associated with another mechanism of maintenance and propagation of atmospheric disturbances: the so-called wave-CISK (Conditional Instability of the Second Kind, Powers and Reed 1993). The wave-CISK is characterized by a coupling between a gravity wave and convection, in which convergence associated with the gravity wave forces moist convection, while convective heating provides the energy for the wave. The wave-CISK has been observed and modelled for the 2003 middle Adriatic meteotsunami (Belušić et al. 2007; Fig. 7), in which the atmospheric disturbance was maintained by an anomalously warm Adriatic Sea over ca. 800 km, after its generation over the Alps.

Comprehensive investigations of atmospheric mesoscale source processes have not been carried out for other regions, although they have been sometimes attempted, e.g., for the Sicily meteotsunamis (Candela et al. 1999). Still, the data used in the analyses were not appropriate to properly document the mesoscale characteristics of the source; therefore, surface data were restricted to 6-h resolution from a reanalysis. Conditions for wave ducting have also been documented for Black Sea meteotsunamis (Vilibić et al. 2010; Šepić et al. 2018b), without applying atmospheric numerical modelling to quantify the processes. In addition, these mechanisms have been proven only for selected meteotsunami events, which normally occur during summer, while a great range of meteotsunamis – including meteotsunamis that occur during winter – have not been researched at all in the Mediterranean.

4.1.3. Surface manifestation of meteotsunamigenic disturbances

The first evidence of a relationship between rapid changes in air pressure and meteotsunami waves was suggested rather early, by Fontserè (1934) and Caloi (1938), who analysed a set of events in the Catalan coast and the Balearic Islands, and the northernmost part of the Adriatic Sea, respectively. The relationship was strongly supported by the identification of abnormal rapid oscillations in atmospheric pressure in the operative chart-type barograms that occurred simultaneously with several significant events in the 1970s and 1980s in the Balearic Islands (Ramis and Jansà 1983). The first digital atmospheric pressure data with a high enough temporal resolution to identify the properties of atmospheric pressure were not available until the early 1990s (Monserrat et al. 1991a 1991b); however, these observations were sparse and not capable of documenting the spatial characteristics of the air pressure disturbances. The first study that used a triangle of microbarographs (Monserrat and Thorpe 1992) found that the atmospheric disturbances connected with meteotsunamis behave as nondispersive waves, i.e., have no significant variations in their speed with frequency. These data, together with microbarograph data collected during subsequent experiments, have been used to map the spectral characteristics of the atmospheric disturbances (Garcies et al. 1996; Rabinovich and Monserrat 1996; Monserrat et al. 1998) to force an ocean numerical model (Vilibić et al. 2008) and to document severe meteotsunami events (Jansà et al. 2007).

In the Adriatic Sea, the microbarograph network was not initially sensitive enough to measure rapid air pressure oscillations. Therefore, no clear records of short period oscillations were derived from measurements for the 1978 Vela Luka meteotsunami. However, the network provided enough information to estimate the speed and propagation direction of the enveloping longest period atmospheric disturbance and to allow the Proudman resonance to be hypothesised as the mechanism responsible for generating meteotsunami waves (Orlić 1980). The synchrony between air pressure and sea level observations has been documented from data collected by the newly installed tide gauge in Split (Vilibić and Mihanović 2003). This study preceded the 2003 middle Adriatic meteotsunami for which several operational microbarographs were available to compute the direction and propagation of air pressure disturbances (Fig. 8), which were later used for numerical modelling of the meteotsunami waves (Vilibić et al. 2004). The shape of the air pressure versus the corresponding energy distribution over frequencies was investigated by Vilibić et al. (2005); the results of this study indicated that higher energies are reached below 2 h for cosine versus box-car disturbances. Subsequently, numerous Adriatic meteotsunami studies mapped air pressure disturbances associated with meteotsunamis, including these coming from a triangle of precise microbarographs installed in the middle Adriatic (Vilibić et al. 2014a). They found that, over a great number of strong high-frequency air pressure observations, the atmospheric disturbances were dispersive and therefore had no potential to generate meteotsunamis. Mapping of the spatial and temporal distribution of the intensity, speed and propagation direction of the meteotsunamigenic atmospheric disturbances has been recently improved by an amateur network of lower accuracy but much higher density observations (Šepić et al. 2016b).

To prove that the multi-meteotsunami events, which occurred in a number of Mediterranean and Black Sea locations, are related to each other, Šepić et al. (2015a) used intense air pressure oscillations collected by different observing networks, which have become standard in recent decades. For other regions, measurements of high-frequency air pressure observations have also been used to investigate meteotsunamis, such as in the Black Sea (Vilibić et al. 2010; Šepić et al. 2018b), south-western Sicily, the Maltese Islands (Drago 2009; Šepić et al. 2018a) and the Gulf of Genoa (Pico et al. 2019).

4.2. Generation and amplification of meteotsunami waves

4.2.1. Open ocean resonant generation

Following the concurrent observations of intense air pressure oscillations and meteotsunami waves and acknowledging pioneer theoretical work by Proudman in 1929 (Proudman 1929), an open ocean resonant mechanism was early assumed to be responsible for the generation of meteotsunami waves. This assumption was particularly applied to the strong seiche events in the Gulf of Trieste (Caloi 1938), which were possibly generated by Proudman resonance. Such a hypothesis has been further proposed by Orlić (1980) for the

1978 Vela Luka meteotsunami, who noted the similarity between the speed of the atmospheric disturbance derived from microbarograph observations (~22 m/s) and the predominant speed of long ocean waves off Vela Luka. However, a further study of this event provided by Orlić et al. (2010) revealed a much higher speed of the atmospheric disturbance (34-36 m/s) as the most efficient method for energy transfer towards the sea.

Based on reproduction of the 2014 middle Adriatic meteotsunami, Šepić et al. (2016b) introduced the so-called "Proudman length", i.e., the percentage of the total length over which a disturbance travelled and for which $0.95<Fr<1.05$ is valid, where $Fr=U/(gH)^{1/2}$ is the Froude number, U is the atmospheric disturbance speed, H is the water depth and g is gravity. However, the Proudman length was much shorter than necessary to claim that the Proudman resonance is responsible for open-ocean generation of meteotsunami waves (Fig. 9), indicating that some other mechanism might also be important in complex regions of the open middle Adriatic. Indeed, no flat regions are present off the middle Adriatic, creating favourable conditions for maintaining Fr in the short range in which meteotsunamis are efficiently generated (Williams et al. 2020). However, variable bathymetry may generate scattering and reflection of meteotsunami waves, forming and amplifying wave packages at different frequencies as they approach coastal regions (Garrett 1970; Vennell 2007). Reflection is also responsible for the few hours lagged occurrence of meteotsunami waves at the Italian coastline during the 1978 Vela Luka meteotsunami, as these waves travelled back over the Adriatic after impacting the eastern coastline (Orlić et al. 2010).

Still, the Proudman resonance has been documented as the major meteotsunami generating force in the relatively flat northern Adriatic (Šepić et al. 2015b) and coastal middle Adriatic waters (Vilibić et al. 2004). Furthermore, Šepić et al. (2015b) note that a small change in the disturbance speed of ca. 10%, which reflects a change in Fr of 10%, may change the open ocean resonance by two or more times. Convincingly, topographic effects play a substantial role even in relatively flat environments, as even a gentle slope was found to substantially decrease the amplification of meteotsunami waves (Williams et al. 2020).

For Ciutadella and the Balearic Islands, the idea of resonance was first suggested by Ramis and Jansà (1983), although atmospheric forcing was assumed to resonantly excite the harbour normal modes directly (so-called Chrystal resonance, Bubalo et al. 2018). The first comprehensive theoretical study on processes responsible for generating meteotsunami waves in the Balearic Islands was carried out by Tintoré et al. (1988), who developed an analytical model and suggested resonant generation of coastally trapped edge waves by atmospheric gravity waves, peaking in energy at the same frequencies previously found for their resonant amplification inside the harbour. Gomis et al. (1993), using the first simultaneous sea level and atmospheric pressure observations over the region, demonstrated that an external oceanic wave was necessary as an intermediate mechanism between the atmospheric forcing and sea level oscillations inside the harbour, but suggested that no substantial amplification was expected to occur outside the inlet. The need for intermediate open ocean resonant amplification was also suggested by Rabinovich and Monserrat (1998). They proposed the eventual generation of long ocean waves on the shelf, between Mallorca and Menorca Island, through the Proudman resonance, following the analysis provided for Japanese meteotsunamis (Hibiya and Kajiura 1982). The importance of the Proudman resonance occurring over the shelf off Menorca was later quantified with a numerical model (Vilibić et al. 2008), which found that the resonance definitively plays an initial role in the generation of meteotsunami waves in Ciutadella, although the energy is definitively later amplified by the coastal slope topography and harbour oscillations (Fig. 10). An ocean numerical model forced by synthetic air pressure oscillations was also used by Ličer et al. (2017), who noted that - in any sensitivity scenario - more than 75% of the meteotsunami wave heights reproduced in Ciutadella are formed on the shelf between Mallorca and Menorca, and not on other parts of the shelf.

The study by Candela et al. (1999) used observations and simplified barotropic momentum and continuity equations to numerically quantify the ocean gravity modes that are coherently occurring in the Strait of Sicily, which they hypothesize are responsible for generating the southwestern Sicily meteotsunamis. They also emphasize the relevance of the propagating air pressure versus wind disturbances, the latter of which is an order of magnitude lower than the former. The high-precision air pressure and sea level measurements conducted in 2007 and an assessment of bathymetry off the most affected city, Mazara del Vallo, revealed the possible existence of Proudman resonance, associated with edge waves that might occur around the circular outer shelf at the observed frequencies (Zemunik et al. 2020). The role of wind disturbances in generating meteotsunami waves has also been quantified by Vilibić et al. (2005), who found their contribution was not more than 30% in the middle Adriatic, where the speed of long ocean waves is between 20 and 30 m/s. However, for shallow regions, such as the coastal northern Adriatic, wind disturbances might be more important, as has been found for other shallow parts of the world ocean (e.g., de Jong and Battjes 2004; Šepić and Rabinovich 2014). The coastal barotropic ocean model forced by measured high-frequency air pressure disturbances travelling with the speed and direction of the wind at 500-hPa reproduced the most observed high-frequency sea level oscillations but also created several false events (Vilibić and Beg Paklar 2006). Air pressure disturbances also have been found to be relevant in the generation of the 2014 Odessa meteotsunami, yet occurred far from the source and were amplified by the Black Sea shelf break almost 200 km off the affected beach. Indeed, for all Mediterranean meteotsunami events that occurred between 23 and 27 June 2014, Šepić et al. (2015a) indicated that suitable resonance conditions (i.e., Fr between 0.9 and 1.1) were present off the affected coastlines, indicating the existence of conditions favourable for occurrence of the Proudman resonance during all these events.

In summary, despite several initial investigations that suggest a direct atmospheric forcing on the inlets in several regions, some open ocean resonance amplification of the atmospheric forcing that acts as an intermediate mechanism is necessary to explain the phenomenon. Several processes have been suggested, of which the Proudman resonance is the more plausible open ocean resonant amplification in most of the meteotsunami hot spots.

4.2.2. Coastal amplification and topographical effects

Once generated, meteotsunami waves propagate towards the coastline and strongly interact with coastal bathymetry. In fact, the coastal amplification of meteotsunami waves was the first process investigated by researchers, regardless of the open ocean generation mechanism (Airy 1878; Fontserè 1934; Colucci and Michelato 1976; Hodžić 1979/1980; Orlić 1980; Ramis and Jansà 1983; Jansà 1986). The theory of seiches and harbour oscillations, worldwide and in the Mediterranean, dates back more than a century (Sterneck 1914; Wilson 1972), including the effects of harbour shape on amplification factors (Miles and Munk 1961; Rabinovich 2009). In addition, the exact mechanism of amplification was established rather early. A proper quantification of the amplification was carried out by implementing numerical models, which estimated the quality factor Q for some hot spots, such as Ciutadella ($Q \approx 10$, Rabinovich et al. 1999), Vela Luka ($Q \approx 28$, Denamiel et al. 2018) and other locations. Interestingly, the quality factor may substantially change with interventions that change the inlet geometry, even when these interventions are restricted to the inner parts of the bay. For example, dredging or building new piers and marinas may substantially change the quality factor (Denamiel et al. 2018). There are a great number of studies that have investigated different aspects of harbour resonance during Mediterranean meteotsunamis (Gomis et al. 1993; Garcies et al. 1996; Rabinovich and Monserrat 1996 1998; Vilibić and Mihanović 2003; Vilibić et al. 2004; Drago 2008 2009; Orfila et al. 2011), emphasizing the role of resonance in creating extreme sea level oscillations at harbour heads.

Harbour resonance may also be modulated by second order effects that may influence the way energy is amplified inside the harbour. For example, the Balearic Islands hot spot – the Ciutadella inlet - is topographically associated with the similar but smaller Platja Gran inlet, forming what would resemble a set of two pendula joined by a string. Liu et al. (2003) documented their resonant coupling through observations and a simple analytical model and found that the coupling is proportional to the distance between the inlets. Further research by Marcos et al. (2004) indicated that these coupling effects may change the amplification factors of each inlet. While such a system was found to slightly decrease oscillations in Ciutadella Harbour, it was found to increase oscillations in Platja Gran.

The inclusion of flooding (and drying) of coastal regions into ocean numerical models also has been found to modulate meteotsunami wave heights. This approach is standard in tsunami run-up numerical modelling estimates (e.g., Titov and Synolakis 1998), but not in meteotsunami research. Using the ADCIRC unstructured model, Bubalo et al. (2019) found that the maximum wave height increased 35% at the top of Vela Luka Bay in comparison with the model simulations in which no coastal flooding was included. This might be quite relevant for assessing the associated risk when the meteotsunami waves are several metres high and there is substantial drying or flooding of the coastal region, such as was witnessed during the 1978 Vela Luka meteotsunami.

A quite unique phenomenon has been observed in the Mazaro River on the southwest coast of Sicily, where a bore propagating upstream has been observed during extreme meteotsunami events (Colucci and Michelato 1976; Candela et al. 1999). It appears that the bore was driven by incoming meteotsunami waves which, due to the shallow and narrowing waterway and its relatively wide V-shaped mouth, met conditions that enabled the bore to form a half kilometre upstream of the mouth (Šepić et al. 2018a, Fig. 11). There, the bore may rise to a metre or more and propagate upstream a few kilometres, damaging small and fishing boats along its way. It should be emphasized that the incoming open ocean waves are additionally amplified by the Mazara del Vallo harbour, before entering the river at the top of the harbour.

In addition to harbour resonance, meteotsunami waves have been found to be affected by coastal topography in different ways. Off the southwestern Sicily, a few kilometres wide channel that separates the inner (coastal) and outer (open sea) shelf may affect the meteotsunami waves that arrive at Mazara del Vallo (Šepić et al. 2018a). Off Ciutadella, a shoaling affects the amplification of the incoming meteotsunami waves, by more than 4 times over just a few kilometres (Vilibić et al. 2008; Fig. 12). Similar amplifications occur in other coastal regions off meteotsunami hot spots (e.g., Vela Luka, Orlić et al. 2010; Šepić et al. 2016b), yet these effects have not been quantified by numerical modelling exercises. When meteotsunami waves last for several hours and occur over hundreds of kilometres, as occurred during the Odessa 2014 meteotsunami, the waves may be channelized by underwater canyons and propagate as rays towards the exact beaches impacted by waves (Šepić et al. 2018b). Such propagation characteristics further resembles the similarities between propagation of meteotsunami and tsunami waves, which are known to be directed by underwater ridges and canyons (Okal and Synolakis 2008; Iglesias et al. 2014).

A better knowledge of the role of coastal amplification of meteotsunami may be obtained by separating the effects of the forcing mechanism from those of the coastal amplification in the energy spectra observed at coastal locations. A pioneering study was carried out by Monserrat et al. (1998), who modified the existing algorithm to separate the source and topography previously used for seismic tsunamis by Rabinovich (1997). For a given event, those similarities observed at different but nearby locations should be related to the forcing and differences due to the coastal amplification. However, for different events measured at a given location, similarities should be related to the coastal amplification at this point and differences in the forcing. When they computed the spectral ratios (event/background) measured at different locations during the same event, the effect of the coastal amplification was removed and the ratios became very similar, elucidating the forcing characteristics for this event (Fig. 13). They also showed that by computing the forcing characteristics of different events and dividing by the observed atmospheric energy during each event, the energy contents should show how the atmospheric energy is transferred to the ocean. These spectral contents were very similar, suggesting that the atmospheric energy during different meteotsunami events was transferred into the ocean in a similar manner (Fig. 13c). These similarities have been used to analyse oscillations at Ciutadella and Cala Ratjada (Menorca Island) where oscillations normally occur first, indicating that sea level measurements at Cala Ratjada could be used to forecast destructive events in Ciutadella (Marcos et al. 2009).

4.3. Teleconnections between different regions in the Mediterranean

Meteotsunamis are normally local phenomena, associated with several specific mesoscale features that rapidly change in time and space, affecting a few nearby locations. However, these mesoscale features are always linked to several specific atmospheric synoptic pattern which may affect large regions and/or last long enough to travel large distances. This implies that meteotsunami events may be simultaneously observed in different sites located relatively far away as the synoptic situation favourable to their generation affect a large area or if the synoptic pattern evolves and travels long distances.

These teleconnections between meteotsunamis observed in distant regions were first suggested by Šepić et al. (2009a) for the Mediterranean Sea. By analysing a set of 32 events reported in the Balearic Islands for the period 1975-1998, the authors found that a significant number (approximately 50%) were also observed, in a 48-h time window, in the Adriatic Sea. When concurrent or subsequent meteotsunamis were observed in both regions, the events were always associated with a specific synoptic pattern, which either simultaneously affected both areas or propagated from one region to the other.

These teleconnections became even more apparent after analysing the 23-27 June 2014 meteotsunamis, during which an atmospheric synoptic pattern propagated eastward over the Mediterranean and generated a chain of destructive meteotsunami events that affected several countries from Spain to Ukraine (Fig. 14, Šepić et al. 2015a). The synoptic conditions favourable to the generation of meteotsunamis, as described in the previous section, were first observed over the Balearic Islands on 23 June, then propagated to the east, over the Adriatic and Tyrrhenian seas (25-26 June) and finally reached the Black Sea on 27 June. The greatest sea level oscillations were observed in each region at the time of the most intense atmospheric instability and when a completely developed mid-troposphere jet stream was located over the given area.

This reported chain of events revealed that meteotsunamis should not be only considered as local phenomena but as a potentially dangerous regional risk that can affect large areas, within distances of thousands of kilometres.

5. Meteotsunami monitoring and forecasting systems

Meteotsunami detection systems rely on four different components used either separately or in combination (Vilibić et al. 2016): (i) identification of tsunamigenic atmospheric synoptic conditions, (ii) real-time high-frequency air pressure and sea level measurements, (iii) high-resolution atmospheric and ocean deterministic forecast, and (iv) stochastic meteotsunami hazard assessments. Due to their cost, these systems are evolving with the available technology and are still underdeveloped in the Mediterranean Sea where the meteotsunami hazard is often overlooked by coastal managers. In fact, at this time, only two research products have been fully tested and published: the Balearic RIssaga Forecasting System (BRIFS; Renault et al. 2011) and the Adriatic Sea and Coast (AdriSC) system (Denamiel et al. 2019a 2019b) (Fig. 15).

5.1. Observational networks

In the Balearic Islands, 1-min real-time sea level and air pressure records are available at 6 tide gauge locations (Andratx, Colonia de Sant Pere, Pollensa, Porto Cristo, Sa Rapita and Sant Antoni) and 20 air pressure sensor locations operated by SOCIB (Balearic Islands Coastal Observing and Forecasting system) and are displayed at http://www.socib.es/index.php?seccion=observingFacilities&facility=mooring (Fig. 15, Tintoré et al. 2013, Heslop et al. 2019). Based on these Balearic tide gauge measurements, a detection algorithm analysing intermittent sea level oscillations and identifying meteotsunami events - via wavelet analysis and more precisely averaged power spectral densities - was developed by André et al. (2013).

In the Adriatic Sea, a pilot microbarograph network of three air pressure sensors with a sampling rate of 1 min, used for real-time detection of intense air pressure disturbances, was first developed by Šepić and Vilibić (2011). Within this system, the air pressure rate of change is determined every 5-min and, when a meteotsunamigenic disturbance is identified, its intensity, period, speed and direction of propagation are automatically calculated. Similar to the procedure developed by Tinti et al. (2012) for seismic tsunamis, the parameters measured are then compared with the meteotsunami warning matrix estimated from historical events. The Adriatic microbarograph network was extended in 2017 to the whole middle Adriatic region by the MESSI project ("Meteotsunamis, destructive long ocean waves in the tsunami frequency band: from observations and simulations towards a warning system", http://www.izor.hr/messi). Presently, the network encompasses nine air pressure sensors located in (1) the eastern Adriatic meteotsunami hot spots of Vela Luka, Stari Grad, and Vrboska, (2) the middle Adriatic islands of Vis, Svetac and Palagruža, to quantify the spatial changes in atmospheric disturbances over the regions in which resonance is expected to occur, and (3) Ancona, Ortona, and Vieste, located on the Italian coast, providing the parameters needed for the early warning system at coastlines where the atmospheric disturbance is expected to occur over the Adriatic Sea. The network also includes three tide gauges located in Vela Luka, Stari Grad and Sobra (Fig. 15). In addition to being used for meteotsunami detection, these measurements are also invaluable for the evaluation of the modelling tools used in the Adriatic Sea (Denamiel et al. 2019a 2019b).

In addition, the meteotsunami community has been collaterally benefiting from large investments made in a real-time 1-min sea level worldwide network developed for tsunami research and managed by the Intergovernmental Oceanographic Commission (IOC, http://www.ioc-sealevelmonitoring.org/map.php). In the Mediterranean and Black Seas, this network encompasses more than 120 stations operational in real-time or near-real-time, principally used to support verification of new tsunami forecasts (Angove et al. 2019); however, this network still has an insufficient spatial coverage to properly identify meteotsunamis with scales of a few tens of kilometres or less (Vilibić et al. 2016).

5.2. Deterministic modelling tools

Both meteotsunami detection systems developed in the Mediterranean Sea are based on the same state-of-the-art numerical models: the Weather Research and Forecasting model (WRF, Skamarock et al. 2005) for the atmosphere and the Regional Ocean Modelling System (ROMS, Shchepetkin and McWilliams 2005 2009) for the ocean, although the modelling strategy implemented in each is quite different.

In BRIFS (Renault et al. 2011), the WRF and ROMS models are coupled off-line, which means that the two grids of the WRF model, which cover the Western Mediterranean basin with a resolution of 20-km and the area around the Balearic Islands with a 4-km resolution, are run for a 12-h spin-up and 24-h forecast period (as described in Fig. 15). Then, the 2-min sea level pressure is extracted from the WRF 4-km results and used to force the two ROMS grids for the 24-h forecast period, covering the Balearic Islands with a resolution of 1 km and the Ciutadella harbour with a resolution of 10 m. The WRF model is set up with 97 vertical levels, refined near the surface to properly resolve the inversion layer associated with *rissaga*, and initialized/forced at the boundaries with the FNL/GFS analysis/forecast from the National Centers for Environmental Prediction (NCEP). The ROMS model, however, is not forced by any density stratification at the boundaries.

In the AdriSC system (Denamiel et al. 2019a), the WRF and ROMS models are coupled on-line every minute within the Coupled Ocean-Atmosphere-Wave-Sediment-Transport (COAWST) modelling system developed by Warner et al. (2010). The WRF domains over the central Mediterranean basin have a resolution of 15 km while those over the entire Adriatic and Ionian Seas have a 3 km resolution. The ROMS domains also cover the Adriatic and Ionian Sea with a 3 km resolution and the Adriatic Sea with a 1 km resolution. Terrain-following coordinates are used for vertical discretization in both ocean and atmosphere models, containing 58 vertical levels in WRF refined in the surface layer (Laprise 1992) and 35 vertical levels in ROMS refined near both the sea surface and bottom floor for the ocean (Shchepetkin and McWilliams 2009). The initial state and boundary conditions are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) Atmospheric Model high resolution 10-day forecast (HRES – Lalaurette 2002; Petroliagis and Pinson 2012; Zsótér 2006; Zsótér et al. 2014) and the Mediterranean Forecasting System (MFS) high resolution 10-day MEDSEA forecast (Pinardi et al. 2003; Pinardi and Coppini 2010; Tonani et al. 2014).

In addition to the COAWST model which is run for a 48-h spin-up and 24-h forecast period, an even more refined WRF domain covering the Adriatic Sea with a 1.5-km resolution is coupled off-line with the unstructured ADvanced CIRCulation ocean model (ADCIRC, Luettich et al. 1991) for a 12-h spin-up and 24-h forecast period covering the last 36-h of the COAWST model run (as described in Fig. 15). The ADCIRC mesh is specifically designed to provide extreme sea level hazard assessments in Croatia, covering the entire Adriatic Sea with a minimum resolution of 100 m along the Croatian coastline and up to 10 m in the harbours of interest (e.g., Vela Luka, Stari Grad, Vrboska, etc.). The ADCIRC model is forced with 1-min high-resolution air pressure and wind stress.

In terms of modelling strategy inter-comparison, BRIFS, which is less computationally expensive, is most probably faster but only provides next day forecasts with atmospheric forcing at a 4-km resolution. This resolution is known to be too coarse to properly represent meteotsunamigenic disturbances in the Mediterranean Sea (Horvath et al. 2018). The AdriSC system can be used to detect air pressure disturbances at 1.5-km resolution at least 30-h in advance. In addition, as the WRF wind fields are also used to force the ocean models (ROMS and ADCIRC), the AdriSC system, which includes a wave component, can forecast atmospherically driven extreme sea level events other than meteotsunamis. However, due to the lack of computational resources and the numerical cost of the modelling suite, the AdriSC system is currently not operational, while BRIFS has run without interruption over the last decade in the Balearic Islands.

5.3. Stochastic hazard assessment

Due to the challenges posed by deterministic forecasting of the meteotsunamigenic atmospheric disturbances in the Mediterranean Sea, it is of prime importance to assess how sensitive meteotsunami hazards are to their direction, intensity, period and speed at hot spot locations. In the Balearic Islands, several sensitivity studies have assessed the meteotsunami hazards in Ciutadella (Marcos et al. 2003; Vilibić et al. 2008; Orfila et al. 2011) for individual events. Ličer et al. (2017) generalized this approach and used 160 numerically generated synthetic atmospheric gravity waves to stochastically investigate the meteotsunami amplification and propagation inside and outside Ciutadella harbour. The study followed previously documented conclusions and found that, given the shape of the Balearic bathymetry, a wide range of gravity wave speeds (between 23 and 36 m/s) and angles of propagation (between 210° and 250°) can lead to substantial meteotsunami amplification (Fig. 16). Furthermore, they found that amplification mainly occurs in the Menorca Channel (described as a focusing lens). The findings of this study thus demonstrate the difficulty in providing timely meteotsunami warning in Ciutadella when the pressure disturbances are locally generated in the Menorca Channel.

In the Adriatic Sea, a similar approach was used by Orlić et al. (2010) and Šepić et al. (2016b), who based sensitivity studies on simplified synthetic disturbances following observations from the 1978 Vela Luka and the 2014 middle Adriatic meteotsunamis, respectively. They found a disturbance speed of 28-36 m/s, which depended on the meteotsunami hot spot affected, i.e., Vela Luka Bay, Stari Grad Bay and Rijeka dubrovačka Bay, and the propagation direction of the disturbance. For the latter, the disturbances that generate the maximum meteotsunami waves were found to travel from 200-240°, 260-300° and 260-290° for Vela Luka, Stari Grad and Rijeka dubrovačka, respectively. For the northern Adriatic meteotsunami sites at Široka Bay (Ist Island) and Mali Lošinj Bay, the greatest resonant transfer of energy towards the sea is reached at smaller propagation velocities due to the decreasing ocean depth encountered towards the northwest (Šepić et al. 2015b). As the ocean is quasi-flat in the northern Adriatic, this sensitivity study suggests that the Proudman resonance is the dominant resonance mechanism in that location.

With the same approach, Šepić et al. (2018b) showed that the most efficient generation of meteotsunami waves during the 2014 Odessa meteotsunami occurred on the shelf break, where the disturbance travelled in parallel to the shelf break, while the meteotsunami waves generated were topographically directed towards the north and the affected beaches.

Denamiel et al. (2018) improved the methodology and assessed the impact of geomorphological changes (i.e., deepening of the bay, dredging the harbour, removing an island, adding a pier or a marina) to the Vela Luka harbour resonance during all potential meteotsunami events. The meteotsunami impacts were assessed for a set of 6401 synthetic air pressure fields used to derive robust statistics. In contradiction to the values obtained with the traditional quality factor derived from the peak frequency of the sea level spectrum, the most substantial increase in meteotsunami amplification was obtained when the Vela Luka harbour was dredged to 5 m depth. New values of the quality and amplification factors were thus re-calculated by integrating the forcing energy content over the full frequency range and were found to be in good agreement with the results of the statistical analysis in Vela Luka Bay (Fig. 17).

Finally, in the Adriatic Sea, a meteotsunami surrogate model based on the generalized Polynomial Chaos Expansion (gPCE; Soize and Ghanem 2004; Xiu and Karniadakis 2002) was developed by Denamiel et al. (2019b 2020). The model uses polynomial expansions to project the probability distribution of the maximum meteotsunami elevation and estimates the meteotsunami maximum elevation distributions at meteotsunami hot spots by propagating the uncertainty in the atmospheric forcing to ocean simulations. With this approach, the sensitivity to the atmospheric disturbance parameters (start location, direction, speed, period, amplitude, and width of the disturbance) may be quantified. The surrogate model, which can use either deterministic forecast results or measurements from air pressure sensors as input parameters, is designed to assess the potential hazard of any meteotsunami event in the middle Adriatic region in only a few minutes (practically at no computational cost) and for a large number of samples. In addition, the gPCE formulation allows for the analytical computation of Sobol' indices (Sobol' 2001; Saltelli et al. 2008; Sudret 2008) used to systematically derive, in the Adriatic Sea, the meteotsunami sensitivity to the six chosen stochastic parameters of the atmospheric disturbance without any additional computations. Not surprisingly, this sensitivity analysis revealed that, for all hot spot locations in the Adriatic Sea, the speed or the period of the atmospheric disturbance is the most critical parameter for meteotsunami harbour amplification, while the effects of the amplitude are of secondary importance.

While stochastic approaches have only been recently successfully implemented in the Balearic and Adriatic regions, they certainly provide important insights concerning meteotsunami amplification linked to atmospheric forcing. This approach must be further developed in both theoretical and operational studies to compensate for the lack of accuracy in the deterministic atmospheric models and to better quantify the uncertainty associated with meteotsunami forecasting.

5.4. Meteotsunami early warning systems

As fully preventing meteotsunami impacts is, for now, close to impossible (Vilibić et al. 2016), the principal goal of meteotsunami early warning systems is to enable the local communities to better prepare for these destructive events (e.g., set up temporary protections against flooding and waves, avoid swimming, etc.) to minimize losses. Such a warning system can be based on different observational and modelling tools: (i) meteotsunamigenic synoptic patterns, (ii) in situ high-frequency observations, and (iii) deterministic and/or stochastic numerical modelling, or a combination of these (Šepić et al.

2017). For the Balearic Islands, the “rissaga warning” is operational up to two days before potential meteotsunamis; however, it is based on qualitative (by a human eye) assessment of forecasted operational synoptic patterns (Jansà et al. 2007). The warning system has been found to fairly forecast moderate meteotsunami events (75-150 cm of wave height in Ciutadella), with a correct forecast in approximately 75% of such events between 2003 and 2006 (Jansà and Ramis 2020). Still, the strongest meteotsunamis (>150 cm of wave height in Ciutadella) are mostly underestimated (in 85% of cases), indicating the existence of specific atmospheric conditions not attainable from synoptic patterns.

The quantification of the connections between synoptic patterns and multi-year sea level observations was also improved by Šepić et al. (2016a) with the definition of the so-called synoptic meteotsunami index (Section 4.1.1), which can also be used to assess meteotsunami changes in the future climate. The latter has been conducted by Vilibić et al. (2018b), who found that meteotsunami occurrences will increase by 1/3 in Ciutadella for the RCP8.5 scenario during the 2071-2100 period. Until now, no such operative tool was developed in other Mediterranean basins - e.g., the Adriatic Sea - although favourable meteotsunamigenic synoptic conditions have been documented. In addition, despite the known propagation of meteotsunamigenic synoptic patterns from the Western to the Eastern Mediterranean and the Black Sea, a large scale meteotsunami early warning based on synoptic conditions has not been developed.

Romero et al. (2019) modified the modelling approach in an meteotsunami early warning system to reproduce key atmospheric and ocean processes, such as (i) the generation of high amplitude atmospheric gravity waves upstream from the Balearic Islands and travelling in the SW–NE direction; (ii) the oceanic response to the respective pressure fluctuations along the Menorca channel; (iii) shelf amplification, which doubles the wave amplitude; and (iv) the harbour resonance within Ciutadella inlet. They tested the simplified warning system on 126 meteotsunamis between 1981 and 2018 and found the best performance for weak meteotsunamis (<20 cm of wave height in Ciutadella), while for intense (100-200 cm of wave height in Ciutadella) and extreme (>200 cm of wave height in Ciutadella) meteotsunamis the proper reproduction (in the same intensity category) was achieved for 43 and 33% of meteotsunamis, respectively.

However, an advanced prototype of a meteotsunami early warning system (Fig. 18) was developed and successfully evaluated in the Adriatic Sea (Šepić et al. 2017, Denamiel et al. 2019b), but it is unfortunately not operational due to a lack of computational resources. This early warning system receives two different type of data: high-resolution atmospheric and ocean model results provided by the AdriSC system and 1-min measurements from the MESSI observational network. Both are used as input to the meteotsunami stochastic surrogate model (presented in Section 5.3) to provide extreme sea level hazard assessment at hot spot locations along the Croatian coastline. In the daily operational mode (Fig. 18), the high-pass filtered sea level pressure is automatically extracted from the WRF 1.5-km results at least 24 h before any potential meteotsunami event. If a pressure disturbance is detected, the meteotsunami maximum elevation distributions (i.e., the probability of the expected maximum elevation) are computed at different locations of interest by the stochastic surrogate model. The maximum elevation probability distributions are revised 2 h before the forecasted meteotsunami event, by analysing the 1-min air pressure measurements from Ancona, Ortona, Vieste, Svetac, and Vis, and imposing the extracted disturbance parameters as constant input values in the model. The final meteotsunami warning is then ready to be published and accessible to users. This system was tested on five meteotsunami events that occurred between 2014 and 2018 and yielded a fair forecast but overestimated several episodes (Denamiel et al. 2019b).

6. Research gaps and emerging research topics

As presented in this review, meteotsunami research has a long tradition in the Mediterranean and Black Seas, where extreme events strongly impact shores, cities and coastal infrastructures. However, in the last decade, it has substantially developed all over the world due to the net increase in available high-frequency sea level and meteorological observations. Observational networks have indeed expanded globally (e.g., IOC Sea Level Station Monitoring Facility network (http://www.ioc-sealevelmonitoring.org/) or regionally (e.g., NOAA Tides and Currents, https://tidesandcurrents.noaa.gov), enabling for mapping of high-frequency sea level oscillations and meteotsunamis in all continents (Rabinovich 2020). In recent years, a great number of meteotsunami studies have been carried out around the world based on observations, modelling and analysis of source processes and in relation to geographical location and local processes (Pellikka et al. 2014; Linares et al. 2016 2019; Sheremet et al. 2016; Olabarrieta et al. 2017; Dusek et al. 2019; Kim et al. 2019; Williams et al. 2019; Heidarzadeh et al. 2020; Shi et al. 2019 2020), which can produce meteotsunamis of different origins than those in the Mediterranean (e.g., frontal zones, hurricanes).

The idea of this chapter is to present research gaps and ideas for future research considering specific Mediterranean and Black Sea meteotsunami issues, but that are also relevant to global meteotsunami research in addition to regional considerations. We classified these ideas into two major categories: (i) improvement of research tools and (ii) meteotsunami research topics themselves:

A. Tools for meteotsunami research

A.1. Extension of high-frequency sea level observations over the whole basin. To properly quantify spatial properties of high-frequency oscillations, the extension of available sea level networks over the entire Mediterranean and Black Sea shores is necessary. Presently, most of these stations are located along the northern shores of the Mediterranean, while the Black Sea and the North Africa coastlines are sparsely populated with high-frequency sea level observations. A unification of such a network (e.g., through a regional Global Ocean Observing System, MonGOOS, www.mongoos.eu) might be adequate to tackle eventual political or funding problems that generally prevent such developments.

A.2. Extension of conjoint high-frequency sea level and meteorological observations. The current standard in meteorological measurements, temporal resolutions of 10 min to 1 h, is not appropriate for observations of meteotsunamigenic disturbances. Presently, only the SOCIB and MESSI networks have a potentially appropriate spatial resolution for meteotsunami research in the Mediterranean region. Efforts to upgrade existing networks (e.g., those presented in the IOC Sea Level Station Monitoring Facility network) and influence national meteorological services to distribute data with at least 1-min resolution should be undertaken. As the technology is mostly ready at actual measuring stations, this should not require large investments.

A.3. Improvement and better usage of amateur meteorological networks and citizen science. Aside from official and standardized meteorological observations, many amateur meteorological networks (e.g., Crometeo in the eastern Adriatic Sea, www.pljusak.com, or global Wunderground network, https://www.wunderground.com, also active in the Mediterranean and Black Seas, or Balearsmeteo in the Balearic Islands, http://balearsmeteo.com) can be used by the research community. These networks do not follow all official meteorological standards and might not be properly calibrated, yet they may provide extremely valuable information on high-frequency air pressure and wind data (e.g., Šepić et al. 2016b) with very good spatial resolution. In addition, school meteorological networks might also be used in research, for example, the School-Based Weather Station Network on the Vancouver Island (http://www.islandweather.ca, Rabinovich et al. 2020). Thus, extending and improving such networks through a citizen science approach (Garcia-Soto et al. 2017) would probably help in quantification of spatial and temporal properties of meteotsunamigenic disturbances.

A.4. Development and installation of state-of-the-art observing platforms adapted to meteotsunami research. As measuring both meteotsunami waves and meteotsunamigenic disturbances requires quite different standards than the ones used by the current observational networks, standards used in new platforms should be adapted to the meteotsunami research. As an example, high-frequency radars, when used in burst mode (Lipa et al. 2014), have been found to be useful for detecting meteotsunami waves off the Mediterranean and Black Sea coastlines (Roarty et al. 2019). At hot spot locations, the automatic extraction of the speed, propagation direction and intensity of meteotsunamigenic disturbances can be developed from well calibrated and verified high-frequency weather radar observations (e.g., following the concept developed for minute weather forecast by AccuWeather; https://www.accuweather.com/en/press/49568860). In addition, the future advancement in technology may also allow for the development of efficient and cheap solutions (e.g., Marques et al. 2019), such as self-communicating autonomous networks of sensors measuring meteorological parameters at high frequencies.

A.5. Availability of precise coastal bathymetry at meteotsunami hot spot locations. As is used for other ocean processes, proper bathymetry at high resolution is necessary to accurately reproduce meteotsunamis in numerical studies. This particularly applies to all Mediterranean and Black Sea hot spots, for which only old charts are available and where a small change in bathymetry may multiply or reduce the estimated meteotsunami wave heights (e.g., Denamiel et al. 2018). Thus, meteotsunami hot spots such as Vela Luka, Ciutadella and other locations should have priority for hydrographic surveys performed with modern mapping technologies (e.g., lidar, Brock and Purkis 2009).

A.6. Development of ocean models with high-resolution bathymetry. Recent studies show that processes occurring nearshore, such as rip currents, may be associated with meteotsunamis. In addition, meteotsunami models still rarely consider coastal flooding effects on the amplification and run-up of meteotsunami waves. To numerically capture such processes, a few metres horizontal resolution is necessary (Linares et al. 2019). Similarly, for complex topography such as in the Mediterranean, models with unstructured grids with down to a metre resolution in the coastal regions (both in sea and at land) are necessary to properly quantify the bathymetric effects on the development and amplification of meteotsunami waves (e.g., Vilibić et al. 2008; Denamiel et al. 2018). For the open sea, the bathymetry should also be of high enough resolution to reproduce scattering of meteotsunami waves, particularly in regions with a complex and changeable bathymetry.

A.7. Development of ultra-high-resolution mesoscale atmospheric models reproducing meteotsunamigenic disturbances and processes. Even with the right set-up, ocean models may misrepresent meteotsunami waves due to the difficulty in properly reproducing meteotsunamigenic disturbances within mesoscale atmospheric models. Several bottlenecks that affect the reliability of mesoscale atmospheric simulations have been identified (e.g., Horvath and Vilibić 2014): proper initialisation, reliable lateral boundary conditions, choice of parameterizations as well as horizontal and vertical resolutions used in the models. As meteotsunamigenic disturbances occur at a kilometre spatial scale, the horizontal model resolution needed is a few hundreds of metres, since mesoscale atmospheric models underestimate processes at scales lower than 7 times the horizontal resolution (Skaramock, 2004). However, the physics of state-of-the-art atmospheric models may not be adaptable to run at these resolutions. Therefore, new approaches in mesoscale modelling should be developed, and tested specifically for meteotsunamis, in collaboration with leading atmospheric model developers (such as National Centres for Atmospheric Research, NCAR). This issue is foreseen as critical in proper deterministic reproduction of meteotsunamis, including the application of operational forecasting and early warning systems.

A.8. Availability of high-performance computing (HPC) facilities for ultra-high-resolution numerical modelling. Following issues raised in A.7, access to HPC facilities is a prerequisite to carry out such a research. For meteotsunami coupled atmosphere-ocean systems, the three dimensional atmospheric part requires the most computational resources and including ultra-high resolutions will increase demand by one to two orders of magnitude.

A.9. Development of stochastic methods in meteotsunami research. As noted above, deterministic reproduction of meteotsunamis and meteotsunamigenic disturbances are not reliable enough to be solely used in forecast and early warning systems. The recent attempts at applying stochastic methods in meteotsunami research are encouraging and have resulted in better assessments of meteotsunami hazards than the deterministic approaches, while demanding much less computational resources. Such approaches also allow for quantification of uncertainties of the meteotsunami forecast, for which deterministic models have no capacity (except if run as ensemble forecast, which would then be extremely costly in terms of numerical resources). In general, stochastic methods are not widely used in ocean research and their applications in meteotsunami research might thus be encouraging for wider hazard assessments of atmospherically driven extreme sea levels.

A.10. A framework for collaborations, research, operational issues and definition of standards in meteotsunami research. All the tools listed above could potentially improve meteotsunami research and would be developed much more efficiently within multidisciplinary collaborations encompassing research groups with expertise in all quoted issues using common resources. For example, a WRF model of 15-km resolution may be set-up for the entire Mediterranean and Black Seas and provide everyday hourly forecast results that could be downscaled (up to 1-km resolution) directly in hot spot areas. Further, the meteotsunami community should take advantage of the already developed tsunami infrastructures, which have teams of operators monitoring seismic activity 24/7 that could be trained to also monitor meteotsunamis. Such a collaborative effort is a priority to better use the limited resources allocated to research and to provide services (i.e., meteotsunami warning) to the society. The Mediterranean and Black Sea meteotsunami collaborations could be part of global formal collaborations, in addition to being dedicated to the specific issues in the region. The recently held First World Conference on Meteotsunamis (www.izor.hr/mts2019) established new collaborations and the enthusiasm should be used to progress in a direction of collaboration.

B. Meteotsunami research topics

B.1. Analysing basin-wide high-frequency sea level events, including their statistics, climatology and probabilistic recurrence functions. Once gaining multi-year or multi-decadal high-frequency sea level dataset, i.e., from the IOC Sea Level Station Monitoring Facility portal or through national networks (e.g., Croatian tide gauges are collecting sea level data with 1-min resolution since 2003), an objective mapping of meteotsunamis and high-frequency oscillations might be carried out, such as was documented for the U.S. East Coast (Dusek et al. 2019). This might also include different statistical aspects such as seasonality, outreach, connection with synoptic patterns, teleconnections, all of which have already been initially analysed in several studies (e.g., Šepić et al. 2009a; 2015c); additional studies could be based on more comprehensive datasets and generalized. For several sites with particularly long measurements, the return periods for meteotsunami events might even be estimated.

B.2. Quantifying relations between meteotsunamis and synoptic patterns. Although the link between meteotsunamis and synoptic patterns has been documented for several Mediterranean and Black Sea hot spots, the only study that quantifies these relations is for the Balearic Islands (Šepić et al. 2016b). Therefore, this approach may be extended to other hot spots to understand which patterns, if any, are relevant for meteotsunamis at those locations. If such a mapping provides reliable results at the basin level, this might be used for proxy-based assessment of meteotsunami characteristics, as atmospheric reanalysis fields cover longer periods than high-frequency sea level measurements.

B.3. Investigating wintertime Mediterranean and Black Sea meteotsunamis and other source mechanisms. Most of the investigated Mediterranean and Black Sea meteotsunamis, i.e., the most destructive events, occurred during warm part of the year, between April and October. However, moderate meteotsunami events may occur during wintertime and may be related to generation mechanisms different than those observed in summertime, i.e., to wind pulsations during storms or other, as high-frequency air pressure disturbance are of lower intensity in winter (Vilibić et al. 2014a). Furthermore, different generation mechanisms for meteotsunamis have been documented for events occurring in higher latitudes (de Jong and Battjes 2004; Wertman et al. 2014; Bechle et al. 2016), including the squall line of 1929 upon which Proudman developed his resonance theory (Proudman 1929). The existence of these additional generation mechanisms, other than wave-duct or wave-CISK, in the Mediterranean and Black Seas is worth investigating.

B.4. Importance of orography in generating meteotsunamigenic disturbances. One important question is to understand how significantly meteotsunamigenic disturbances are affected by high orography such as the Apennines and Alps located ca. 200-400 km from the meteotsunami hot spots in the Adriatic Sea (e.g., Belušić et al. 2007) or the Atlas Mountains (north Africa) close to the Balearic Islands. The quantification of the orography influence can be accessed via process-oriented numerical modelling studies that alter and/or remove the orography from the model and compare the physics of meteotsunamigenic disturbances reproduced with and without orography included.

B.5. Assessing meteotsunami potential in the future climate. Climate models are not capable to reproduce temporal and spatial scales of meteotsunamigenic disturbances; thus, they cannot be used for assessment of meteotsunamis in the future climate. However, there are indirect methods that might be used, such as using synoptic proxies (as done first for Ciutadella, Vilibić et al. 2018b) or using surrogate short-time simulations, where boundary conditions are changed to future climate scenarios by the so-called pseudo-global warming (PGW) methodology (Schär et al. 1996). The first method may be applied for meteotsunami hot spots where correlation is high between meteotsunamis and synoptic patterns, while the second approach is feasible for any meteotsunami hot sport, with reliability of results equivalent to the reliability of the regional climate model used.

B.6. Estimation of meteotsunami hazard and risk at hot spots. Meteotsunami hazard has been assessed for the Adriatic and Balearic sites (e.g., Vilibić et al. 2008; Orlić et al. 2010; Šepić et al. 2016a; Ličer et al. 2017; Denamiel et al. 2020), but not for other regions, such as southwestern Sicily coast and the Maltese Islands. Additionally, risk assessment has not been carried out for any of the Mediterranean and Black Sea hot spots, even for those which are known to regularly suffer from meteotsunami damage (Vučetić and Barčot, 2008; Vučetić et al. 2009). In addition, the risk to coastal infrastructure, goods, houses and other items is highly variable from one destructive meteotsunami event to the other. For example, in Vela Luka, which has become a highly touristic place in recent decades, the highest risk should be assessed by defining how much damage would be produced if an event similar to the meteotsunami of 21 June 1978 occurred today. This type of risk assessments should be developed at all locations where destructive meteotsunamis are known to occur.

B.7. Reducing meteotsunami hazard at hot spots. It is of highest importance to assess any interventions in coastal line and bathymetry at meteotsunami hot spots, as even small interventions and extensions may strongly change amplification characteristics and eigen oscillations of the bay or harbour (e.g., Marcos et al. 2005; Denamiel et al. 2018). Several solutions such as radial piers in a bay (Rabinovich 1992) may reduce the amplification factor and therefore the maximum wave height at the harbour head. However, such eventual interventions should be first assessed by targeted numerical modelling, as construction that narrows the entrance in a harbour or bay may even increase the amplification (Miles and Munk 1961; Rabinovich 2009).

B.8. Development and verification of meteotsunami early warning systems. Currently, only two meteotsunami early warning systems are available for the Mediterranean and Black Seas: in the middle Adriatic and the Balearic Islands. Simultaneously, the research is providing new and cost-effective methodologies that might be used to improve meteotsunami forecast, focusing exclusively on important meteotsunamigenic parameters (Romero et al. 2019). All these concepts might be used to improve the present meteotsunami early warning systems and their extension to other meteotsunami hot spots. Naturally, a catalogue of meteotsunami events or long-term high-frequency sea level measurements should be available at these sites first.

B.9. Assessing socio-economic aspects of meteotsunamis. The impact of meteotsunamis to coastal communities, including their reactions to the hazard, awareness of the hazards, development of societal services, mitigation and adaptation measures, at the level of the community as well as on the level of individuals, has not been researched in the

Mediterranean and Black seas. Such research could be carried out for all meteotsunami hot spots and then the societal parameters could be intercompared and used to improve the related societal services.

7. Concluding remarks

This review is the first attempt to present meteotsunami research in the Mediterranean and Black Seas, a region in which these extreme events have traditionally been studied over the last 40 years. All meteotsunami aspects are presented, including several of ideas for future developments that may help researchers not only in this region but also worldwide. In addition, an initial bibliographical review has been performed, which will hopefully be extended globally in more comprehensive future studies.

It should be emphasized here that observational networks are crucial in geosciences and should be further developed in the Mediterranean Sea to better understand, quantify and detect the hazards posed by meteotsunami events, which are likely to increase in frequency and intensity under climate change (Vilibić et al. 2018b). However, because of the cost of such systems (particularly the long-term cost of maintenance and repair) and the lack of funding dedicated to the sustainability of oceanographic observational networks, there is doubt about how research institutes will be able to maintain and further develop these networks. A way forward may be building up targeted networks with cheaper sensors, which will become available with future technological developments, while fulfilling the specific standard (resolution, precision, long-term stability) for measuring meteotsunamis. Aside from measurements, the growing application of numerical models at high resolutions in meteotsunami research is a great opportunity for model developments, which are generally based on finding new solutions to reproduce non-standard processes (i.e., processes at the edge of reproducibility). Hopefully, future development of meteotsunami tools and the research in the Mediterranean and Black Seas will follow these directions.

This review is intended primarily for oceanographers, atmospheric scientists and ocean engineers, but meteotsunami research is a comprehensive subject that requires much wider competences, i.e., of mathematicians, statisticians, coastal managers, economists, policy makers, and more. The societal benefits of this research should be properly acknowledged in the future, as a gap between research and societal needs still exists. We expect that this review will eventually help to better connect research with society.

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Figure 1. Locations (red circles) and photos of the most prominent meteotsunami events in the Mediterranean Sea: (a) the Balearic meteotsunami of the 21 June 1984 and (b) 15 June 2006, (c) the middle Adriatic meteotsunami of 21 June 1978, (d) the Mali Lošinj meteotsunami of 15 August 2008, (e) the Mazara del Vallo meteotsunami of 25 June 2014, and (f) the Odessa meteotsunami of 27 June 2014.

Figure 2. Announcement of public works provided by local authorities the day after the 21 June 1978 Vela Luka meteotsunami (reproduced from Vučetić and Barčot, 2008).

Figure 3. Ciutadella harbour view taken during the 21st June 1984 rissaga event (courtesy of Josep Gornes).

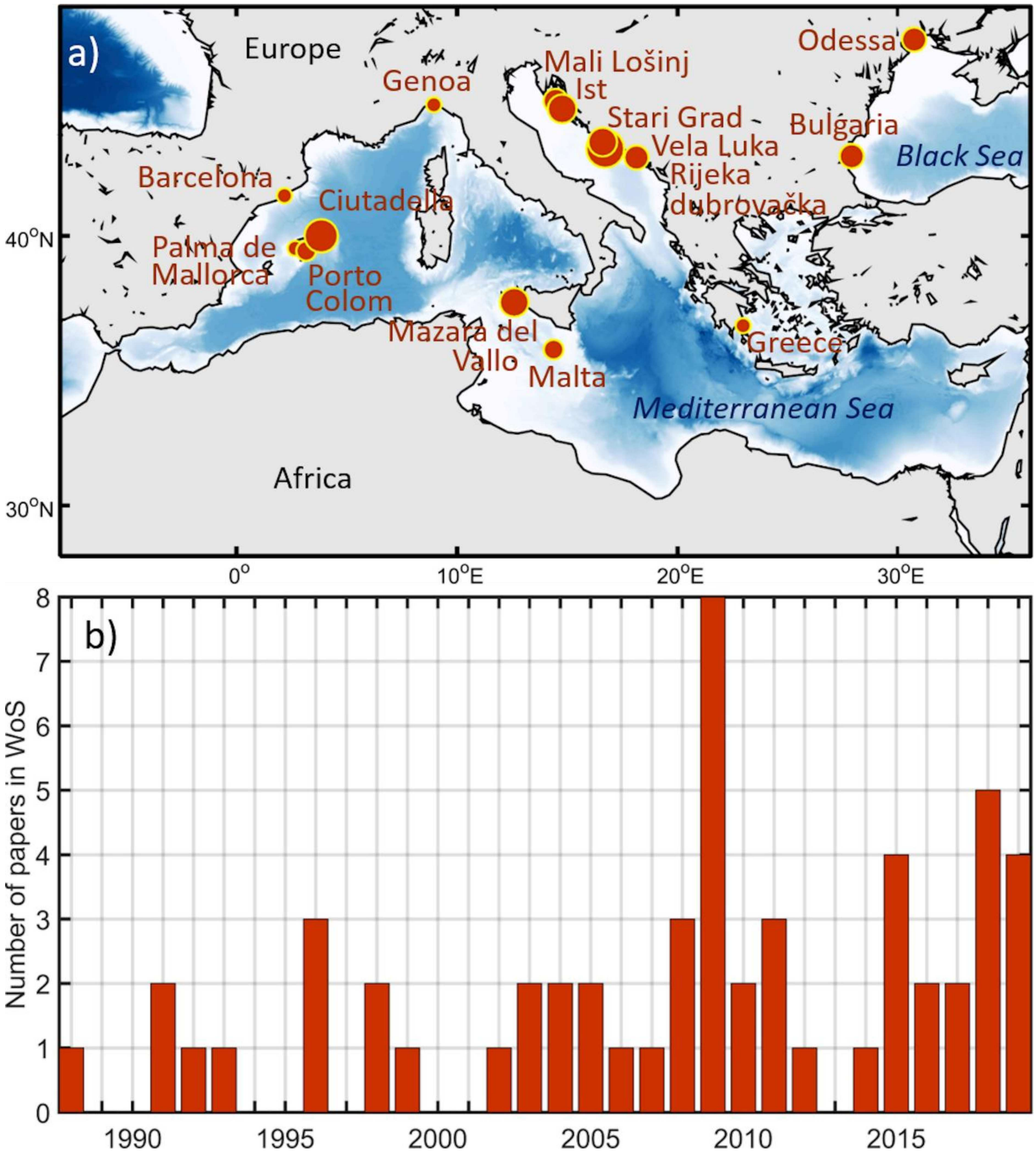

Figure 4. (a) Meteotsunami hot spots (red circles) in the Mediterranean and Black Sea as documented in the research literature; and (b) number of Mediterranean and Black Sea meteotsunami papers published in Web of Science per year. The size of the circle is proportional to the observed or eyewitnessed wave height.

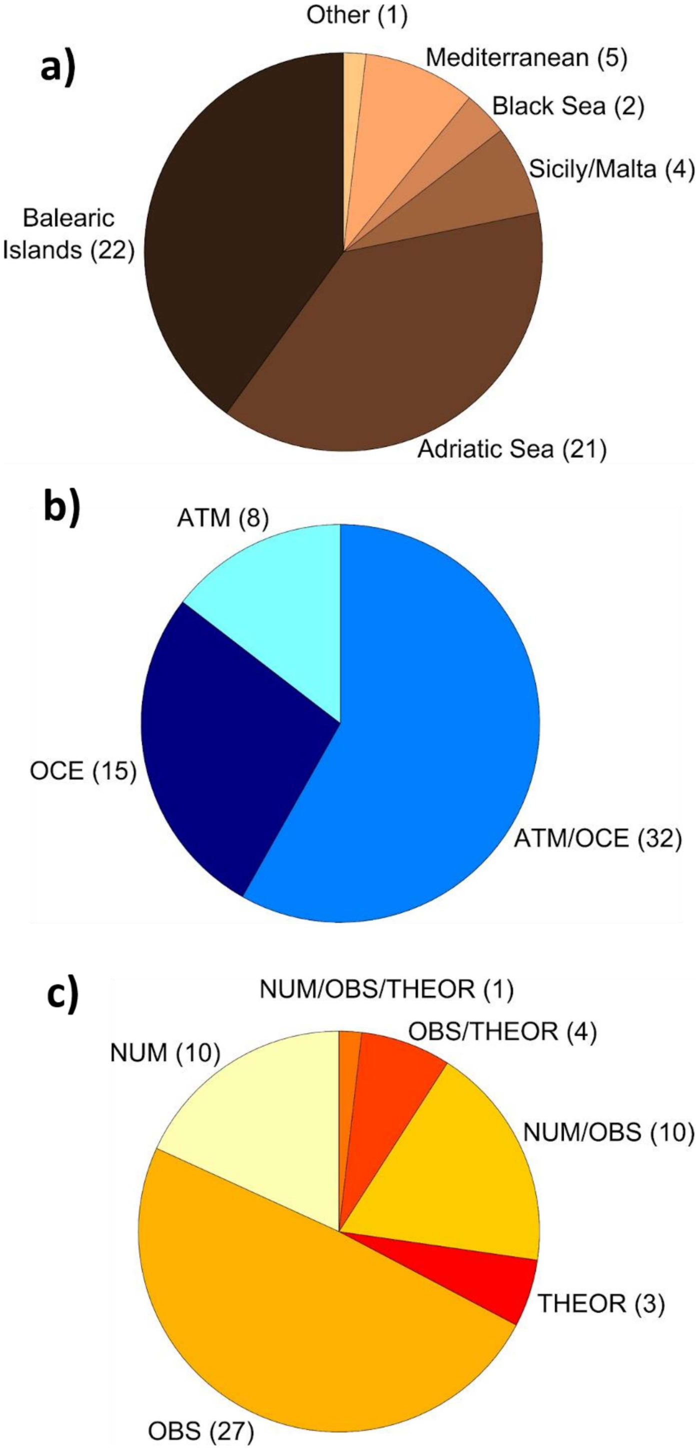

Figure 5. Number of meteotsunami papers published in Web of Science categorized by (a) region of interest (Mediterranean stands for papers examining at least two regions or the whole basin), (b) studied process – atmospheric (ATM), ocean (OCE) or ocean-atmosphere (ATM/OCE) and (c) type of investigation – observational (OBS), numerical modelling (NUM), analytical modelling (THEOR) or combinations (NUM/OBS/THEOR).

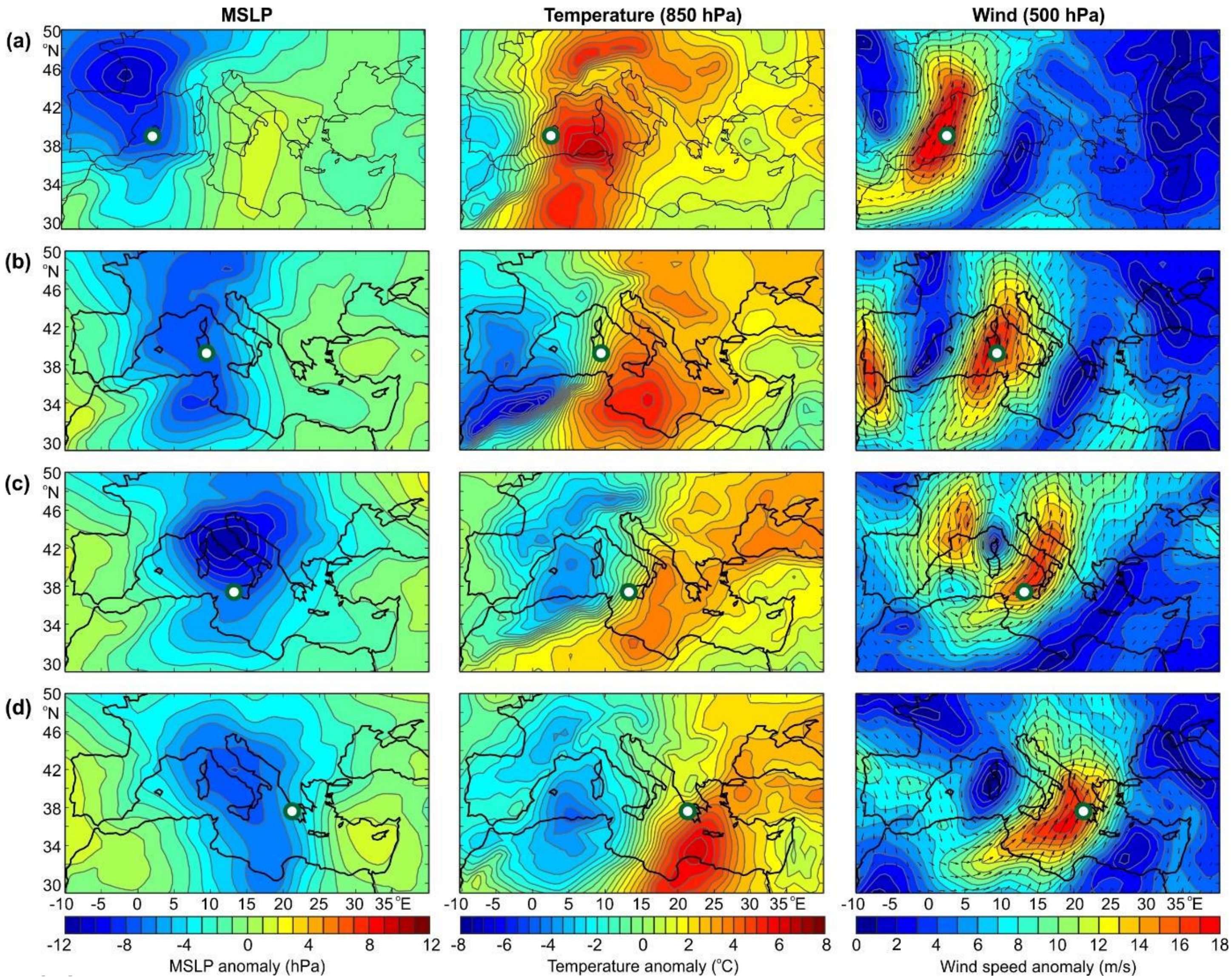

Figure 6. Common synoptic patterns conducive for the observed Mediterranean high-frequency sea level oscillations: mean sea level pressure (MSLP) anomaly, temperature at 850 hPa anomaly, and wind anomaly at 500 hPa averaged over selected events measured at (a) Palma de Mallorca, (b) Cagliari, (c) Porto Empedocle and (d) Katakolo tide gauge stations. Twelve high-frequency sea level oscillation events, 6 in each season (May–October, November–April), are selected per quoted station between 2008 and 2014, with the full info on events listed by Šepić et al. (2015c). The anomaly has been computed as the difference between the actual synoptic field and the climatological synoptic field for the month in which the event occurred. The figure is reproduced from Šepić et al. (2015c).

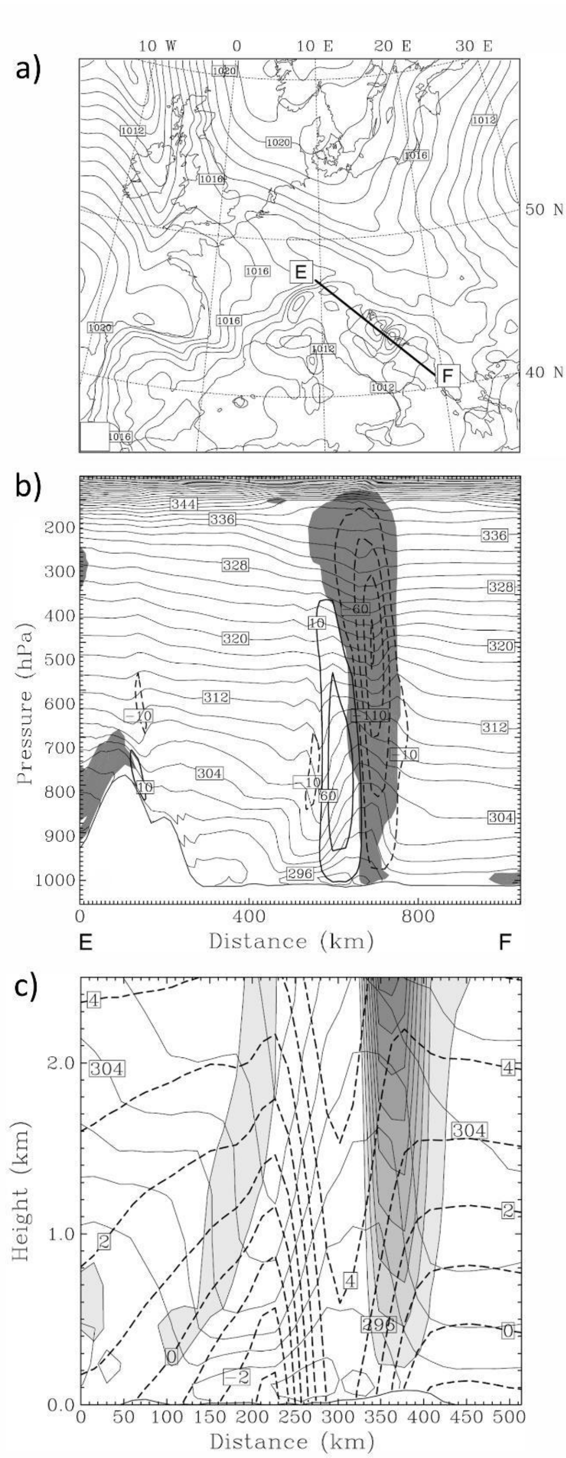

Figure 7. Results of the numerical modelling exercise in reproduction of the 2003 middle Adriatic meteotsunami event: (a) mean sea level pressure and (b) vertical cross-section of potential temperature, cloud water/ice mixing ratio (shaded above 0.005 g/kg) and vertical velocity (contours of 10, 60 and 110 dPa/s, negative values standing for updrafts and are dashed), and (c) zoomed potential temperature (solid lines, interval 2 K), pressure perturbation (dashed lines, interval 1 hPa), and vertical velocity (shaded above 5 cm/s, contour interval 10 cm/s), all on 27 June 2003 at 02 UTC. The figures are taken from Belušić et al. (2007).

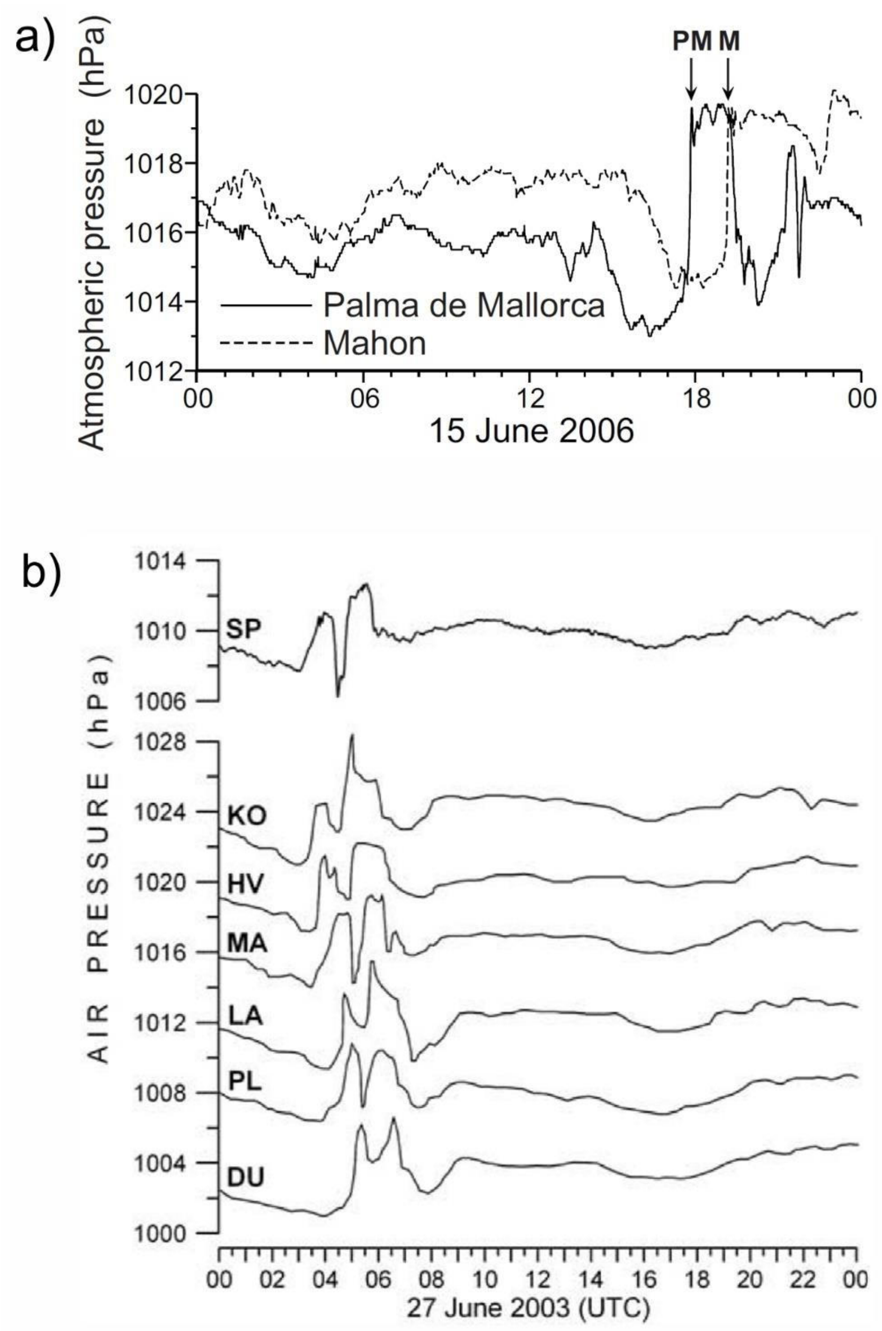

Figure 8. Air pressure series measured at microbarograph stations (a) during the 15 June 2006 Balearic meteotsunami (after Monserrat et al. 2006), and (b) during the 27 June 2003 Adriatic meteotsunami (after Vilibić et al. 2004). PM, M, SP, KO, HV, MA, LA, PL and DU stand for Palma de Mallorca, Mahon, Split, Komiža, Hvar, Makarska, Lastovo, Ploče and Dubrovnik, respectively.

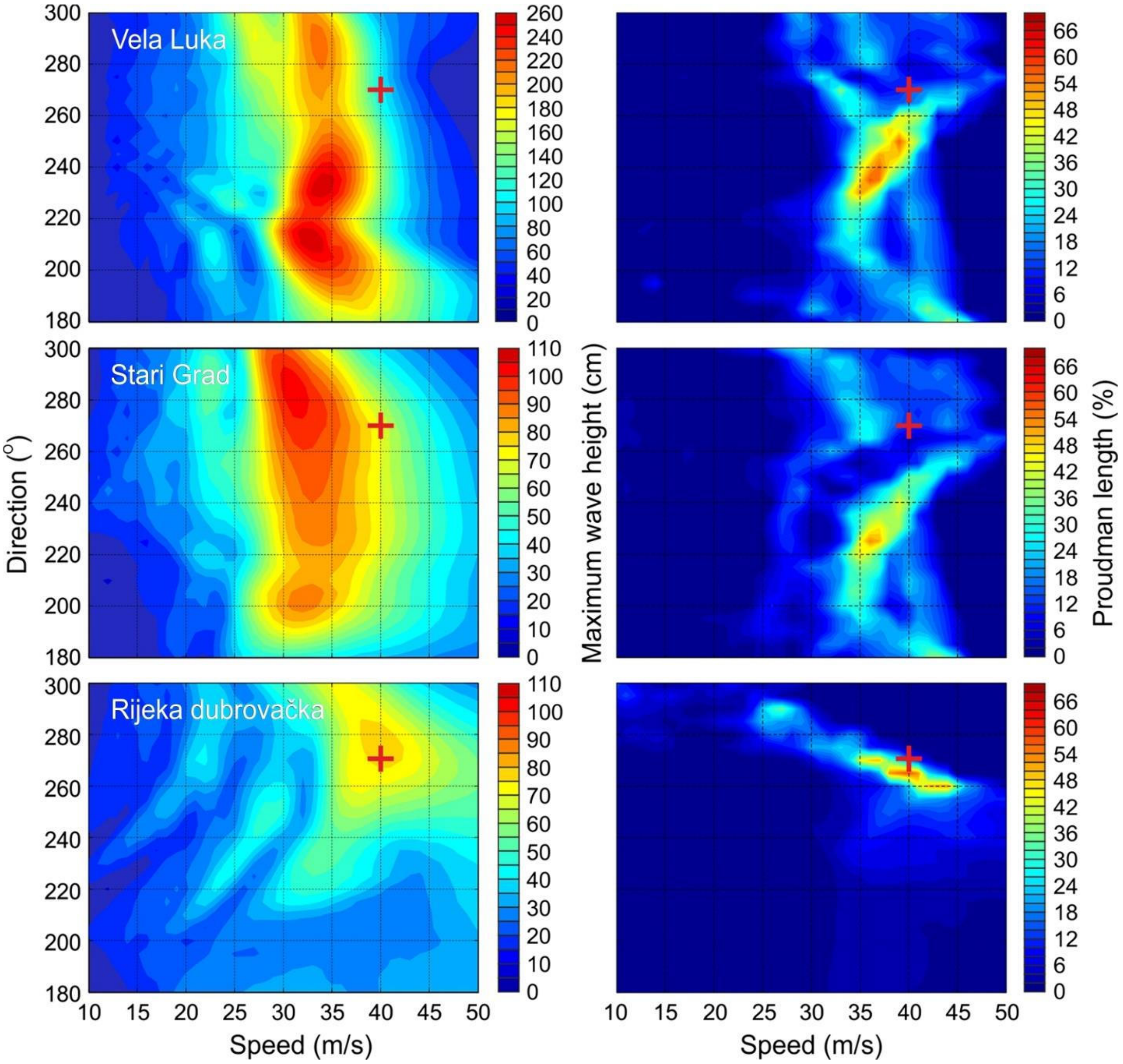

Figure 9. Sensitivity modelling study of the 25 June 2014 Adriatic meteotsunami: (a) maximum wave heights obtained for the tops of Vela Luka, Stari Grad and Rijeka dubrovačka bays for a set of experiments forced by a box-car air pressure disturbance. (b) Proudman length at the tops of Vela Luka, Stari Grad and Rijeka dubrovačka bays, defined as a percentage of total length over which a disturbance travelled, and for which $0.95<Fr<1.05$ is valid, where *Fr* is Froude number defined as ratio between the speed of atmospheric disturbance and long ocean waves. Red plus signs mark maximum wave height and Proudman length as obtained in experiment forced by a disturbance propagating with speed and direction estimated from measurements ($u = 40$ m/s, $c = 270^o$). The figure is reproduced from Šepić et al. (2016b).

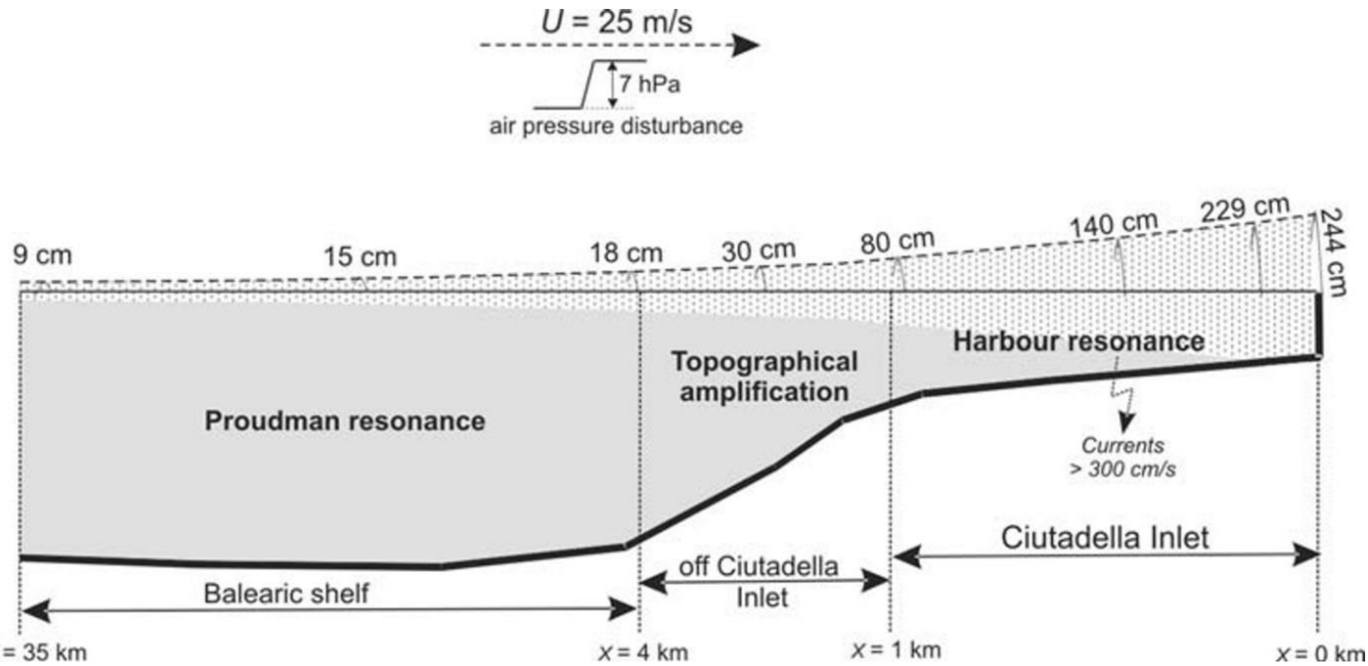

Figure 10. A sketch illustrating the physical mechanisms responsible for the formation of the destructive rissaga on 15 June 2006 in Ciutadella Harbour, Menorca Island (after Vilibić et al. 2008).

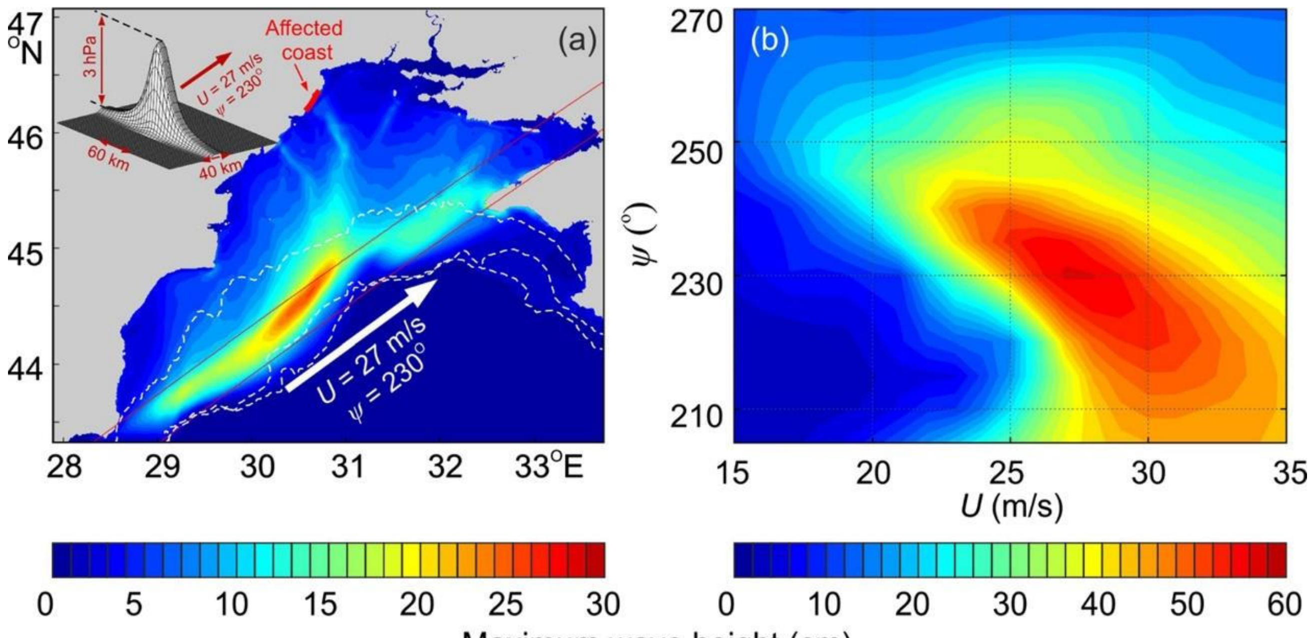

Figure 11. Topographical channelling of the meteotsunami waves: (a) maximum modelled wave height across western Black Sea model domain for experiment in which an air pressure disturbance propagates with a speed of 27 m/s and a direction of 230^o, and (b) maximum simulated wave heights at Odessa as function of speed, *U*, and direction, *ψ*, of the propagating air pressure disturbance (after Šepić et al. 2018a).

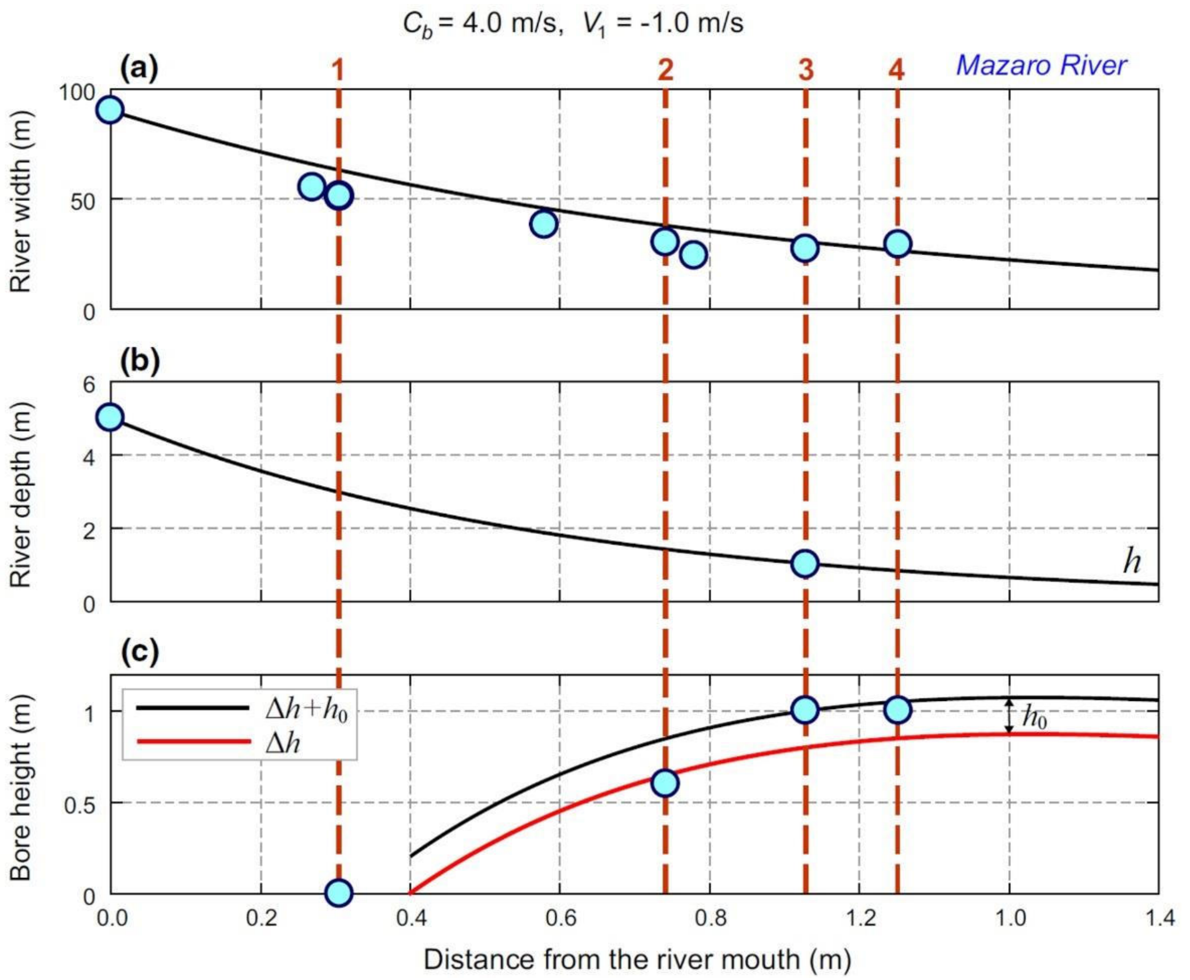

Figure 12. Approximate profiles of the Mazaro River (a) width and (b) depth; (c) estimated meteobore heights. Light blue circles denote data available on the river bathymetry and from video footages (the latter are indicated by vertical dashed red lines). Black and red solid lines indicate meteobore heights estimated by the model with and without incoming open-sea wave height (h_0), respectively (after Šepić et al. 2018b).

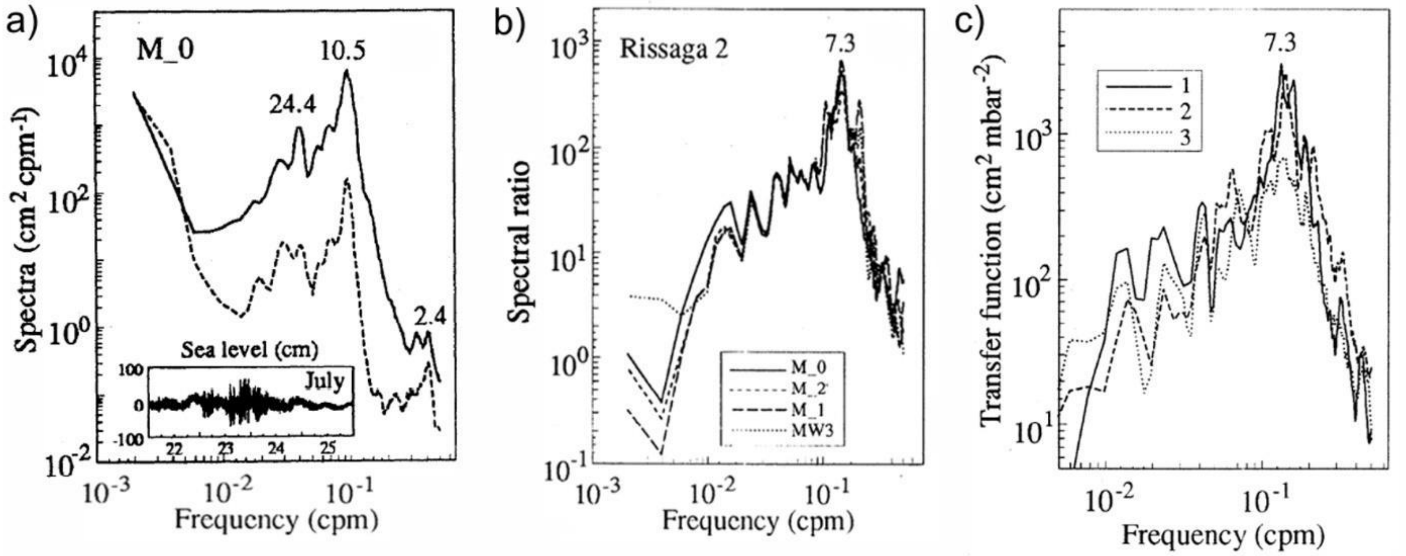

Figure 13. (a) Sea level spectra at Ciutadella (Menorca Island) computed during the meteotsunami of 22-25 July 1997 (solid line) and during a background period (dashed line), (b) event-vs-background spectral ratio for the same meteotsunami event computed at two points in Ciutadella (M_0 and M_2), in nearby inlet Platja Gran (M_1) and over the external platform (MW3) , and (c) atmosphere-ocean transfer function for three different meteotsunami events observed during summer 1997 (after Monserrat et al. 1998).

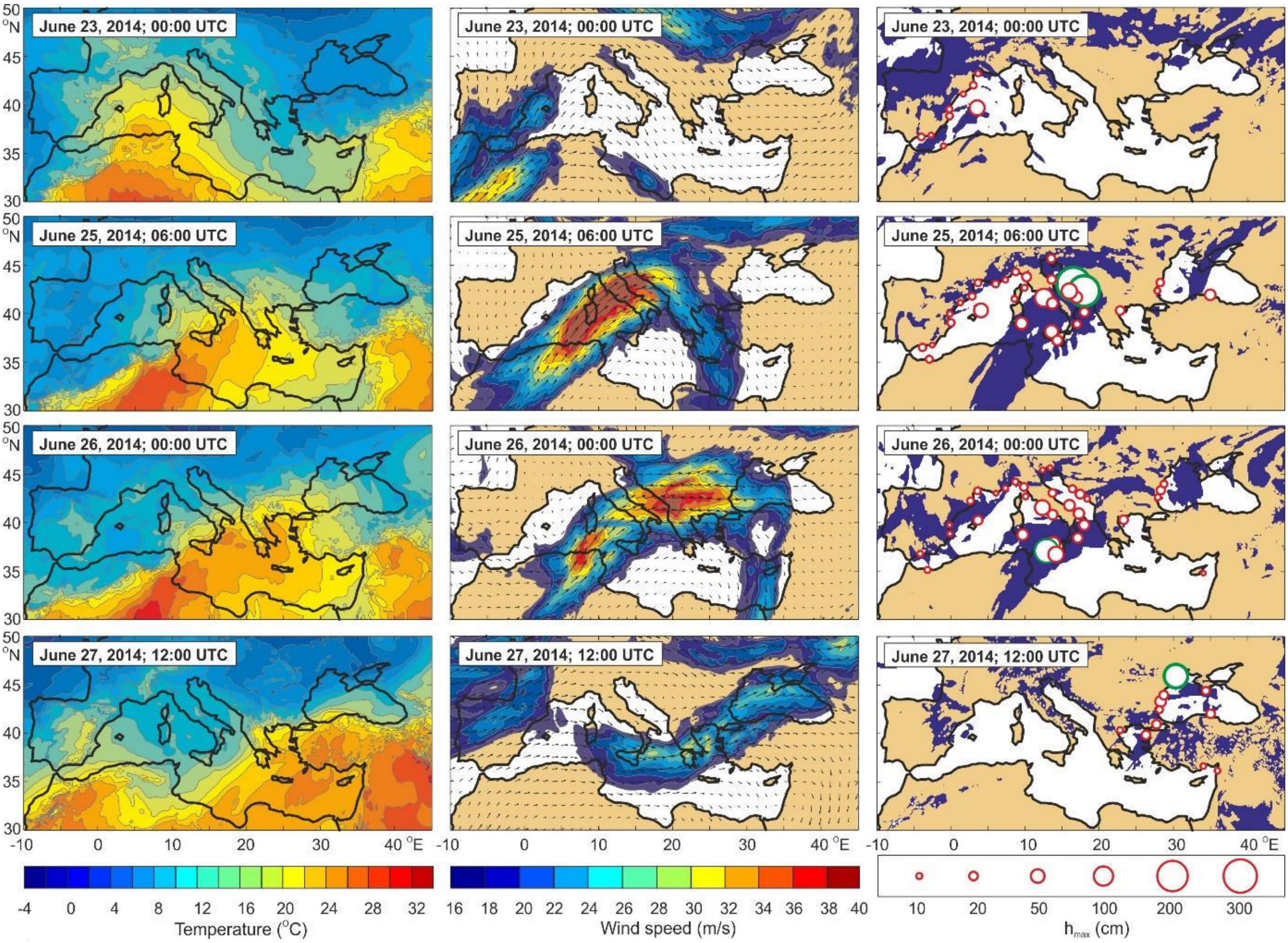

Figure 14. The sequence of meteotsunamigenic synoptic patterns conjoined with high-frequency sea level oscillations (reproduced from Šepić et al. 2015a). Left panel: temperature at 850 hPa; middle panel: wind speed and direction at 500 hPa: and right panel: the dynamically instable atmospheric layers (collared denotes Ri < 0.25) overlaid by circles showing the maximum height of high-frequency (periods < 3 h) sea level oscillations; the red circles denote measured wave heights; the green circles denote wave heights estimated from videos and eyewitness reports.

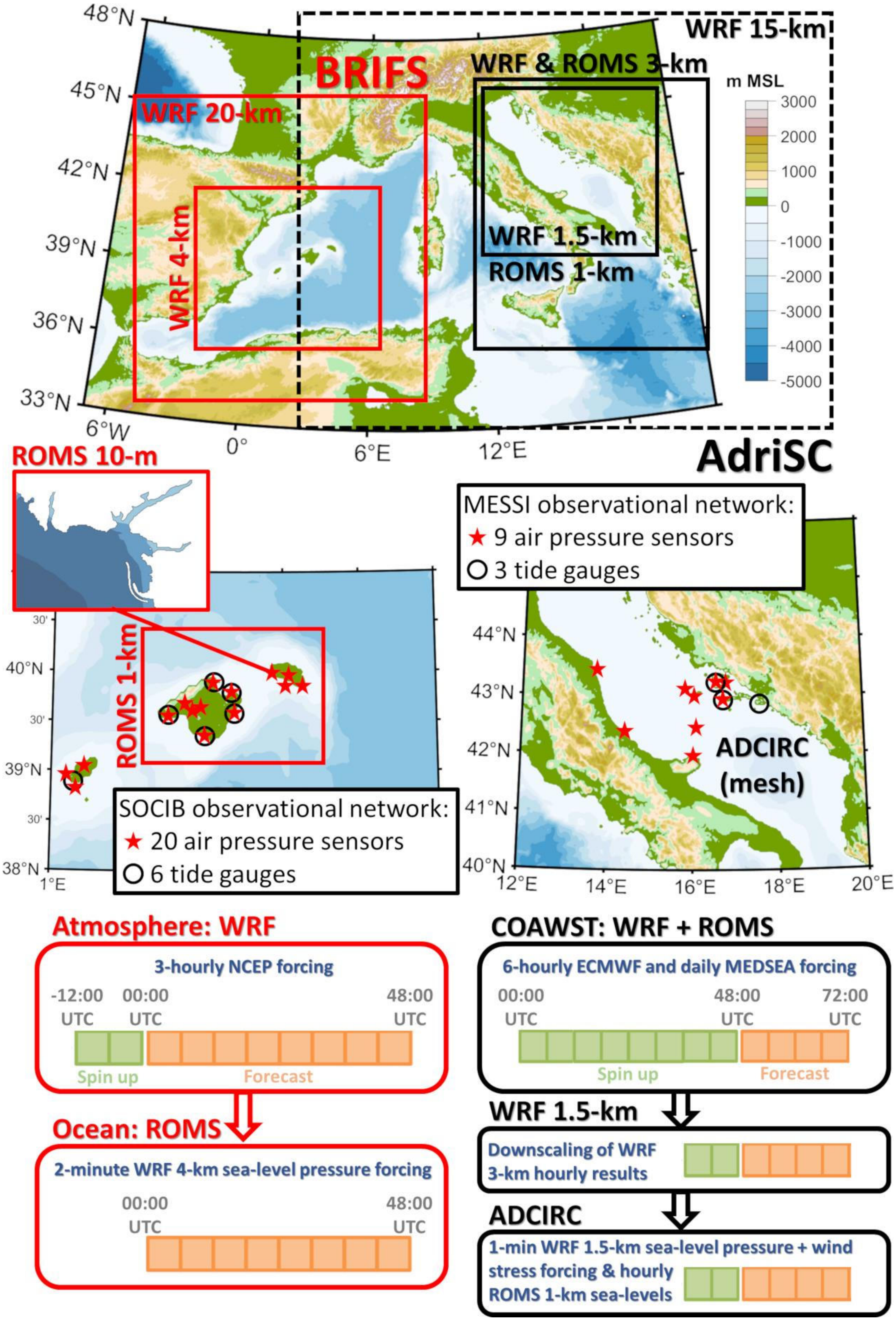

Figure 15. Existing meteotsunami monitoring and forecasting systems in the Mediterranean Sea: BRIFS (in red) associated with the SOCIB observational network in the Balearic Islands and AdriSC forecast system (in black) associated with the MESSI observational network in the Adriatic Sea.

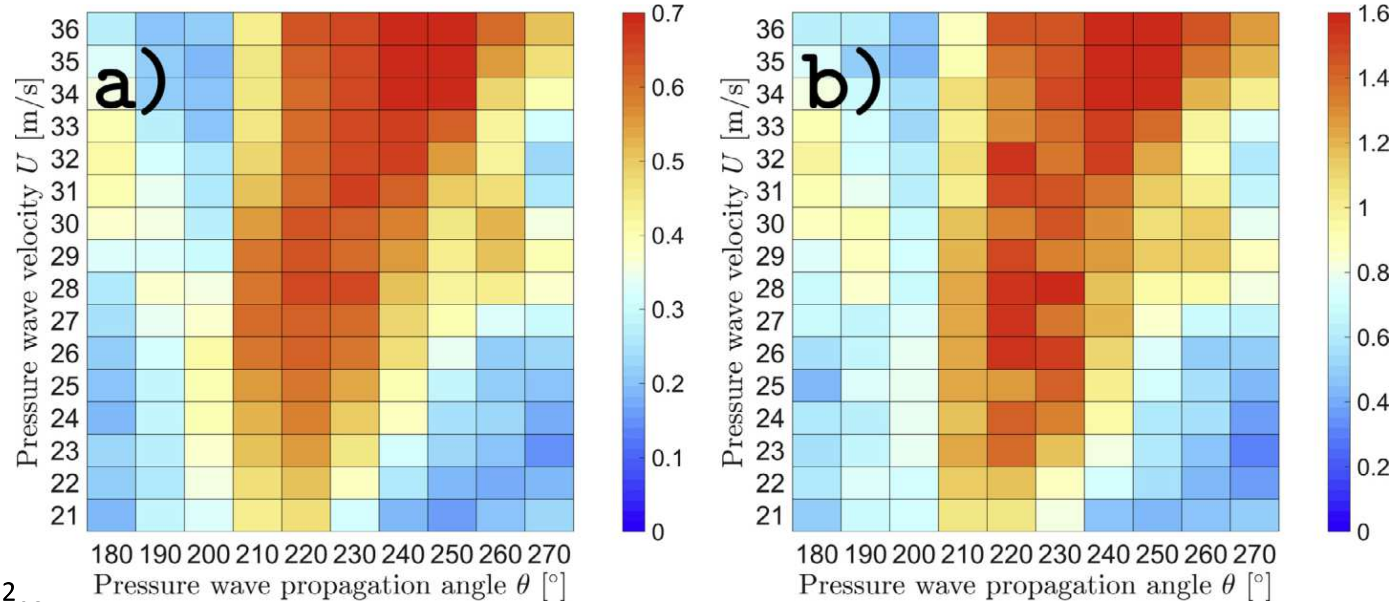

Figure 16. Dependence of the maximum generated sea surface anomaly (m) on the forcing gravity wave incident angle θ and speed U (a) outside and (b) inside Ciutadella Harbour (after Ličer et al. 2017).

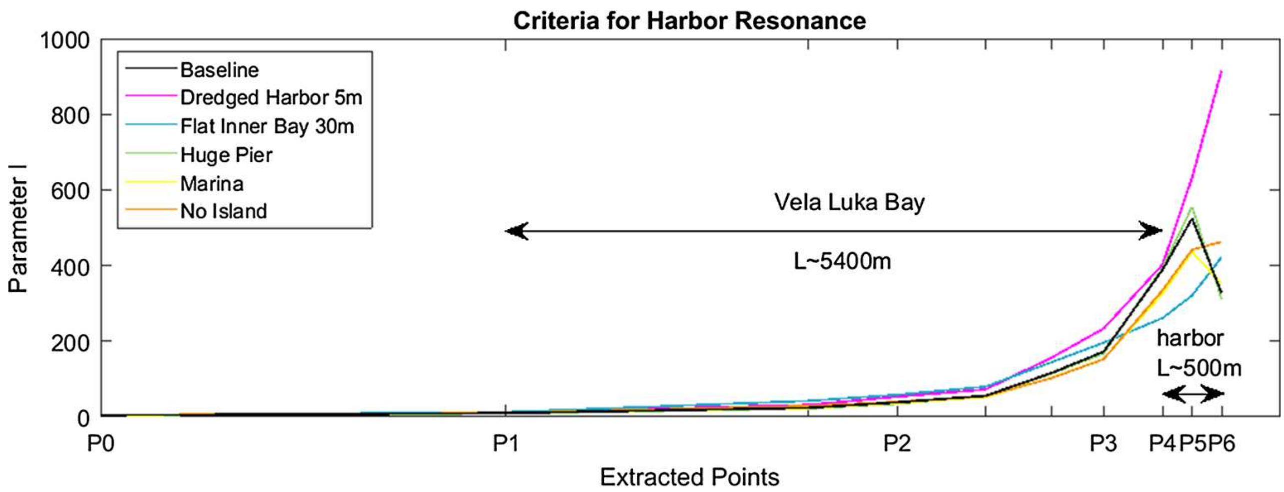

Figure 17. Variation of the re-calculated amplification factor (I) along the Vela Luka Bay (with P_0 located at the entrance of the bay and P_4 to P_6 inside of the harbour) for different geomorphologies (after Denamiel et al. 2018).

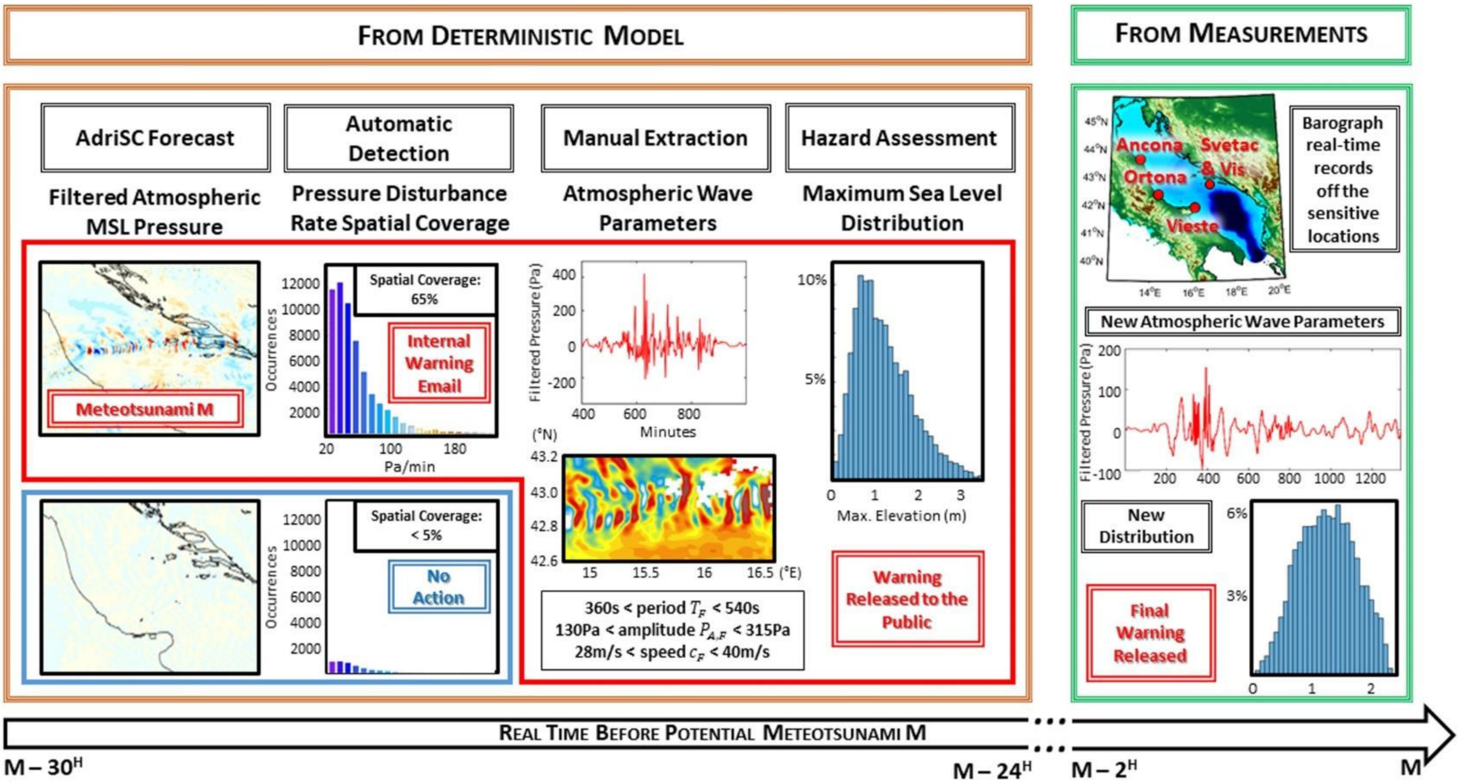

Figure 18. Operational meteotsunami hazard forecast within the Croatian Meteotsunami Early Warning System, based on atmospheric pressure field input from both (1) the deterministic model results (brown box) and (2) the measurements (green box). Every day, at least 30 hr before any meteotsunami event, the high-pass filtered pressure is extracted from the AdriSC forecast and used to automatically detect meteotsunamis by checking the spatial coverage of the values above 20 Pa per 4-min interval of the maximal pressure temporal rate. If this coverage is below 5%, then no meteotsunami is forecasted (blue box)—“silent” warning mode, otherwise a potential meteotsunami M is foreseen to occur (red box)—“event” warning mode, and an email is sent to the AdriSC team. At least 24 hr before the potential meteotsunami M occurs, the first forecast of hazard assessment is derived from the stochastic surrogate model used with ranges of pressure wave parameters manually extracted from the modelled filtered pressure. Finally, when the real-time observations become available, the hazard assessment is updated with new parameters extracted from the measurements (after Denamiel et al. 2019b).