Pure Appl. Geophys. 174 (2017), 3765–3811

DOI 10.1007/s00024-017-1625-8

Pure and Applied Geophysics

The Adriatic Sea: A Long-Standing Laboratory for Sea Level Studies

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Abstract—The paper provides a comprehensive review of all aspects of Adriatic Sea level research covered by the literature. It discusses changes occurring over millennial timescales and documented by a variety of natural and man-made proxies and post-glacial rebound models; mean sea level changes occurring over centennial to annual timescales and measured by modern instruments; and daily and higher-frequency changes (with periods ranging from minutes to a day) that are contributing to sea level extremes and are relevant for present-day flooding of coastal areas. Special tribute is paid to the historic sea level studies that shaped modern sea level research in the Adriatic, followed by a discussion of existing in situ and remote sensing observing systems operating in the Adriatic area, operational forecasting systems for Adriatic storm surges, as well as warning systems for tsunamis and meteotsunamis. Projections and predictions of sea level and related hazards are also included in the review. Based on this review, open issues and research gaps in the Adriatic Sea level studies are identified, as well as the additional research efforts needed to fill the gaps. The Adriatic Sea, thus, remains a laboratory for coastal sea level studies for semi-enclosed, coastal and marginal seas in the world ocean.

Key words: Adriatic Sea, sea level, various temporal and spatial scales, operational systems, open research issues.

1. Introduction

One of the most hazardous consequences of ongoing climate change is sea level rise. It came early into a research focus because it has the potential to cause substantial damage to coastal areas, particulary during extreme events (Nicholls and Cazenave 2010; Hinkel et al. 2014). A comprehensive report on ongoing global research activities, which covered a variety of timescales and focused on the processes that contribute to mean sea level changes and sea level extremes but mostly addressing global issues, is provided in the Intergovernmental Panel for Climate Change (IPCC)'s Fifth Assessment Report (Church et al. 2013). However, the impacts of sea level rise are also occurring on local scales (Cazenave and Le Cozannet 2014). For that reason, global hazard and risk assessment research should be downscaled to local communities which are threatened by sea level hazards (Cutter et al. 2008; Baker et al. 2012).

Sea level changes at the local level embrace a variety of processes that range from millennial to minute timescales and operate at different spatial scales. Taken together, they contribute to observed sea levels that, in the end, impact coastal areas and their populations. Mean sea level changes occur over seasonal and interannual to millennial timescales, act on both global and regional spatial scales and follow the combined effect of vertical land motions, long-term forcing at the surface and ocean volume changes. The latter include changes in ocean currents and ocean density at both upper and deep ocean (Levermann et al. 2005; Lombard et al. 2007; Lorbacher et al. 2010; Li et al. 2013), while redistribution of water mass between the ocean, land and ice is also largely contributing to mean sea level changes (Stammer 2008; Lorbacher et al. 2012). Vertical land movements may occur due to different processes, including glacial isostatic adjustment (Peltier et al. 2015), tectonic activity or subsidence (Wöppelmann and Marcos 2012; King et al. 2012), anthropogenically induced subsidence (Syvitski et al. 2009) and changes in sediment load (Blum and Roberts 2009). Finally, atmospheric loading and forcing effects (Piecuch and Ponte 2015) and seasonality of air pressure and winds (Feng et al. 2015) may substantially modulate mean sea level changes.

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Considering shorter periods (i.e., on periods shorter than a month but longer than a few hours) over which changes are contributing to sea level extremes, the processes have a clear regional outreach. Synoptic and planetary-scale disturbances become dominant in driving high sea levels and storm surges over periods of a day to a few weeks, especially in shallow seas and over wide shelves (Zhang et al. 2000). The surges can be modified by tidal oscillations (Pickering et al. 2012) and basin-wide seiches (Jönsson et al. 2008), while local and regional bathymetry plays an important role in shaping the intensity of an extreme event, including bathymetry changes close to tide gauges (Mawdsley et al. 2015).

High-frequency phenomena are affecting sea level changes occurring at periods lower than a few hours and are particularly important in driving sea level extremes in bays and channels with high amplification rates (Rabinovich 2009). They may reach destructive levels at certain hot spots during meteotsunami events, particularly in low-tidal area where the sea shore is not adapted to strong and rapid sea level oscillations (Monserrat et al. 2006). Although potentially dangerous (Churchill et al. 1995), meteotsunamis are not as destructive as seismically and landslide-driven tsunamis, which are rare but extremely destructive processes which hit coastal regions and act on time scales ranging from minutes to an hour (Okal 2015).

Even though the identification of processes that influence sea level changes in an area is a prerequisite for hazard assessment, the quantification of the potential sea level hazards is governed by their uncertainties (Hinkel et al. 2015). This also applies to estimation of coastal flood impacts (e.g., Wolff et al. 2016), where uncertainties are strongly dependent on the input parameters and the data resolutions. The better knowledge of the processes leads to lower uncertainties, which is an important input to policy-makers, spatial planners and other users when planning adaptation and mitigation measures in coastal areas threatened by sea level changes (Bell et al. 2014; Sorensen et al. 2016).

The Adriatic Sea (Fig. 1) is a long-standing example of a basin in which research activities have covered a majority of the processes contributing to sea level change. Sea level has been monitored there for almost two centuries. The tradition of sea level research has persisted despite changes in political regimes, constitutions and countries, and has maintained all the while its high quality standards. The Adriatic Sea is the northernmost embayment of the Mediterranean Sea and is bordered by Italy on the western and northern side and by the Balkan countries (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania, Greece) on the eastern side. The turbulent geopolitics of the region have strongly affected Adriatic sea level research, preventing collaboration between countries and thus preventing proper classification of some observed phenomena. However, collaboration has been steadily improving in recent decades. An example is the Great Vela Luka Flood of 1978. At the time, Croatian researchers ascribed this destructive natural hazard event to atmospherically driven sea level oscillations (Hodžić 1979/1980; Orlić 1980) using only observations from the eastern Adriatic. In contrast, Italian researchers posited a submarine landslide source based only on Italian observations (Bedosti 1980). Thirty years later, an integral approach was applied (Vučetić et al. 2009; Orlić et al. 2010) to explain all the basin-wide observations related to this event. In addition, countries bordering the Adriatic have been characterised, throughout their history, by different degrees of economic potential and societal needs. These characteristics have been reflected in different and country-dependent levels of recognition of sea level research in public policy, which has affected the quality and quantity of long-term sea level observations, as well as sea level research at national levels.

This paper attempts to review the history and present status of Adriatic Sea level research. It also describes the status of sea level monitoring systems and the availability of data for sea level research. Such an approach may provide a signpost for doing a synthesis in other similar basins and regions. In the end, it may facilitate better use of sea level knowledge in coastal management applications. An overview of the centuries-long history of sea level research in the Adriatic up until the 1980s is presented in Sect. 2, while the status of monitoring systems and capacities for sea level research is presented in Sect. 3. Section 4 contains a process-oriented review of sea level knowledge, including both slow sea level changes and changes over minutes and hours. Sea level projections

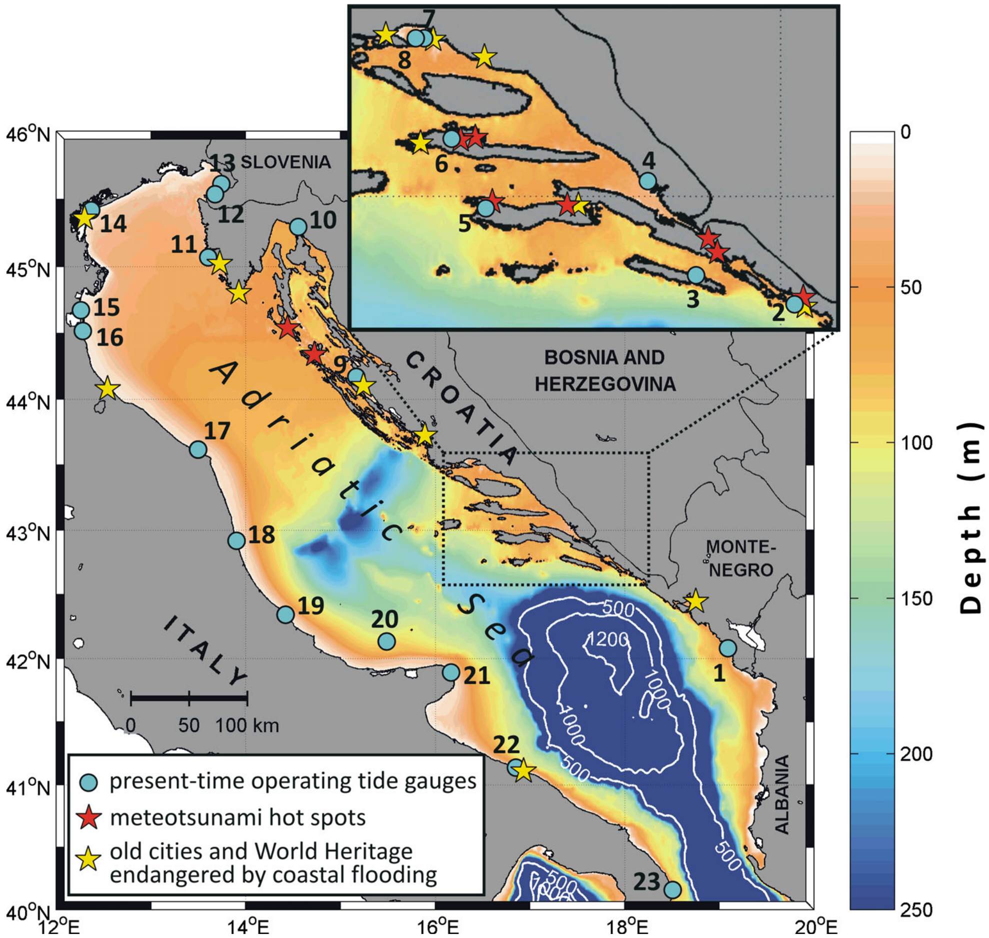


Figure 1

Map and bathymetry of the Adriatic Sea. Present-time operating tide gauge sites, locations hit by meteotsunamis and heritage cities endangered by coastal floods are also indicated. Numbers denote tide gauges at Bar (*1*), Dubrovnik (*2*), Sobra-Mljet (3), Ploče (*4*), Vela Luka (*5*), Stari Grad (*6*), Split Harbour (*7*), Split Marjan (*8*), Zadar (*9*), Bakar (*10*), Rovinj (*11*), Koper (*12*), Trieste (*13*), Venice (*14*), Porto Garibaldi (*15*), Ravenna (*16*), Ancona (*17*), San Benedetto del Tronto (*18*), Ortona (*19*), Tremiti (*20*), Vieste (*21*), Bari (*22*), and Otranto (*23*)

for the future, including mean sea levels, as well as extremes and the associated warning systems for the most destructive processes, are discussed in Sect. 5. Section 6 documents the open-sea level research issues for the Adriatic from the perspective of existing knowledge and gaps in that knowledge. Section 7 concludes the manuscript.

2. A History of Adriatic Sea Level Research

Although the sea level in the Adriatic had been observed from time immemorial, research into its changes, in the modern sense of the word, was initiated by Renaissance scholars. The results obtained up to the 1980s are briefly reviewed in this section. Various processes controlling the Adriatic sea level are discussed, starting with the lowest frequencies and progressing towards the highest frequencies. As will become clear from the text, research carried out in the Adriatic was often influenced by measurement techniques and the theoretical approaches developed elsewhere, but on some occasions the work done in the Adriatic area resulted in pioneering contributions to the wider field.

Relative movements of the sea and the land in the Adriatic area were often mentioned by Enlightenment scholars (e.g., Donati 1758; Fortis 1774). The prevailing conclusion, based mostly on archaeological evidence, was that a rise of sea level with respect to the land had occurred since the Roman times along the northern and eastern Adriatic coasts. Along the western coast, an advance of the land and a retreat of the sea were observed, being related to the material brought into the Adriatic by numerous rivers and to the subsequent sedimentation. More recently, a number of authors have used geomorphological (e.g., Grund 1907) and biostratigraphic (e.g., Milojević 1926) methods to confirm the relative sea level rise along the eastern Adriatic coast.

In the nineteenth century, tide gauge measurements started in the Adriatic Sea. On the one hand, these instruments were installed at ports of particular interest. For example, a tide gauge was installed at Trieste in 1859 (Godin and Trotti 1975) and at Venice in 1867 (Enzi and Camuffo 1995). On the other hand, tide gauge measurements were carried out at a network of stations on several occasions, such as when the Ständige Commission für die Adria started its activity in 1869, when the Militärgeographisches Institut in Vienna became involved in sea level studies in 1906, and when the Commission internationale pour l'exploration de la mer Adriatique was founded in 1910 (Kasumović 1968). It took some time for the tide gauge data to become useful in the study of relative sea level changes because long time series were necessary for the purpose. Linear trends were extracted for the first time from the reasonably extensive time series by Polli (1938). On the basis of measurements carried out at Trieste over the interval between 1905 and 1936, he estimated a sea level rise of approximately 2 cm per decade. Based on data collected at Venice from 1917 to 1936, he concluded that the rise was much faster there. Nonlinearities began to be considered by Polli (1947), who applied a bandpass filtering method and detected a number of oscillations, including a bidecadal one, in the Trieste (Fig. 2) and Venice records, and by Mosetti (1961), who used a low-pass filter to document changing trends in the Trieste record. Later studies benefited from data collected at modern tide gauge networks, which were established in the Adriatic in the 1950s.

The availability of long tide gauge records stimulated an interest in the seasonal oscillations in sea level. Polli (1938) determined monthly mean values from several decades of measurements in Trieste and Venice, performed harmonic analysis of the 12-month time series thus obtained, and related the annual cycle to the corresponding variability of several parameters (air pressure, wind, river outflows, and evaporation). Pattullo et al. (1955) included the Adriatic Sea in their global analysis of the seasonal oscillation. They confirmed that the typical annual cycle in the area is characterised by a February minimum and a November maximum and by a range of approximately 12 cm. Moreover, they compared measured sea levels to steric sea levels. Zore (1960) took a further step and related measured sea level slopes to differences in steric sea levels. She found a slope directed from the mouth to the head of the basin in both data sets. This slope attained a maximum in summer and a minimum in winter.

An average annual cycle is obviously a simplification that approaches typical conditions but may differ from values observed in any particular year. Consequently, analyses of seasonal oscillations are sometimes combined with studies of interannual variability. The latter started in the Adriatic area only recently and will, therefore, be considered elsewhere in this paper.

The Adriatic coastal area is prone to floods, which are often related to extremely high sea levels that last for hours and occur in a wide region. This phenomenon is known in Venice as *acqua alta*. The occurrence of extremes is controlled by several processes, one of which is the response of the sea to planetary-scale atmospheric forcing. However, the importance of this forcing was recognised rather late (Penzar et al. 1980), and thus an overview of this process appears in a subsequent section of the paper.

Tides also contribute to the Adriatic Sea level extremes. Due to their regular nature, the tides were already well documented in the pre-instrumental era. Thus, Galilei (1632) noticed that the Adriatic tides are large in comparison with the tides occurring elsewhere in the Mediterranean. Toaldo (1777) corroborated this finding with numerous observations collected in the Venice area. The empirical result was, therefore, well known to Airy (1845) when he

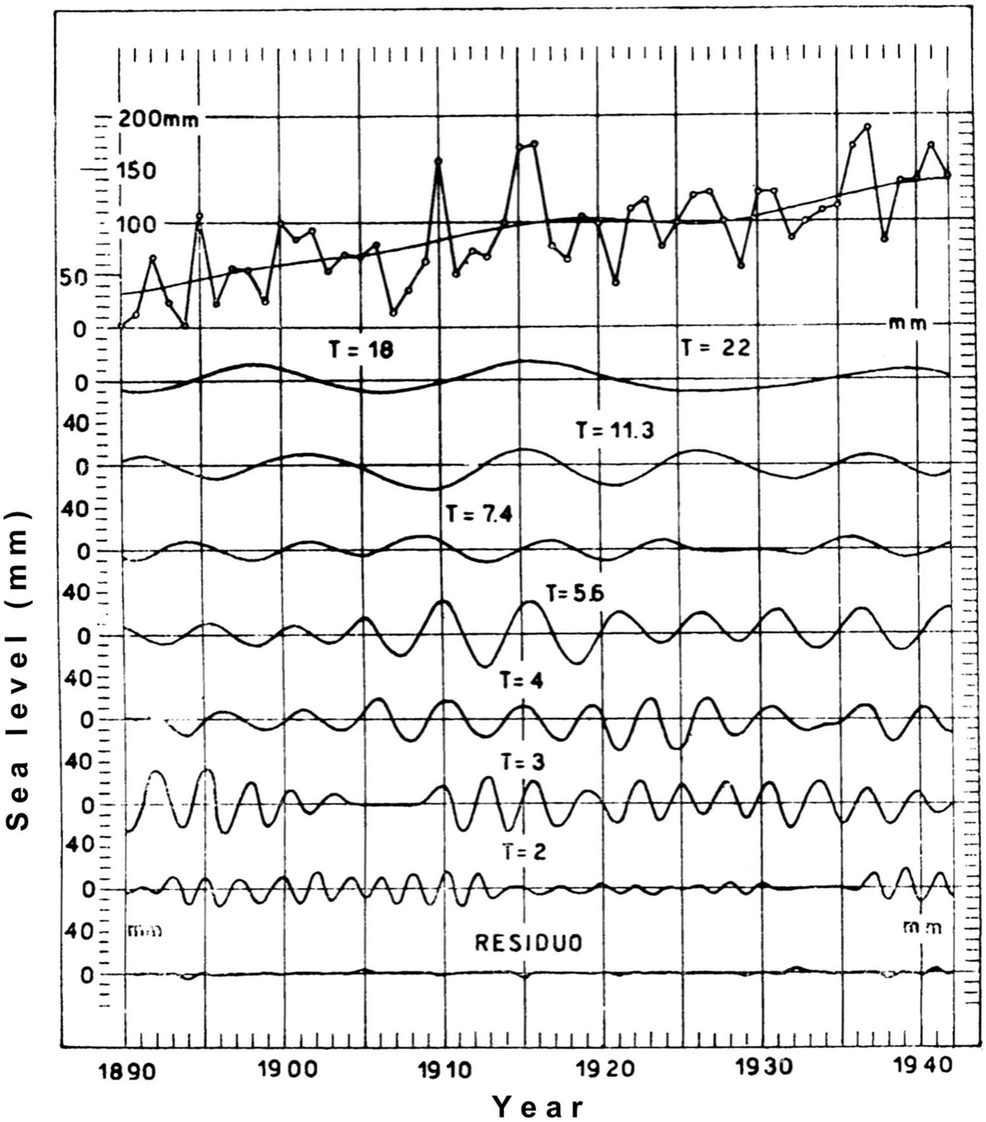


Figure 2
Annual mean sea levels measured at Trieste between 1890 and 1942 and the decomposition of the time series into a number of oscillations (Polli 1947)

developed a simple analytical model of tides in a rectangular basin driven by periodic forcing at the open boundary. Airy noticed the possibility of resonance when the period of the forcing equals the period of a normal mode of the basin, and he invoked the Adriatic tides as an example of this process at work (his other example came from the Bay of Fundy). Thus, the study of Adriatic Sea levels provided inspiration for a theoretical result that was globally relevant.

Soon after tide gauge measurements started in the Adriatic, researchers subjected the records to harmonic analysis. The largest early effort, which resulted in harmonic constants for sixteen Adriatic stations, was documented by Kesslitz (1919). He showed that the Adriatic tides could be reasonably well approximated by seven harmonic constituents, four semidiurnal and three diurnal. His amplitudes and phases served, with some updates, as the basis for the construction of the first maps depicting the

Adriatic corange and cotidal lines (Polli 1959, Fig. 3). The thorough empirical documentation inspired further theoretical work. Sterneck (1915, 1919) performed numerical modelling of the Adriatic tides by balancing local accelerations and pressure gradients in the along-basin direction and Coriolis acceleration and pressure gradient in the cross-basin direction. He obtained good agreement with the observations by assuming that the Adriatic tides largely co-oscillate with the Mediterranean tides. His paper-and-pencil numerical modelling represented a pioneering effort, not only in global sea level research, but also in geophysical fluid dynamics. The first two-dimensional numerical modelling of the

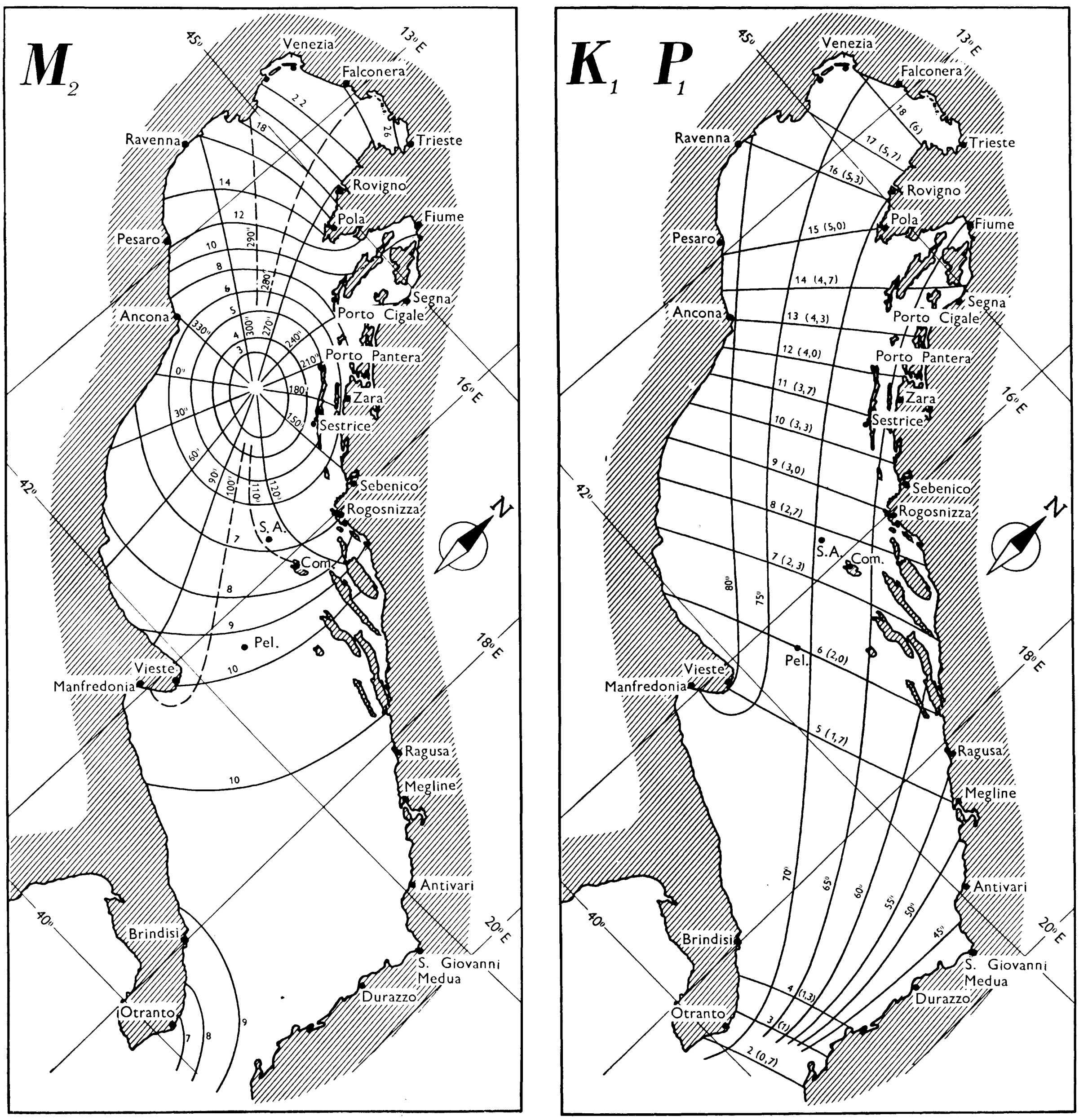


Figure 3
Corange and cotidal maps depicting the semidiurnal (*left*) and diurnal (*right*) tidal constituents in the Adriatic Sea (Polli 1959)

Adriatic tides, which was carried out by Accerboni and Manca (1973), confirmed Sterneck's basic finding, namely, that the Adriatic tides could be realistically reproduced by including only the forcing from the Mediterranean. In the meantime, Hendershott and Speranza (1971) carried out an important analytical study enabling a comparison of tides in the Adriatic Sea and the Gulf of California. They showed that the semidiurnal tides in both basins could be reasonably well reproduced by two oppositely travelling Kelvin waves, in agreement with Taylor's (1921) solution for bays that are narrow and deep. Moreover, they demonstrated that the position of the amphidromic point depends sensitively on the reflection of the incoming Kelvin wave at the head of the basin, which is almost devoid of energy loss in the Adriatic Sea and prone to loss in the Gulf of California.

The most important contribution to Adriatic floods comes from storm surges, transient increases in sea level due to synoptic-scale air pressure and wind forcing. These have been observed in Venice since the eighth century (Enzi and Camuffo 1995). Early on, it has been noticed that storm surges in Venice are related to strong winds. The most frequent culprit is the sirocco wind, with occasional contributions from the bora wind (Patritius 1591). The importance of air pressure was recognised much later using observations carried out at Hvar, where the wind effect is relatively weak (Bučić 1861). A balanced view was provided by Lorenz (1863): relying on data collected visually at Rijeka, he concluded that low air pressures and sirocco winds combine to increase sea levels and that high air pressures and bora winds reinforce each other in lowering sea levels.

Tide gauge measurements provided fresh impetus to storm surge research. Harmonic analysis and synthesis enabled tides to be eliminated from the records and residual sea levels to be interpreted in terms of atmospheric forcing. This approach was pioneered in the Adriatic by Kesslitz (1911), who attributed residual sea levels recorded at Pula on the night of 15–16 November 1910 to a cyclone centred over the northern Adriatic and to the low air pressure and strong sirocco wind related to it. The availability of time series encouraged several authors to perform correlation and regression analysis of sea level and various meteorological parameters. Kasumović (1958) showed that the day-to-day response of sea level at Bakar to air pressure forcing is close to the inverted barometer response. Mosetti and Bartole (1974) established a relationship between setup in the northern Adriatic and southerly winds blowing over the middle and south Adriatic. A similar rationale led to the development of an early forecasting system, with residual sea levels in Venice given as a function of earlier sea levels at the same location and of various powers of simultaneous air pressure gradients above the Adriatic (Sguazzero et al. 1972). An alternative method of forecasting involved pioneering numerical modelling of the Adriatic storm surges: one-dimensional (Accerboni et al. 1971), two-dimensional with a linear parameterization of bottom friction (Stravisi 1973), and two-dimensional with a non-linear parameterization of bottom friction (Accerboni and Manca 1973). The models were limited to the Adriatic area, with the nodal line being imposed in the Otranto Strait.

Closely connected with storm surges are Adriatic-wide seiches, which usually form when the sirocco wind ceases and the surge driven by it relaxes through a series of oscillations. The resulting seiches can reinforce other storm surge events occurring later. The existence of the Adriatic normal modes was already implicit in the theoretical interpretation of the Adriatic tides offered by Airy (1845). However, the basin-wide seiches were actually documented for the first time by Kesslitz (1910), who used the harmonic method of detiding to isolate oscillations with periods of 23, 12 and 5 h from the Pula tide gauge records. Vercelli (1941) later applied detiding and a digital filtering method to extract periods of 22 and 8.3 h from the Zadar time series. Finally, Bozzi Zadro and Poretti (1971) utilised spectral analysis to obtain periods of 21.6, 12.4 and 6.7–7.4 h from the Trieste tide gauge measurements. A striking feature of the Adriatic seiche analysis is a gradual decrease of the fundamental period as determined over the years. The estimated period has gone from 23 to 22 h and later to 21.6 h. It is still not clear whether this decrease is an artefact of the various methods of analysis employed or a symptom of some real physical process at work.

To interpret the periods extracted from tide gauge records, several theoretical approaches were followed. Defant (1911) used a simple analytical solution and some corrections allowing for the realistic basin configuration to obtain a period of 22.4 h for the fundamental Adriatic mode. Sterneck (1919) applied his one-dimensional numerical model and the so-called mouth correction to determine 23.3 h as the period of the lowest Adriatic mode. Finally, Accerboni and Manca (1973) utilised a two-dimensional numerical model with the nodal line assumed to be in the Otranto Strait to compute a period of 20.6 h for the principal Adriatic seiche. The spread of periods computed over the years is large, probably due to different treatments of the open-boundary condition.

Extensive observational and modelling investigations of the Adriatic seiches were carried out subsequently, as described in detail in Sect. 4.2.3.

Adriatic Sea level varies at even higher, supradaily frequencies, which may result in coastal floods that are short-lived and local but often quite harmful. It seems that the high-frequency variability, not only of sea level but also of the related currents, has been known to Adriatic fishermen for centuries. The process was also mentioned in an early publication: Patritius (1591) described observations carried out in the Osor Channel, which separates the islands of Cres and Lošinj, and stressed that more than twenty current reversals could be observed in a day. When tide gauge measurements started, the high-frequency oscillations immediately attracted the interest of researchers because they were obvious in the records. A pioneering study was published by Gratzl (1891), who reported the existence of a 29.4-min oscillation in the Pula records, compared the period with the value predicted by the so-called Merian formula, and concluded that the oscillation was due to the harbour's fundamental seiche. An extensive study of the local seiches of the Adriatic was undertaken by Sterneck (1914), who considered tide gauge records from twenty-seven stations. The periods he was able to extract from those data remain the only values available in the literature for a number of locations. Sterneck further compared the observed periods with the corresponding values computed from the Merian formula. Subsequent studies of the local seiches never approached the breadth of Sterneck's effort. However, they introduced novel empirical and theoretical methods. Goldberg and Kempni (1937) studied seiches in Bakar Bay using simultaneous measurements at various locations inside the bay and detected periods of fifteen different modes. They interpreted the findings with the aid of a one-dimensional numerical model. Vercelli (1941) used a digital filtering method to study not only the Adriatic-wide seiches but also the local seiches documented by the Zadar tide gauge records. Dovier et al. (1974) performed spectral analysis of the Trieste and Grado records to determine the prevailing periods. They then used a two-dimensional numerical model to interpret the periods in terms of normal modes of the Gulf of Trieste.

Up to now, fifteen earthquakes that resulted in tsunamis have been documented in the Adriatic area. The earliest earthquake–tsunami pair occurred in the year 1511 (Pasarić et al. 2012). Over the centuries, however, their study was limited to simple descriptions and an occasional listing of the events. In-depth dynamical studies and proper cataloguing started just a few decades ago, and therefore the findings obtained will be reviewed elsewhere in this paper.

Observations of meteotsunamis commenced more recently, probably because the forcing agents are much less obvious in this case and the conspicuous sea level variability depends sensitively on the resonant transfer of energy from the atmosphere to the sea. Still, twenty-one such events have been observed just in Croatian coastal waters since the year 1931 (Orlić 2015). Moreover, meteotsunamis developing between Venice and Trieste were carefully analysed by Caloi (1938, Fig. 4). The heights that Caloi detected in the northernmost Adriatic were much smaller than the heights observed along the Croatian coast. This may be attributed to the fact that only the open-sea resonance was found to be at work within the profile extending from Venice to Trieste, whereas both the open-sea and coastal resonances were found to be important in the Croatian archipelago. Analysis of the latter type of dynamics started in the year 1980, when the term 'Proudman resonance' was also introduced to describe resonant mechanisms operating in the open sea (Orlić 1980). Therefore, a proper overview of Adriatic meteotsunami research falls beyond the scope of the present section.

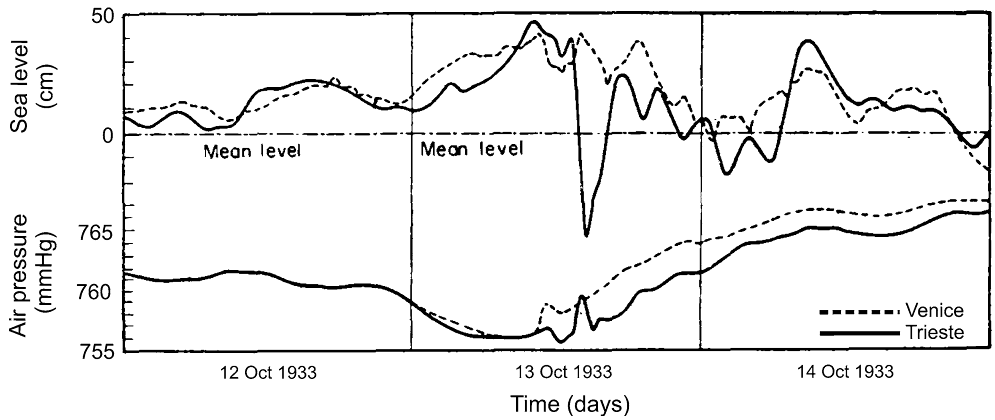


Figure 4
Residual sea levels (*top*) and air pressures (*bottom*) measured at Venice (*dashed lines*) and Trieste (*full lines*) between 12 and 14 October 1933 (Caloi 1938, redrawn by Defant 1961). It is obvious that the air pressure perturbation of 13 October 1933 propagated from Venice to Trieste and that the sea level perturbation was much larger at Trieste than at Venice

Several centuries of investigation provided a rich heritage with which the Adriatic Sea level studies entered the last decades of the twentieth century. The most recent efforts provided new insights based on comprehensive data sets, new modelling tools, and advanced methods of analysis of empirical and theoretical time series. These insights will now be considered in some detail.

3. Present-Day Sea Level Monitoring Facilities in the Adriatic

Present-day tide gauge capacities in the Adriatic Sea are composed of several separate systems that are operated on the national or sub-national level. In Croatia, the largest sea level data provider is the Hydrographic Institute of the Republic of Croatia (www.hhi.hr), which manages the tide gauges in Dubrovnik, Ploče, Split Harbour, Zadar and Rovinj (Fig. 1), of which Dubrovnik, Split Harbour and Rovinj have been operational for more than 50 years. These tide gauges are of the float type and are installed in rock- and concrete-made stilling wells. They record on weekly charts, but they have also been equipped with OTT Thalimedes shaft encoders since 2003. They, thus, provide high-resolution sea level data at 1 min resolution usable for a number of ocean studies (such as meteotsunamis; e.g., Vilibić et al. 2004). The charts are still used for determining hourly and lower frequency sea level values needed for climate studies, as shaft encoders are prone to drifts in their records (Vilibić et al. 2005b). The oldest tide gauge in Croatia, the Bakar tide gauge, is operated by the Andrija Mohorovičić Geophysical Institute of the Faculty of Science, University of Zagreb (www.pmf.unizg.hr/geof) and has been operational since 1929 (Orlić 2001). It is also a float-type instrument that uses charts and a standby Thalimedes shaft encoder for recording sea levels. This station is supplemented by a radar tide gauge (OTT Kalesto) that has been operational since 2004 and is mounted a few hundred metres from the float-type tide gauge. The third sea level data provider in Croatia is the Institute of Oceanography and Fisheries (www.izor.hr), which has operated the Split Marjan tide gauge since 1955. This instrument has also been equipped recently with a Thalimedes shaft encoder. The installation of three more stations with radar instruments (Vela Luka, Stari Grad, and Sobra–Mljet; Fig. 1) for monitoring high-frequency sea level oscillations has been done in mid 2017, and their data will be publicly available soon at pages of the MESSI project (www.izor.hr/messi).

A tide gauge in Montenegro that has been in operation for a long time is situated in Bar and is presently operated by the Institute of Hydrometeorology and Seismology of Montenegro (www.zhms.

gov.me). The tide gauge has been operated since 1964, and is of the same type as the long-term tide gauges in Croatia. In Slovenia, the tide gauge at Koper has been operational since 1958 and is presently maintained by the Environmental Agency of the Republic of Slovenia (www.arso.gov.si). It has recently been moved to a newly built building, but the float-type stilling well system has been maintained to ensure the homogeneity of the long-term sea level time series. High-precision levelling was used to connect the new tide gauge to the geodetic network.

Quasi-regular levelling of tide gauge benchmarks to the geodetic network along the eastern Adriatic coast (Rožić 2001) was conducted every 5–10 years during the most of the operating interval, ensuring the stability of the eastern Adriatic float-type long-term operating tide gauges.

Aside Vela Luka, Stari Grad and Sobra-Mljet stations, whose data will be publicly available once being operational, the rest of the sea level data along the eastern Adriatic coast (Croatia, Slovenia, Montenegro) is available upon request from the listed data providers. All stations record with temporal resolution of 1 min.

The Italian national tide gauge network in the Adriatic Sea consists of ten stations (Trieste, Venice, Ravenna, Ancona, San Benedetto del Tronto, Ortona, Tremiti, Vieste, Bari, and Otranto) that are operated by the Istituto Superiore per la Protezione a la Ricerca Ambientale (ISPRA). The network was renovated and unified in the 1990s, and the tide gauges mostly use radar and ultrasonic technology. Each station is supplemented by standard meteorological sensors that measure air temperature, humidity, pressure and winds, plus ocean temperature. Hourly quality-checked data are available at www.mareografico.it, while 1-min raw (not quality-checked) sea level data from these stations are also available at the Intergovernmental Oceanographic Commission (IOC) Sea Level Station Monitoring Facility webpage. Another Italian tide gauge network, the Venetian and Northern-Adriatic Tide Gauge network, encompasses approximately 50 tide gauges within the Venetian Lagoon and the surrounding region (Ferla et al. 2007). Half of these tide gauges transmit their data in real time to the centre and are used for operational forecasting of *acqua alta* in the lagoon (Umgiesser et al. 2004). Furthermore, there are some Italian long-term tide gauges which are not a part of these networks, like the Trieste tide gauge at Molo Santorio, which is a long-lasting part of the Global Sea Level Observing System (GLOSS) network and has been in operation since the late nineteenth century.

Monthly data from most of the Adriatic tide gauges, including the metadata and tide gauge documentation, may be obtained from the Permanent Service for Mean Sea Level (PSMSL) webpages.

The setting of the present tide gauge network and associated systems in the Adriatic Sea is illustrated in Fig. 1, while webpages where Adriatic Sea level data products can be obtained are listed in Table 1.

The only tide gauges collocated with Continuous GPS (CGPS) measurements intended to measure vertical crustal movements (Teferle et al. 2008) are those at Porto Garibaldi, Koper and Split. Several other tide gauges have CGPS measurement stations within a kilometre (Ancona, Dubrovnik, and Zadar). These CGPS measurements are obtainable from the SONEL webpages and extend to the early 2000s.

The altimetry data for the Adriatic are reachable from the AVISO website. Few studies have focused on altimetry data from the Adriatic Sea (e.g., Fenoglio-Marc et al. 2012); such studies are more often dedicated to sea level and mean dynamic topography variability and trends throughout the Mediterranean (e.g., Woodworth et al. 2015). Additionally, sea level changes associated with the Adriatic-Ionian decadal variability and bimodal oscillations have been documented using the altimetry data (Vera et al. 2009).

Operational sea level forecasting in the Adriatic Sea is primarily intended to produce tidal forecasts, which are available for the Adriatic harbours from several websites covering the world oceans (Table 1). The forecasting of periods of *acqua alta* in Venice is managed by the Istituzione Centro Previsioni e Segnalazioni Maree. Operational sea level forecasts for the Adriatic are also available through the CMCC Adriatic Forecasting System and BORA Adriatic Marine Forecast.

Table 1

List of sea level product webpages available for the Adriatic Sea

Sea level products	Web page
Italian Tide Gauge Network	www.mareografico.it
Venice Lagoon tide gauge network	www.venezia.isprambiente.it/index.php?folder_id=1&lang_id=2
Trieste Molo Sartorio tide gauge	www.ts.ismar.cnr.it/node/15
IOC sea level station monitoring facility	www.ioc-sealevelmonitoring.org
Permanent Service for Mean Sea Level (PSMSL)	www.psmsl.org
University of Hawaii Sea Level Center (UHSLC)	www.uhslc.soest.hawaii.edu
SONEL GPS	www.sonel.org/-GPS-.html
AVISO + Satellite Altimetry Data	www.aviso.altimetry.fr
Admiralty easy tide	www.ukho.gov.uk/easytide/EasyTide/index.aspx
Tide forecast	www.tide-forecast.com
IOF high and low waters	www.izor.hr/web/guest/visoke-i-niske-vode
HHI tides on-line	www.hhi.hr/en/mareo
Centro Previsioni e Segnalazioni Maree	www.comune.venezia.it/archivio/1748
CMCC Adriatic forecasting system	www.oceanlab.cmcc.it/afs
BORA Adriatic marine forecast	www.bora.gekom.hr

4. State-of-the-Art of the Adriatic Sea Level Knowledge

4.1. Seasonal and Interannual to Millennial Mean Sea Level Changes

4.1.1 Sea Level Changes Over the Last Millennia

As the instrumental era of sea level monitoring covers only the last 100 and 50 years or so, different geoarchaeological and geomorphological markers have been used for assessment of relative sea level changes during the recent millennia. Moreover, modelling of the eustatic and glacio-hydro-isostatic contributions can be used to explain the observed sea level changes. In the Adriatic, assessment of relative sea level changes over the last millennia has been done using ancient (mostly Roman) structures, including slipways, coastal quarries, fish tanks, piers, coastal buildings and harbour constructions (Flemming 1969). Chemical, biological, and geomorphological markers that have been used include tidal notches, corniches, speleothems, and vermetids, as well as other indicators (Lambeck et al. 2004).

In the northern Adriatic, which is the most investigated part of the Adriatic Sea, relative sea level rise is driven largely by post-glacial rebound, vertical land movement and local subsidence processes, with average rates of 1–2 m in the last 2000 years (Antonioli et al. 2007, 2009; Florido et al. 2011; Furlani et al. 2011). Significant subsidence rates have also been found there by Lambeck et al. (2004) based on assessment of markers, while modelling indicates that relative sea level changes increase in magnitude from the north towards the southern Adriatic (Lambeck and Purcell 2005). According to this Mediterranean-scale study, relative sea level in the last 2000 years rose by 0–0.5 m in the northernmost part of the Adriatic, while the southern Adriatic exhibited a sea level rise of about 1 m over the same time interval.

A number of underwater and coastal archaeology studies supported these estimates (Fouache et al. 2006; Lambeck et al. 2011; Radić Rossi 2012) and verified the applied models. These studies examined ancient harbours (Faivre et al. 2010), fish tanks (Florido et al. 2011), millstone coastal quarries (Lo Presti et al. 2014) and old coastal buildings (Pagliarulo et al. 2013) to detect sea level changes that have taken place from Roman times until the Middle Ages. Approaching modern times and considering the endangered city of Venice, relative sea level rise has been determined from paintings, which realistically reproduce the city in Renaissance and Baroque times, including the height of the algae on palace fronts (Camuffo and Sturaro 2003).

Geomorphological markers found in the Adriatic also support the model results; however, some controversy has been found when using submerged tidal notches (Marriner et al. 2014), as their generation is the result of an ensemble of processes (Antonioli et al. 2015) and not only wave action during periods of stable sea level. Therefore, a multi-proxy approach is used; for example, Antonioli et al. (2009) examined six archaeological sites and a number of tidal notches in the northern Adriatic and reported a relative sea level rise of approximately 2.1 m since Roman times (~1900 year). In addition to these markers, stratigraphic and sedimentological measurements in the northern Adriatic (which is strongly influenced by rivers and therefore has experienced much stronger sediment dynamics in the last several millennia than the middle and southern Adriatic) were also used for determination of relative sea level changes (Furlani et al. 2011; Zecchin et al. 2015). These measurements indicate tectonic subsidence and submersion of that region. Finally, biological markers taken from the western coast of Istria (Faivre et al. 2011) and the central Adriatic (Faivre et al. 2010, 2013) indicate, together with other sea level proxies, that sea level in the last two millennia experienced both stable and changing phases (Fig. 5). The stable ones occurred during the Medieval Warm Period (1000–1500 AD) and are presumably responsible for the creation of most of the tidal notches in the Adriatic.

Finally, computations of isostatically driven land movements in the Adriatic area indicate predominant subsidence of the Adriatic coastal region with rates of 0.3–0.5 mm/year (Stocchi and Spada 2009), which contrast with the results of older models that estimated an uplift rate of 0.2–0.3 mm/year (e.g., Tushingham and Peltier 1989). An exception occurs in the northeastern part, where uplift was documented, presumably due to deglaciation of the Alpine area since the last glacial maximum (Stocchi et al. 2005). These results are in line with recent studies, which find a tectonically driven uplift of the northeastern coastal area of 0.1–0.25 mm/year in the last 80 kyr (Surić et al. 2014).

4.1.2 Present-Day Vertical Land Movements

Before the era of satellites and precise GPS measurements, the determination of vertical land movements in the Adriatic region has been based largely on models of post-glacial rebound and eustatic sea level rise (Pirazzoli 2005), taking into account the tectonics of the area (Nicolich 2010). Tectonically driven sea level changes are modelled to contribute to a subsidence ranging from 0.4 mm/year along the Italian coastline to zero along the eastern Adriatic coast (Di Donato et al. 1999). Older in situ data that include an analysis of comprehensive levelling data indicate subsidence over the majority of the eastern Adriatic coastline (Joó et al. 1981). A contrasting conclusion has been reached based on an analysis of only long-term tide gauge time series (Orlić and Pasarić 2000), and this study found a 1 mm/year relative uplift of the southeastern vs. the northeastern Adriatic coastline. The latter has been confirmed by kinematic models (Rožić 2015). The above differences between various analyses may result from different measuring periods or epochs, and indicate that there are still open research questions to be investigated in the future.

The era of satellites provided a new tool for estimating vertical land movements at different sites by using altimeter data (García et al. 2007) and continuous GPS measurements collocated with tide gauges (Wöppelmann et al. 2007). Buble et al. (2010) estimated vertical land motions along the eastern Adriatic that ranged between moderate subsidence (−1.7 ± 0.4 mm/year) in the southern Adriatic Sea and steady state (0.0 ± 0.4 mm/year) in the northern Adriatic. However, upon applying an advanced algorithm to GPS and tide gauge data, Wöppelmann and Marcos (2012) identified uplift along the eastern Adriatic coastline that ranged from 1.33 ± 0.24 mm/year at Dubrovnik to 1.58 ± 0.20 mm/year at Trieste (Table 2). Subsidence is certainly ongoing along the northwestern Adriatic coast, with vertical land movement values from −1.2 to −2.0 mm/year at Venice and much stronger subsidence in the southern Po plain (Zerbini et al. 2015). Subsidence at Venice has been locally amplified by anthropogenic activities in the mid-twentieth century and is still detectable in the recent vertical land movements (Bock et al. 2012; Tosi et al. 2013).

4.1.3 Sea Level Trends and Their Multidecadal and Decadal-Scale Variability

At the end of the twentieth century, sea level time series of considerable length became available for a

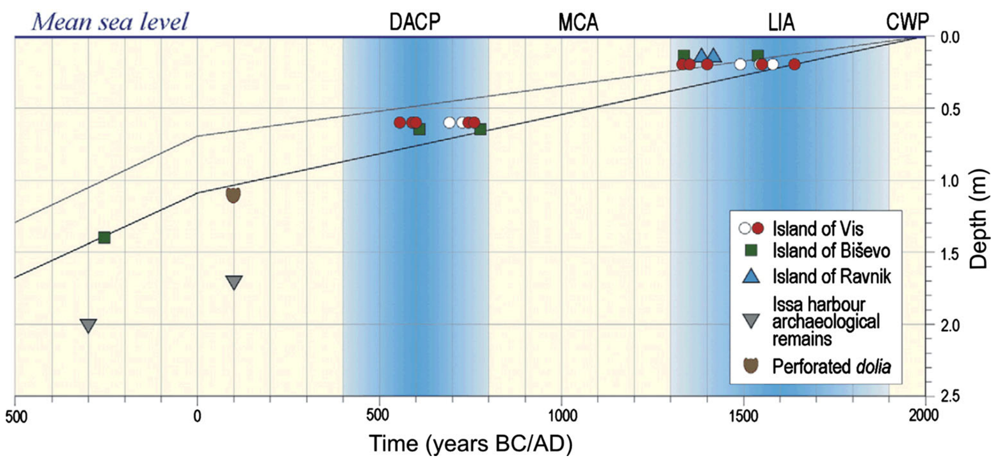


Figure 5
Comparison between the model predicted relative sea level change for the Central Adriatic, *black line*—Lambeck et al. (2004), *grey line*—Lambeck and Purcell (2005), and the 14C dated algal rim samples from the Vis, Biševo and Ravnik Islands. *Empty circles* indicate results obtained with AMS technique and *full symbols* by LSC technique (Faivre et al. 2013)

Table 2

Rates of sea level change from tide gauge records and corrected for land movements from different solutions: combination of altimetry and tide gauge data using the classical and the advanced approaches, GPS, and GIA

Station (PSMSL)	No correction	Altimeter—TG (classic)	Altimeter—TG (advanced)	GPS-corrected (ULR solution)	GIA-corrected (SELEN)
Venezia (PDS)	2.45 ± 0.09	0.42 ± 1.32	1.24 ± 0.21	3.85 ± 3.06	2.02 ± 0.21
Trieste	1.28 ± 0.07	0.97 ± 0.4	1.58 ± 0.20		0.87 ± 0.20
Rovinj	0.53 ± 0.17	2.48 ± 0.45	1.27 ± 0.25		0.07 ± 0.26
Bakar	1.03 ± 0.12	1.06 ± 0.51	1.46 ± 0.22		0.46 ± 0.26
Split Marjan	0.64 ± 0.16	0.20 ± 0.47	1.25 ± 0.24		0.06 ± 0.26
Split G. Luka	0.64 ± 0.16	−0.05 ± 0.48	1.33 ± 0.24		0.06 ± 0.26
Dubrovnik	1.02 ± 0.16	0.52 ± 0.41	1.33 ± 0.24	0.1 ± 0.35	0.42 ± 0.23

Values are in mm/year (from Wöppelmann and Marcos 2012)

number of Adriatic tide gauge stations, stimulating widespread interest in the underlying trends. The simplest approach, which was followed by a series of authors, was to fit a straight line to the whole time series obtainable from each particular station (Barnett 1984; Pirazzoli 1986; Stravisi and Ferraro 1986; Bilajbegović and Marchesini 1991; Emery and Aubrey 1991; Šegota 1996; Tsimplis and Spencer 1997). Most studies showed that the relative sea level rise is quite similar at stations in the eastern Adriatic (Trieste, Rovinj, Bakar, Split and Dubrovnik) as recorded from the beginning of measurements (1870–1950s) to the 1980s, with trends ranging from 0.8 to 1.4 mm/year. The corresponding trend at Venice was found to be higher and to amount to 2.5 mm/year, which was attributed to the pumping of water from underground sources (Pirazzoli 1986; Tosi et al. 2013). The largest trend (8.3 mm/year) was detected at the Porto Corsini station in the western Adriatic between the years 1937 and 1972 (Emery and Aubrey 1991), pointing to pronounced land subsidence in the area.

At the start of continuous measurements by satellite altimeters in 1993, a comparison of trends documented by the new instruments with the trends provided by tide gauges became feasible. The comparison performed for the whole Adriatic over the period 1993–2008 (Fenoglio-Marc et al. 2012) indicated that the satellite altimetry trend (3.2 mm/year) was higher than the tide gauge trend (1.9 mm/year). Both were, however, considerably larger than the trends provided by a majority of Adriatic tide gauges over longer time intervals, thus indicating that the rate of sea level rise has changed recently. These trends have also been quantified by a variety of ocean models applied to the Mediterranean (e.g., Calafat et al. 2012). Although they provide reasonable qualitative estimates, the models are still not fully capable of reproducing the Adriatic Sea level trends, given that (i) they do not account for exchanges with larger basins, since they are regional and boundary conditions are limited by constant sea level in general (Tsimplis et al. 2013), on top of (ii) some processes, such as dense water generation, decadal oscillatory patterns and deep thermohaline changes, that are not yet properly quantified (Dunić et al. 2016).

It has been known from at least the 1940s that the Adriatic trends vary with time and depend heavily on the length of the time series over which they are computed. The accumulation of data enabled the processes involved to be addressed more thoroughly. Thus, for example, trends computed for the Porto Corsini station before and after 1950 showed an increase from 3.7 mm/year to 16.9 mm/year (Bondesan et al. 1995; Marzocchi and Mulargia 1996), indicating an intensification of local land subsidence in the mid-twentieth century.

The deceleration of sea level rise observed in the Adriatic and elsewhere in the Mediterranean in the 1960s was important for the whole region. This peculiar behaviour was noted by Douglas (1992, 1997), Orlić and Pasarić (1994, 2000), Tsimplis and Baker (2000) and Woodworth (2003, Fig. 6). They applied a variety of techniques and identified a decrease in sea level trends in the second half of the twentieth century, not only at the Adriatic stations Trieste, Rovinj, Bakar, Split and Dubrovnik, but also in the Western Mediterranean (stations Marseille and Genova). This finding stimulated an interest in the possible causes. The deceleration was partly attributed to air pressure and wind forcing, based on the relationship between meteorological and sea level data (Orlić and Pasarić 1994, 2000; Tsimplis and Baker 2000) and on the results obtained using a barotropic model of the Mediterranean Sea (Tsimplis et al. 2005). Moreover, an increase in density of the Adriatic and Mediterranean waters was found to occur at the time when sea level was at minimum (Tsimplis and Baker 2000). This finding was further supported by considering the variability of steric sea levels in various parts of the Mediterranean (Tsimplis and Rixen 2002; Tsimplis et al. 2008b), including the Adriatic Sea (Tsimplis et al. 2012). To summarise, in the second half of the twentieth century, the Mediterranean Sea level was influenced by the Atlantic sea level but was also modulated by some regional phenomena—anomalous air pressure and wind forcing and contraction of the water column.

A recent preliminary analysis, which relied on the Adriatic and Mediterranean Sea level data collected over the period 1928–2008, subjected to a low-pass filter and approximated by a third-degree polynomial, reproduced the deceleration in sea level rise in the middle of the twentieth century and revealed an acceleration that commenced in the 1990s (Orlić and Pasarić 2013a, Fig. 7). It would, thus, appear that the Adriatic/Mediterranean Sea level standstill is over, as is also indicated by satellite altimeter measurements (Fenoglio-Marc et al. 2012), which coincidentally started when the dynamics of the area changed.

In addition to the multidecadal variability, decadal-scale oscillations are also considerable in the Adriatic Sea. The latter had been detected already in the 1940s, and subsequent measurements showed that the oscillations persisted with a remarkable stability of amplitudes and phases. Bidecadal and/or decadal oscillations were detected by fitting a cosine to the time series collected at Trieste (Stravisi and Ferraro 1986) as well as Rovinj, Bakar, Split and Dubrovnik (Orlić and Pasarić 1994, 2000), by applying a filtering method to the Trieste data (Mosetti et al. 1989) and by spectrally analysing the Trieste time series (Unal and Ghil 1995). It has been found that the amplitude of the bidecadal oscillation is close to 2 cm, and that these oscillations peaked in the beginning of the 1960s and the 1980s over the whole Adriatic (Orlić and Pasarić 2000). Because neither the amplitude nor the phase of the Adriatic bidecadal oscillation agrees with the theoretical

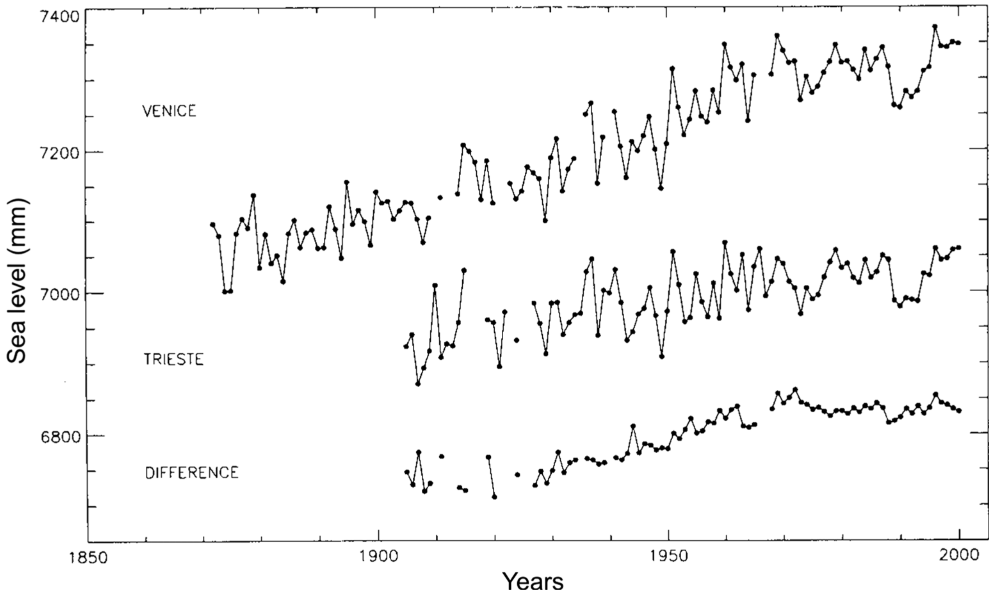


Figure 6
Annual mean sea levels recorded at Venice (*top*) and Trieste (*middle*) and their difference (*bottom*). Offset of the time series is arbitrary (Woodworth 2003). It is obvious that during the first half of the twentieth century the sea level increase was much larger at Venice than at Trieste, and that the increase slowed down at both stations during the second half of the century

values for the equilibrium nodal tide, it has been concluded that the oscillation is not of tidal origin. On the other hand, the Adriatic bidecadal oscillation could be related to the global bidecadal signal, which manifested itself in the Adriatic area in the low air pressures and the high air and sea surface temperatures that occurred in the early 1960s and 1980s, as well as in the low salinities that were observed at the beginning of the 1980s. All these factors caused Adriatic Sea level to have a bidecadal rhythm (Orlić and Pasarić 2000).

It is an open question how the pronounced decadal oscillations in the oceanographic properties of the Adriatic, including the interplay between warmer and saltier and colder and fresher water masses entering the Adriatic through the Adriatic–Ionian Bimodal Oscillating System (BiOS, Gačić et al. 2010), affect the Adriatic Sea level oscillations. Additionally, the BiOS is strongly manifested in the northern Ionian Sea, where it can severely affect the trend estimates (Vera et al. 2009; Calafat and Gomis 2009). The existence of decadal-scale oscillations in the Adriatic and Mediterranean Seas implies that the sea level trends could incorporate prohibitively large errors if determined over short time intervals. An analysis of the incurred errors showed that the interval should be at least 30 years long if the error is to stay below ±0.2 mm/year (Orlić and Pasarić 2000).

4.1.4 Seasonal Sea Level Changes and Interannual Variability

Recent investigations of seasonal sea level changes benefited from time series secured from lengthy tide gauge measurements. Tsimplis and Woodworth (1994) fitted annual and semiannual cycles to a global dataset. For the Adriatic area they obtained annual amplitudes ranging between 3.8 and 4.7 cm and semiannual amplitudes varying from 2.4 to 4.0 cm. The corresponding phases implied that the maxima occurred in October/December at the annual period and in May/June and November/December at the semiannual period. Similar computations performed over 5-year intervals on the Split sea level series by Vilibić (2006b) revealed strong interannual and decadal variability, with annual and semiannual cycle amplitudes both ranging between 1 and 8 cm.

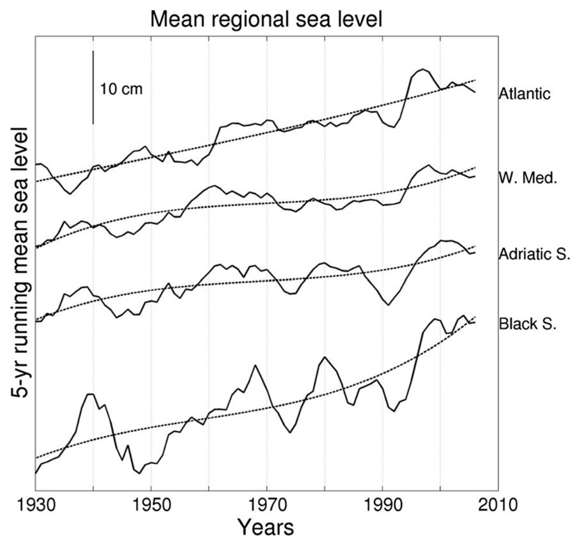


Figure 7
Full lines depict time series of sea level registered by tide gauges in the Atlantic close to Gibraltar and in the Western Mediterranean, Adriatic and Black Seas and smoothed by a 5-year moving average (Orlić and Pasarić 2013a). *Dashed lines* indicate cubic fits superimposed to the time series. It is obvious that the Atlantic sea level was rising and was slightly accelerating during the interval considered, whereas the sea level rise in the other areas decelerated in the middle of the twentieth century and accelerated at the end of the century. The rise was much larger in the Black Sea than in the Western Mediterranean and Adriatic Seas

The annual cycle maximum was found to occur between October and February, with a significant trend from late autumn and early winter (December) in the 1950s and 1960s towards mid-autumn (October–November) in the 1990s. The analysis performed by Larnicol et al. (2002) on the satellite altimeter data revealed that the annual amplitudes vary considerably over the open Adriatic, unlike the annual phases that are quite stable in the basin. A further contribution to the study of seasonal sea level changes came from satellite gravimetry. Preliminary analyses of the data by Fenoglio-Marc et al. (2006), although they did not address the Adriatic specifically but rather the whole Mediterranean, showed that the seasonal sea level cycle is influenced not only by steric contributions but also by variations in the mass of the seawater.

Theoretical studies indicate that seasonal sea level changes depend on air pressure and wind effects (Gill and Niiler 1973), on the influence of heat flux, and on the water-flux forcing resulting in both isostatic and non-isostatic variability (Orlić 1993). To determine the origin of seasonal sea level changes in the Mediterranean area, various numerical models have been used. By applying a barotropic model driven by air pressure and wind forcing, Marcos and Tsimplis (2007) obtained for the Adriatic area amplitudes for the two cycles not surpassing 2 cm. According to this analysis, the cycles' maxima occur in March/April (annual cycle) and in January/February and July/August (semiannual cycle). Fukumori et al. (2007) accounted for not only the wind stress but also the boundary heat and water fluxes in their baroclinic modelling, thus reproducing both the wind- and buoyancy-driven seasonal changes and therefore bringing the computed seasonal sea level cycle closer to the observed one. Additionally, Pinardi et al. (2014) allowed for mass transport through the sea surface and through the Strait of Gibraltar in their modelling study and showed that the variability of the mass of seawater is important in the Mediterranean area at seasonal scales.

Interannual sea level variability was investigated in the Adriatic and the wider Mediterranean area using various time series: anomalies computed relative to the mean seasonal cycle (Orlić and Pasarić 1994, 2000, Fig. 8; Bregant et al. 2005; Fukumori et al. 2007; Landerer and Volkov 2013), mean annual values (Tsimplis and Josey 2001; Tsimplis et al. 2013), mean seasonal (usually wintertime) values (Tsimplis and Josey 2001; Zanchettin et al. 2006; Tsimplis et al. 2013), and annual and semiannual amplitudes and phases computed for each available year (Marcos and Tsimplis 2007). The studies resulted in several findings that are consistent and therefore reinforce each other.

Orlić and Pasarić (1994, 2000) showed that the Adriatic Sea level anomalies are strongly related to the air pressure anomalies occurring at the same time. Regression analysis indicated that a 1.0 mbar increase (decrease) of air pressure corresponds to a 1.8–2.0 cm lowering (rising) of sea level. The inverted barometer overshoot was explained in that sea level responds not only to air pressure but also to other coherent forcing agents (e.g., wind). Fukumori et al. (2007) compared wind-driven sea level anomalies obtained using the Mediterranean model with satellite-derived sea level anomalies corrected for the inverted barometer effect. The correlation

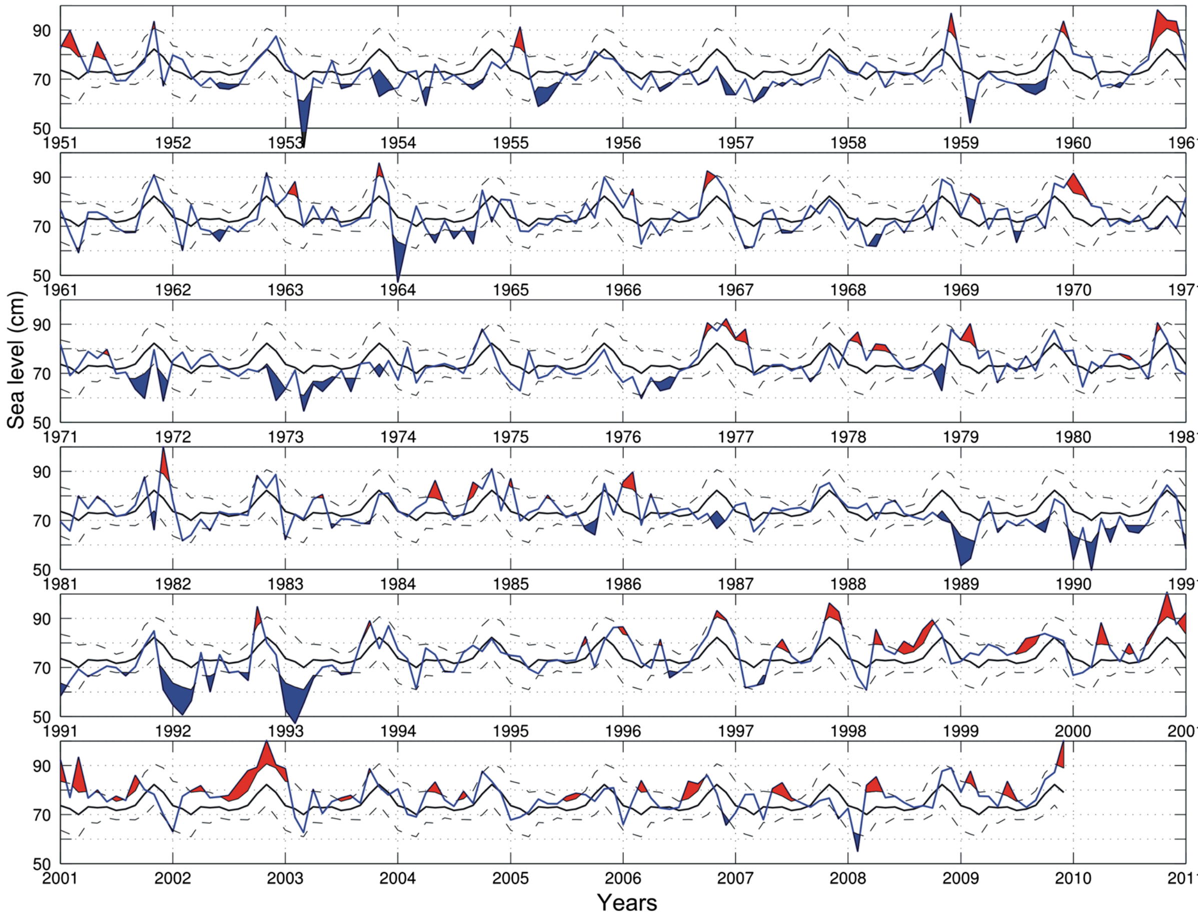


Figure 8

Monthly mean sea levels recorded at Bakar between 1951 and 2009 (Orlić and Pasarić 1994, with updates). Also shown is the mean seasonal cycle, computed over the whole interval and drawn for each year (*black solid line*), together with the corresponding standard deviations (*black dashed lines*). Significant positive anomalies are *shaded red*, whereas significant negative anomalies are *shaded blue*

coefficients were found to be high (amounting to 0.75). A careful analysis of the model results showed that the variability is driven by winds at the Strait of Gibraltar and its neighbouring regions: the winds force a net mass flux through the strait and thus influence the Mediterranean Sea level. Landerer and Volkov (2013) found a close relationship between anomalies determined from satellite altimetry and corrected for the air pressure effect and those registered by satellite gravimeters. They, therefore, concluded that the Mediterranean Sea level anomalies are mostly of a barotropic nature. Moreover, they attributed the air pressure-adjusted sea level anomalies to concurrent wind anomalies near the Strait of Gibraltar, and found that the correlation is highest between the Adriatic sea levels and the Strait of Gibraltar winds.

A number of authors found a link between interannual sea level variability and the North Atlantic Oscillation—NAO (Tsimplis and Josey 2001; Bregant et al. 2005; Zanchettin et al. 2006; Tsimplis et al. 2013). The analyses revealed that the NAO impact on the Adriatic and Mediterranean sea levels is mostly related to the air pressure and wind forcing, and to some other processes controlling mass exchange between the Atlantic and the Mediterranean.

4.2. *Regional Sea Level Extremes*

4.2.1 *Response to Planetary-Scale Atmospheric Forcing*

About one-third of the Adriatic Sea level variability occurs at time scales between 10 days and several months (Pasarić and Orlić 2001). It is induced by slowly varying air pressure changes and the associated winds related to the passage of planetary atmospheric waves over the sea (Penzar et al. 1980; Orlić 1983). These waves are best observed in the middle troposphere (Fig. 9). Due to seasonal variability of the atmospheric forcing, these subsynoptic (here we refer to frequencies 0.01 cpd $< f <$ 0.1 cpd) sea level oscillations are particularly energetic in winter (Pasarić and Orlić 1992) when their amplitude occasionally surpasses 30 cm. The sea level field is highly coherent over the Adriatic (Pasarić et al. 2000) and throughout the northeastern Mediterranean (Lascaratos and Gačić 1990). The oscillations are in phase over the region, with somewhat larger amplitudes in the northern Adriatic than further south.

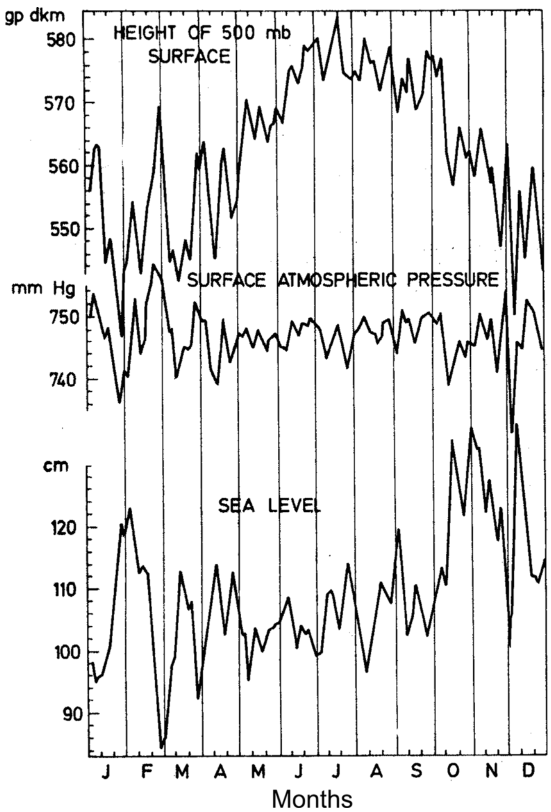


Figure 9
Time series of geopotential height of 500 hPa level over the Adriatic (*top*), surface air pressure (*middle*) and sea level (*bottom*) at Dubrovnik, from January to December 1976, all low-pass filtered at 10 days (Penzar et al. 1980)

According to empirical analyses, the adjustment of sea level to local, slowly varying air pressure departs from the inverse barometer (IB) response of −1.0 cm/hPa in the Adriatic (Pasarić and Orlić 1992) and other parts of the Mediterranean (Palumbo and Mazzarella 1982; Tsimplis and Vlahakis 1994; Tsimplis 1995; Le Traon and Gauzelin 1997). However, theoretical results indicate that the Otranto (Lascaratos and Gačić 1990) and other major Mediterranean straits should not restrict the flow at low frequencies and that the IB response is to be expected (Garrett 1983; Garrett and Majaess 1984; Candela 1991; Pasarić and Orlić 1992). The apparent overshoot in the observed sea level response in the Adriatic is attributed to wind setup. The longshore wind has substantial energy at subsynoptic frequencies. It is highly coherent with the along-basin air pressure gradient, which produces a strongly biased estimate of the barometric factor (Pasarić et al. 2000). As is the case for interannual variability, the atmospheric pressure over the Mediterranean Sea is the main force that drives subinertial flow through Gibraltar, but wind stress on the Atlantic side of Gibraltar may contribute noticeably to the net exchange (García Lafuente et al. 2002; Landerer and Volkov 2013) and produce the apparent departure from the IB adjustment in the Mediterranean (Fukumori et al. 2007). The full explanation is provided in next-to-last paragraph of Sect. 4.1.4.

Subsynoptic air pressure disturbances and the related winds, which are associated with planetary waves, lead to prolonged intervals of raised (or lowered) sea level, thus providing long-term preconditions for flooding. However, the physics and timescales of the forcing create the potential to forecast the floods a week in advance (Pasarić and Orlić 2001). Storminess and extreme sea level amplitudes associated with the planetary-scale forcing show a weakly negative trend in the Adriatic and other parts of the Mediterranean over the last fifty or so years, in contrast to the predominantly positive trends in the northern Europe (Vilibić and Šepić

2010), which may be attributed to changes in general atmospheric circulation.

4.2.2 Storm Surges

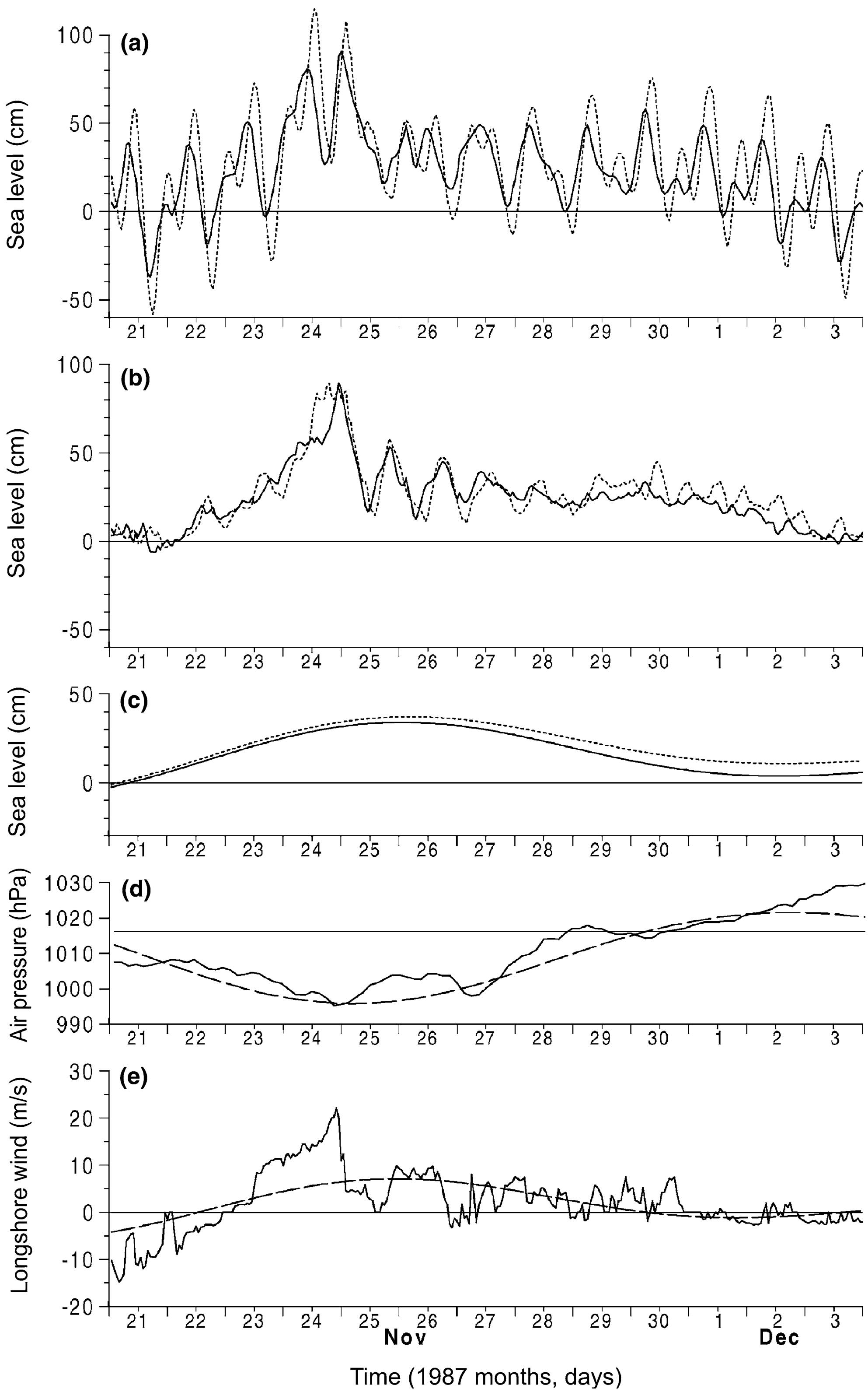
By the end of the twentieth century, decades-long measurements of the Adriatic Sea level enabled not only case studies of storm surges to be carried out but also statistics of the events to be considered. Moreover, available computing power had so increased at the time that the modelling of storm surges could be extended from the Adriatic to the wider Mediterranean area. Thus, the problem of selecting open-boundary conditions in the Otranto Strait could be avoided.

The Adriatic flooding events (Fig. 10) are influenced by a number of processes, but the strongest events are predominantly controlled by storm surges (Pasarić and Orlić 2001, Fig. 11). Therefore, when interpreting statistics of extremely high sea levels, most authors primarily concentrate on storm surges and, when considering long time intervals, also on sea level trends. Sea levels that are expected to be exceeded with various return periods were reported for Venice (Smith 1986), Rovinj (Vilibić et al. 2000) and a number of other Adriatic stations (Marcos et al. 2009b). The typical 50-year return sea levels expressed relative to the mean sea level were found to amount to approximately 150 cm in the northernmost Adriatic and to decrease in a southeastward direction.

Figure 10
Photos of the flood (acqua alta) in Venice in 1902 (*top*, https://oliaklodvenitiens.wordpress.com/tag/venezia) and 1966 (*bottom*, http://www.veniceguideandboat.it/history-of-venice)

Several authors have addressed the temporal evolution of sea level maxima. Analyses of the mean annual cycle have confirmed that the highest sea levels tend to occur from October to April (Trigo and Davies 2002; Raicich 2003; Lionello et al. 2012a).

Even more attention has been paid to the long-term variability in extremes related to the corresponding variability of storm surges on the one hand and of mean sea level on the other hand. In Venice, it has been found that storm surges were more frequent in the 1751–1792 interval than in the 1872–2004 interval (Raicich 2015), that the frequency of large storm surges was stable while the frequency of moderate storm surges decreased between 1940 and 2008 (Lionello et al. 2012a), that the number of independent high sea level events, i.e., those separated by at least a week, increased between 1927 and 1997 but remained stable between 1958 and 1997 (Trigo and Davies 2002), that the frequency of extremely high sea levels was stable while the frequency of moderately high sea levels increased between 1968 and 2000 (Pirazzoli and Tomasin 2002), and that the frequency of extremely high sea levels decreased while the frequency of moderately high sea levels was stable between 1957 and 2005 (Raicich 2010). In Trieste, a decrease in the frequency of large storm surges and little change in the frequency of moderate storm surges has been observed between 1939 and 2001 (Raicich 2003), a stable frequency of extremely high sea levels and an increasing frequency of moderately high sea levels has been detected between 1939 and 2001 (Raicich 2003), a stability of highest monthly sea levels has been documented between 1927 and 2011 (Masina and Lamberti 2013), and a slight increase in maximum sea levels has been found between 1939 and 2005 (Marcos et al. 2009b).


(a)
(b)
(c)
(d)
(e)
Sea level (cm)
Air pressure (hPa)
Longshore wind (m/s)
21 22 23 24 25 26 27 28 29 30 1 2 3
Nov
Dec
Time (1987 months, days)

◀Figure 11
The Adriatic flood of 24 November 1987 (Pasarić and Orlić 2001). The time series of **a** sea level at Bakar (*full line*) and Venice (*dashed line*), **b** corresponding residual sea levels, **c** corresponding sea levels low-pass filtered at 10 days, **d** air pressure recorded at Rijeka (*full line*) and low-pass filtered at 10 days (*dashed line*), and **e** northwestward wind measured at Split (*full line*) and low-pass filtered at 10 days (*dashed line*)

An overall picture emerging from these studies is that variability of sea level extremes was controlled by variability of both storm surges and mean sea level during the twentieth century but it was influenced primarily by storm surge variability during the last part of the twentieth century. This agrees with the finding, documented in Sect. 4.1.3, according to which the Adriatic mean sea level was stable between 1960s and 1990s and it was rising before and after that interval. Difference in the variability of storm surges as observed in Venice (Lionello et al. 2012a) and Trieste (Raicich 2003) could probably be ascribed to a change in the type of storm surges and related cross-basin sea level slope. Apparent inconsistencies between some of the findings may be reconciled by allowing for different ways of defining sea level extremes. Thus, for example, Pirazzoli and Tomasin (2002) have computed their frequencies from hourly values, whereas Raicich (2010) has determined his frequencies from the highest daily values, implying that their differing findings probably reflect a change in duration of storm surges rather than an inconsistency.

On at least three occasions, it has been noted that there is an 11-year signal in the sea level maxima observed at Venice since 1930s (Smith 1986; Pirazzoli and Tomasin 2007/2008; Barriopedro et al. 2010). It is, however, not clear whether the signal is related to the sunspot cycle, as claimed by some authors, or to the decadal (and possibly bidecadal) oscillation in the atmosphere–sea system, which is mentioned in Sect. 4.1.3 of the present paper.

Studies of particular storm surges have continued over the last several decades, and these studies are usually based on a combination of data analysis and numerical modelling. They have provided some novel findings on the processes controlling storm surges. Because the response of the Adriatic Sea to the synoptic air pressure forcing approaches the inverted barometer response, as confirmed by a cross-spectral analysis of meteorological and oceanographic data (Karabeg and Orlić 1982), recent studies have addressed primarily the wind forcing. Cerovečki and Orlić (1989) considered the flood of 31 January–1 February 1986 and have attributed it to a constructive superposition of two successive sirocco-driven maxima. Orlić et al. (1994) have analysed the bora-driven event of 14 April 1982 and showed that the wind-curl effect resulted in considerable spatial variability of both positive sea surface displacements along the west coast and negative sea surface displacements along the east coast. Moreover, Zecchetto et al. (1997) concentrated on the bora-driven episode of 22–24 December 1994 and found that the Venice Lagoon reacts to the bora forcing by a southwestward upsloping of sea level and by an inflow to the lagoon through the Lido inlet and an outflow through the Malamocco and Chioggia inlets. De Zolt et al. (2006) revisited the famous Adriatic storm surge of 4 November 1966 and showed that it was related to a sirocco characterised by an exceptionally long fetch. Finally, Međugorac et al. (2015) compared the recent flood of 1 December 2008, which was more pronounced along the east coast, to the storm surge of 4 November 1966, which had the greatest impact along the west coast, and concluded that the difference between the two cases depended heavily on the sirocco wind shear, which was considerable in 2008 and negligible in 1966.

On several occasions, the Adriatic storm surges have been hindcasted by numerical models and the model performance has, thus, been tested (De Vries et al. 1995; Wakelin and Proctor 2002; Zampato et al. 2006, 2016; Calafat et al. 2014). All of these storm surge models covered the whole Mediterranean, therefore providing sea levels and currents in the Otranto Strait. It has been shown that the model results in the strait could depart from observations made there and that these differences considerably influence sea levels computed for the basin interior. The storm surge models were driven by the air pressure and wind fields produced by various global and regional meteorological models, not only for the cases in which a sirocco was blowing over the whole Adriatic, but also for the cases when a bora over the northern Adriatic was combined with a sirocco over the middle and south Adriatic. As could be expected, it has been demonstrated that the results of oceanographic models sensitively depend on the atmospheric forcing imposed on them. The usage of ECMWF or Mediterranean-wide atmospheric products for ocean model forcing led to a substantial underestimation of the northern Adriatic storm surges, with significant improvement gained by embedding QuikSCAT wind measurements into the forcing fields, whereas the usage of mesoscale atmospheric model forcing limited to the Adriatic area greatly improved the reproduction of peak storm surge events. These studies have stimulated interest in regular modelling of the Adriatic storm surges and have encouraged increasing use of the models in operational oceanography in the Adriatic.

4.2.3 Basin-Wide Seiches

Due to the sea's complex bathymetry, seiches in the Adriatic Sea span a range of sub-diurnal periods. Aside from seiches which appear locally in bays and harbours at a large number of locations, a prominent feature detectable in sea level records is the Adriatic seiche, the fundamental bay mode of the whole Adriatic Sea, which has a period of approximately 21.2 h (Cerovečki et al. 1997) and makes about 2–3% of the total sea level variance (Vilibić 2006a, Fig. 12). Its higher modes are detected from the sea level time series. These basin-wide seiches have been ascribed mostly to wind forcing; the temporal and spatial characteristics of the sirocco wind are responsible for their strength and modal distribution (Raicich et al. 1999). The first documentation of the Adriatic seiche is a century old (see Sect. 2), and the research on this topic intensified in the second part of the twentieth century, when mathematical and computing techniques (like spectral analysis) became a standard part of ocean research.

At that time, a number of observational studies tried to determine the eigenperiods of the Adriatic-free oscillations. For example, Manca et al. (1974) applied spectral analysis to several years of sea level data from eight Adriatic stations, extracted dominant seiche periods of 21.3 and 10.8 h, and attributed them to the fundamental and the first mode of the Adriatic Sea; they also reported on a number of other significant oscillations. They also quantified the basin-wide distribution of the seiche amplitudes, pointing to the predominance of the fundamental Adriatic mode, which strongly increases in amplitude towards the northern Adriatic. Other spectral analyses of sea level data (Sguazzero et al. 1972; Godin and Trotti 1975; Mosetti and Purga 1983) reported slightly higher periods, potentially resulting from imprecise determination due to the spectral resolution applied and sea level data quality or due to real changes induced by stratification or other processes (Cushman-Roisin et al. 2005) or by changes in mean sea level (Lionello et al. 2005). Cerovečki et al. (1997) analysed twelve prominent seiche episodes over an interval covering a quarter-century, estimated the decay time of the seiche to be 3.2 ± 0.5 days, and ascribed it to energy leakage though the open boundary (the Otranto Strait) as well as to frictional effects. A somewhat higher decay time was estimated by Raicich et al. (1999), but this estimate was based on a single extreme seiche episode that contributed to flooding in the northern Adriatic. Year-to-year changes in the seiche amplitude extracted by a specifically designed bandpass filter documented seasonal variability in its intensity (Vilibić 2000, 2006a), which peaked in February–March with amplitudes two times larger than during the summer. The trend in seiche amplitude has been found to be negative over the 1957–2002 interval (Vilibić 2006a), indicating a change in the forcing mechanism over time.

It is worth mentioning that the Adriatic seiche may induce strong currents with amplitudes amounting to 30 cm/s at topographic constrictions, as was reported in the single observational study done by Leder and Orlić (2004) at the Adriatic shelf break.

Numerical modelling of the Adriatic seiches reproduced the observed seiche periods roughly (Kasumović 1963; Sguazzero et al. 1972; Mosetti and Purga 1983). The estimated periods are highly dependent on the position of the nodal line, which could be adjusted in computations to match the simulated periods with observations. The first computations using 2-D numerical models were performed in the 1970s and successfully reproduced different Adriatic free oscillations (Accerboni and Manca 1973; Michelato et al. 1985). An advancement

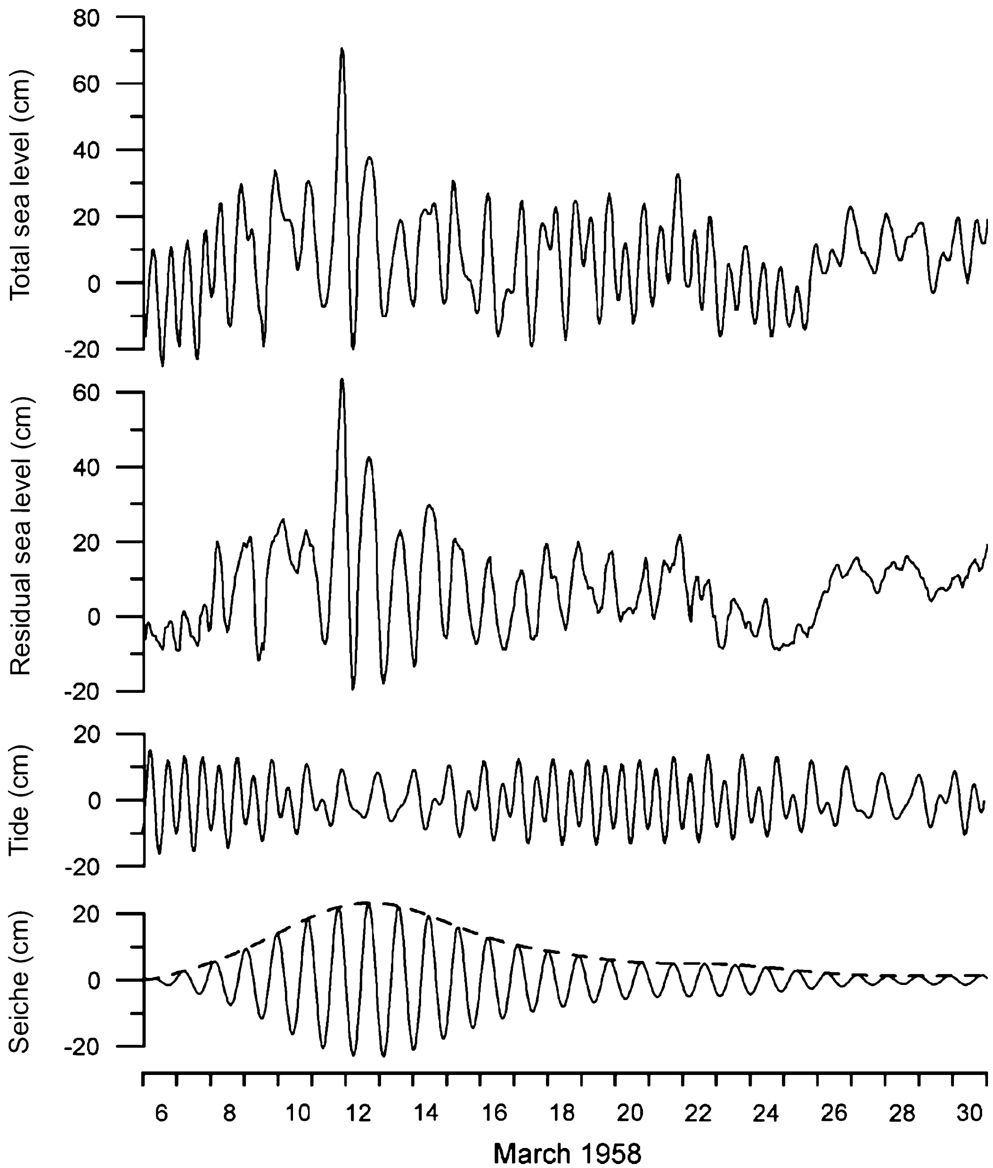


Figure 12
Total sea level and its components (residuals, tides, the Adriatic seiche) extracted during the extreme seiche episode in March 1958 at station Split (after Vilibić 2006a)

in numerical modelling of the seiche was achieved by Leder and Orlić (2004), who satisfactorily reproduced the observed currents and plotted the basin-wide distribution of seiche-induced currents. Nevertheless, all of these studies impose a fixed nodal line in the Otranto Strait, affecting the estimated seiche periods. It is advisable to impose an open boundary at least one wavelength from a presumed nodal line (Okihiro et al. 1993). This restriction was overcome by Schwab and Rao (1983), who extended the modelling domain to the whole Mediterranean and estimated the periods of the fundamental and the first two modes at 21.9, 10.7 and 6.7 h. They also found that the outer nodal line is positioned south of the Otranto Strait and differs in position between various Adriatic seiches.

4.2.4 Tides

The propagation of the Adriatic tides has been known for a century, following early (in the nineteenth century; Pugh 1987) developments of the tidal theory, as harmonic analysis methods were applied to tide gauge data existing in the early twentieth century (Kesslitz 1919; Vilibić et al. 2005b). Older research activities on the Adriatic tides have been reviewed in Sect. 2, while the first basin-wide mapping of the seven Adriatic tidal significant constituents (M2, S2, N2, K2, K1, O1, P1) performed by Polli (1959) should be acknowledged here. He showed that the semidiurnal tides have an amphidromic point in the open Adriatic between Šibenik and Ancona, grow in amplitudes towards the northernmost Adriatic, and have secondary maxima along the southern Palagruža Sill; on the other hand, the diurnal tides rise in amplitudes from the southern to the northern Adriatic. Altogether, the tidal sea level range reaches a metre in the Gulf of Trieste, which makes the Adriatic one of the areas with the largest tides in the Mediterranean. Large semidiurnal tides are a consequence of the Adriatic-wide tidal co-oscillation with incoming and reflecting Kelvin waves (Hendershott and Speranza 1971). Diurnal tides propagate as topographic waves across the basin (Malačič et al. 2000). Both semidiurnal and diurnal tides are near-resonantly amplified on the shallow north Adriatic shelf, as their periods are close to the eigenperiods of the Adriatic Sea (Godin and Trotti 1975).

More recent research activities were mostly concentrated on reproduction of the Adriatic tides with numerical models, first by applying the models to the Mediterranean as a whole (Lozano and Candela 1995; Tsimplis et al. 1995), then by downscaling them to the Adriatic (Cushman-Roisin and Naimie 2002) and finally by assimilation techniques (Janeković et al. 2003; Janeković and Kuzmić 2005). Further downscaling of tidal simulations to the shallow northern Adriatic (Malačič and Viezzoli 2000; Malačič et al. 2000) aimed at documenting topographically driven variability of tidal currents rather than sea level oscillations. This was supported by the analysis of numerous current-meter series in the area (Book et al. 2009), which elucidated details of the tidal dynamics, such as the contribution of the energy flux from the Kvarner Bay to the semidiurnal dynamics. Finally, altimeter data have been used to estimate tidal amplitudes and phases in the Mediterranean and Adriatic regions (Arabelos et al. 2011). The results strengthen the findings of previous modelling and observational studies on the Adriatic tides. The only exception is the area of the Po River delta, where strong variability in both sea level amplitudes and phases has been reported and is also supported by in situ measurements; it is probably the result of strong stratification and horizontal/vertical shear (Chavanne et al. 2007).

4.3. High-Frequency Phenomena

4.3.1 Local Seiches

In contrast to the Adriatic-wide seiches, seiches in Adriatic bays and harbours are predominantly driven by long ocean waves advancing towards a bay or harbour (Vilibić and Mihanović 2003, 2005), as direct forcing is usually not capable of generating significant oscillations within small basins (Vilibić et al. 2005a; Šepić et al. 2008). Incoming waves are normally generated through resonant energy transfer off the harbour entrance (see Sect. 4.3.3). Once they reach a bay or harbour, the waves excite harbour oscillations through harbour resonance. The seiches are stronger if the energy maximum of the incoming waves matches the eigenperiod of the bay or harbour (Rabinovich 2009). For a long time, these oscillations have been commonly noticed by local people in a number of the Adriatic harbours, bays and channels (see details in Sect. 2).

Recent studies on the bay or harbour seiches have been conducted for several Adriatic harbours with long-term high-frequency sea level records, including Split Harbour (Vilibić and Mihanović 2002), Ploče Harbour (Vilibić and Mihanović 2005) and Bakar Bay (Orlić and Pasarić 1997; Šepić et al. 2008). Split Harbour is the largest Adriatic passenger harbour, Ploče Harbour sees large amounts of cargo traffic, and the longest-operating Croatian Adriatic tide gauge is positioned in the Bakar Bay.

Vilibić and Mihanović (2002) applied a numerical model to the Split Harbour, estimated the periods of the normal modes and their distribution and compared them to observations. A similar study has been conducted for the Ploče Harbour (Vilibić and Mihanović 2005), where the measured sea level spectrum (Fig. 13) indicated that a number of normal modes occur in the harbour. The fundamental harbour mode, which has a period of 30 min, dominates the spectrum, but a number of other modes are found to be significant (4.1, 2.6, 1.5 h), probably resulting from the complex bathymetry of the eastern central Adriatic. The 4.1-h oscillation has been frequently found when analysing sea level records in the area, and it may be as strong as the tides there (Vilibić et al. 2005a). The Bakar Bay seiches have been examined for a long time (see chronology in Sect. 2), with recent investigations pointing to the existence of a multi-nodal line of the fundamental bay seiche at the entrance. This line is presumably sensitive to the frequency and energy of the incoming waves, resulting in a wide energy peak between 19 and 27 min (Orlić and Pasarić 1997). Higher normal modes (7.8, 4.3 min) are also observed. Bakar Bay seiches have also been investigated by Šepić et al. (2008), who documented their simultaneous occurrence with air pressure oscillations. A simple analytical model applied to the bay revealed that the local seiches could not be generated by direct atmospheric forcing propagating over the bay; instead, they are produced by distant forcings and the associated waves that propagate towards the bay entrance.

A change in seiche properties induced by interventions to a bay or harbour bathymetry has been modelled for the Split Harbour, where a nautical marina recently built within the harbour affected seiche periods and the spatial distribution of eigenmodes (Vilibić and Mihanović 2005). Seiches of Vela Luka Bay, which are known to have large amplification factors (Orlić et al. 2010) and may flood the city of Vela Luka, may be reduced in height by 30% by construction of a protective pier off the inner harbour (Lončar et al. 2010).

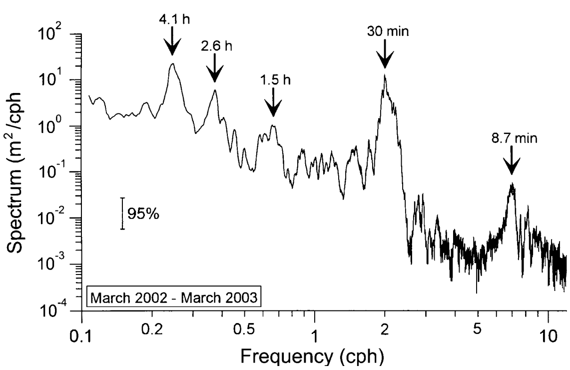


Figure 13
Power spectrum of one-year sea level data (March 2002–March 2003) collected at the Ploče tide gauge. Periods related to significant peaks are indicated (Vilibić and Mihanović 2005)

Remote excitation of local seiches has been extensively researched within the area of meteotsunami studies, where amplification factors have been estimated for Stari Grad Bay (Vilibić et al. 2004) and Vela Luka Bay (Orlić et al. 2010), as detailed in Sect. 4.3.3. The ringing of a number of harbour and channel modes along both sides of the Adriatic has been documented by Šepić et al. (2016), and this excitation is associated with the propagation of open-ocean waves towards the affected harbours. Channel seiches are common along the eastern Adriatic coast, which is characterised by a number of elongated channels such as the Zadar and Pašman Channels (Vilibić and Orlić 1999) and the Pelješac and Mljet Channels (Šepić et al. 2016). The latter seiches have been reproduced with a numerical model, which underlined the importance of bathymetry in the formation of large sea level oscillations and the eventual flooding that was seen by eyewitnesses at a number of coastal settlements.

4.3.2 Seismic and Landslide Tsunamis

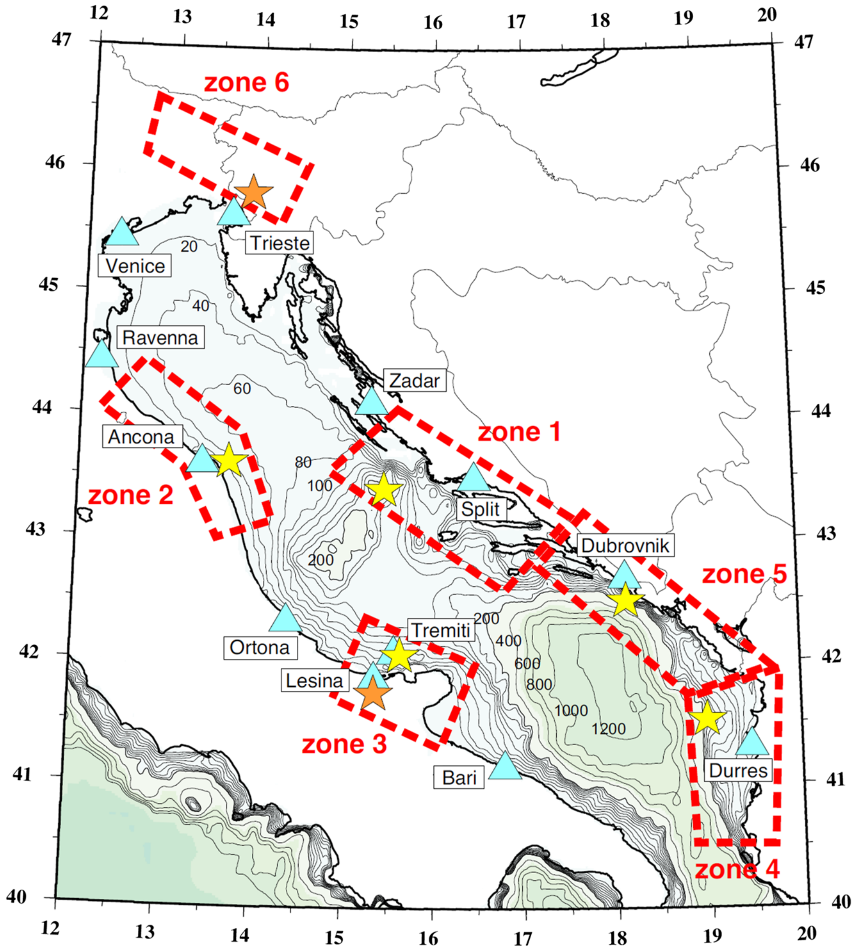
Although the Adriatic has much lower seismic and tsunamigenic potential than some parts of the Mediterranean (Vannucci et al. 2004; Lorito et al. 2015), destructive seismically triggered tsunamis have occurred in the past. Several regional tsunami catalogues cover the Adriatic Sea (e.g., Soloviev et al. 2000; Ambraseys and Synolakis 2010; Maramai et al. 2014) and there are some catalogues that focus on a country rather than on a basin (Tinti and Maramai 1999; Tinti et al. 2004; Maramai et al. 2007). The Adriatic tsunami catalogue (Pasarić et al. 2012) was compiled by re-evaluating all the events reported in the numerous existing catalogues. The analysis of original documents from contemporary sources revealed that a number of these events were actually seaquakes (i.e., seismic P-waves) and not tsunamis. However, several historical tsunamis that did not appear in earlier catalogues were brought to light and added to the list.

The most investigated Adriatic tsunami is the 1627 Gargano event. This tsunami, together with the destructive earthquake that caused it, claimed more than 4000 victims (Guidoboni and Tinti 1988). However, due to imprecise determination of the earthquake magnitude, a reliable reproduction of the event could not be obtained. The developed scenarios strongly underestimated the eyewitness observations (Tinti and Piatanesi 1996), pointing to a coexisting seismically triggered landslide tsunami over the neighbouring shelf break (Minisini et al. 2006). Gargano Promontory is indeed a region in the Adriatic with strong tsunamigenic potential (Tinti et al. 1995). The most recent Adriatic seismic tsunami, recorded by tide gauges with peak-to-trough values of approximately 45 cm, occurred along the southeastern Adriatic coastline after the 1979 Montenegrin earthquake ($M_w = 6.9$) (Orlić 1983/1984; Pasarić et al. 2012). However, eyewitnesses reported the occurrence of several-metre-high tsunami waves at some locations, with one person drowning. Another instrumentally recorded tsunami with a maximum wave height of approximately 10 cm occurring after the 1962 Makarska earthquake ($M_w = 6.1$) has been documented and modelled (Herak et al. 2001). The 1978 Vela Luka meteotsunami, which was recorded by a number of tide gauges, should also be mentioned here, as it was wrongly characterised as a seismic or landslide tsunami (Zore-Armanda 1979; Bedosti 1980); therefore, caution is needed when trying to assign a cause to a particular tsunami-like event. There are a number of other historic tsunami events, and the Adriatic tsunami catalogues (e.g., Pasarić et al. 2012, and references therein) can be consulted for further reading.

The hazard scenarios developed in the Adriatic for seismic tsunamis by Paulatto et al. (2007) and Tiberti et al. (2008) are based on seismological potential derived from earthquake studies and catalogues. Paulatto et al. (2007) mapped six zones in the Adriatic with appreciable tsunamigenic potential, developed worst-case tsunamigenic hazards and performed numerical simulations to estimate maximum tsunami wave heights along the Adriatic shorelines (Fig. 14). They estimated the most hazardous scenario to exist along the southern Croatian and Montenegrin coast, with the maximum wave amplitude of 5 m modelled at Dubrovnik for the most tsunamigenic earthquake with a $M_w = 7.5$ and a focal depth of 10 km. A lower tsunami hazard estimate was obtained by Orlić (1983/1984), who developed the worst-case scenario for the 1979 Montenegrin earthquake, which resulted in 3-m high waves (1.5 m in amplitude) occurring sporadically along the eastern coast. However, according to Paulatto et al. (2007) an earthquake of $M_w = 7.0$, similar to the one that occurred in 1979, would result in a maximum tsunami amplitude lower than 1 m. They also modelled significant tsunami waves for tsunamigenic earthquakes with $M_w = 7.5$ and 10 km focal depth in the central Adriatic (Split area) and Albanian coast, while worst-case north Adriatic tsunamigenic earthquakes have been modelled to have almost negligible tsunamigenic potential. The latter conclusion was also reached by Tiberti et al. (2008), who mapped tsunami maximum wave heights for the Italian coastline only. Furthermore, they found the most hazardous tsunamigenic earthquakes to occur along the southern Adriatic eastern margin, yielding maximum tsunami amplitudes of 2 m at some locations in the western Adriatic.

4.3.3 Meteotsunamis

Meteotsunamis are long ocean waves that have approximately the same spatial and temporal scales as ordinary tsunamis and can affect coastal regions in a similarly destructive way. Meteotsunamis are, however, not generated by underwater earthquakes, volcanic explosions or landslides, but by atmospheric pressure disturbances related to hurricanes, frontal passages, squall lines, internal atmospheric waves, and other processes (Monserrat et al. 2006). Meteotsunamis occur throughout the world ocean (Pattiaratchi and Wijeratne 2015; Vilibić et al. 2016), but the Adriatic Sea is considered to be a meteotsunami "hot spot", i.e., one of the locations where meteotsunamis are common, strong and occasionally destructive (Monserrat et al. 2006; Vilibić and Šepić 2009; Orlić 2015). The locations of known



M	6.5			7.0			7.5			Travel
H (km)	10	20	30	10	20	30	10	20	30	time (min)
Bari	0.02	0.01	<0.01	0.09	0.03	0.01	0.50	0.18	0.05	*42*
Durres	0.05	0.02	0.01	0.29	0.10	0.03	**1.62**	0.56	0.15	*48*
Ortona	0.02	0.01	<0.01	0.12	0.04	0.01	0.67	0.24	0.07	*112*
Dubrovnik	0.16	0.05	0.02	0.89	0.31	0.08	**4.98**	**1.72**	0.47	*4*

Figure 14

Bathymetric map of the Adriatic Sea, with contours of the six tsunamigenic zones shown in *red*, the *yellow* and *orange* stars being the earthquake epicentres of the modelled tsunami events (*yellow*: offshore, *orange*: inland) and the *blue triangles* corresponding to the locations for which tsunami hazard has been estimated. The table gives maximum amplitudes (in metres) and travel times for the Zone 5 earthquake, where *M* is the earthquake magnitude and *H* is earthquake focal depth (Paulatto et al. 2007)

Adriatic meteotsunamis are marked in Fig. 1. It is thus not surprising that much pioneering meteotsunami research has been done precisely for the Adriatic Sea.

The occurrence of atmospherically induced tsunami-like waves in the Adriatic Sea was first described by Caloi (1938) for Trieste. However, research on Adriatic meteotsunamis began in earnest about four decades later, after the Great Vela Luka Flood of 21 June 1978 (Fig. 15). During this event, Vela Luka, a small town on Korčula Island, was struck by a series of devastating tsunami-like waves (heights up to 6 m). The damage was enormous (7 million US dollars, equalling one quarter of the entire annual income of Korčula Island, Vučetić et al. 2009), and the event attracted wide public and scientific attention. Several explanations were soon offered; the event was said to be (i) an earthquake tsunami (Zore-Armanda 1979); (ii) a landslide tsunami (Bedosti 1980); (iii) due to long ocean waves generated by a cyclone (Hodžić 1979/1980); or (iv) due to long ocean waves generated by air pressure disturbances, i.e., due to meteotsunami waves (Orlić 1980). The latter hypothesis was confirmed three decades later by extensive data analysis and numerical modelling (Orlić et al. 2010). The Great Vela Luka Flood remains the strongest known meteotsunami to date.

Subsequent decades brought more destructive events. On 27 June 2003, 3-m high waves flooded Stari Grad on Hvar Island and strong sea currents destroyed a shellfish farm in Mali Ston Bay (Vilibić et al. 2004; Belušić et al. 2007a). In 2007 and 2008, two bays in the northern Adriatic were struck by meteotsunamis; on 22 August 2007, Široka Bay on Ist Island was struck by 4 m high waves (Šepić et al. 2009), and on 15 August 2008, Mali Lošinj on Lošinj Island was struck by 3.5 m high waves (Belušić and Strelec Mahović 2009). Then, on 25 and 26 June 2014, a number of locations in the middle Adriatic were struck by destructive meteotsunami waves reaching maximum wave heights of 3 m in Vela Luka (Šepić et al. 2016). The latter study showed that a number of atmospheric disturbances were responsible for the generation of meteotsunamis along different segments of the coastline, with small details determining large changes in the sea level response. The 2014 event was part of a series of meteotsunami waves which struck the Mediterranean and Black Seas between 23 and 27 June 2014 (Šepić et al. 2015c, Fig. 16). Recently, Orlić (2015) composed an Adriatic meteotsunami catalogue in which a number of additional events, mostly occurring in the middle Adriatic, were described. There is now a regularly updated version of this catalogue on-line as well (Šepić and Orlić 2016).

The Adriatic meteotsunamis occur almost exclusively in summer months, with only 7 out of 22 known events occurring during the colder part of the year (Orlić 2015; Šepić et al. 2016). They are commonly associated with a synoptic situation favourable to meteotsunamis, which includes (i) advection of warm air of African origin from the southwest that is most clearly seen at a height of 850 hPa (ii) strong southwesterly winds with speeds higher than 20 m/s at heights of ~500 hPa embedded in (iii) unstable atmospheric layers present at heights of ~600–400 hPa (Vilibić and Šepić 2009; Šepić et al. 2015a). These conditions, which are also typical of meteotsunamis occurring at other

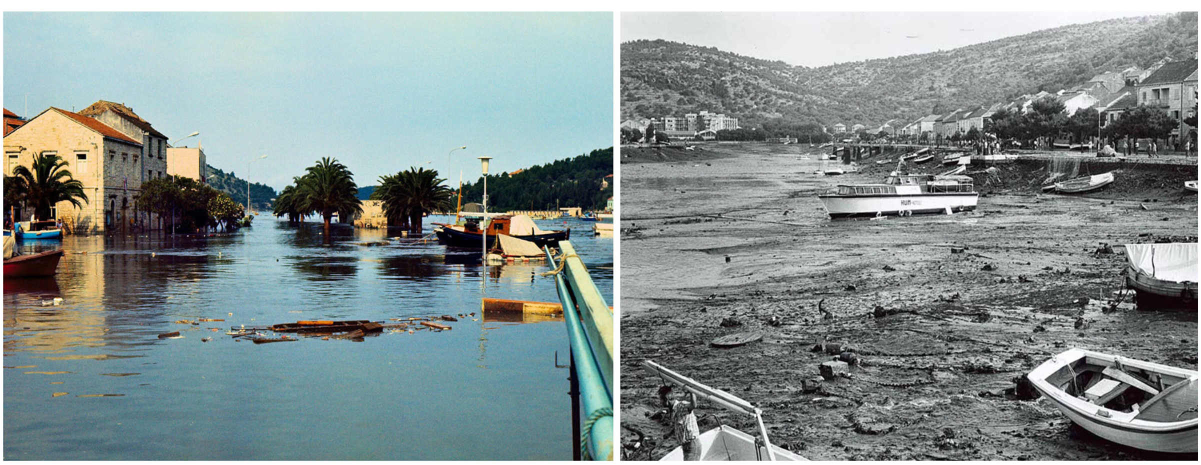


Figure 15
Photos of the Great Vela Luka meteotsunami of 21 June 1978 (after Vučetić and Barčot 2008)

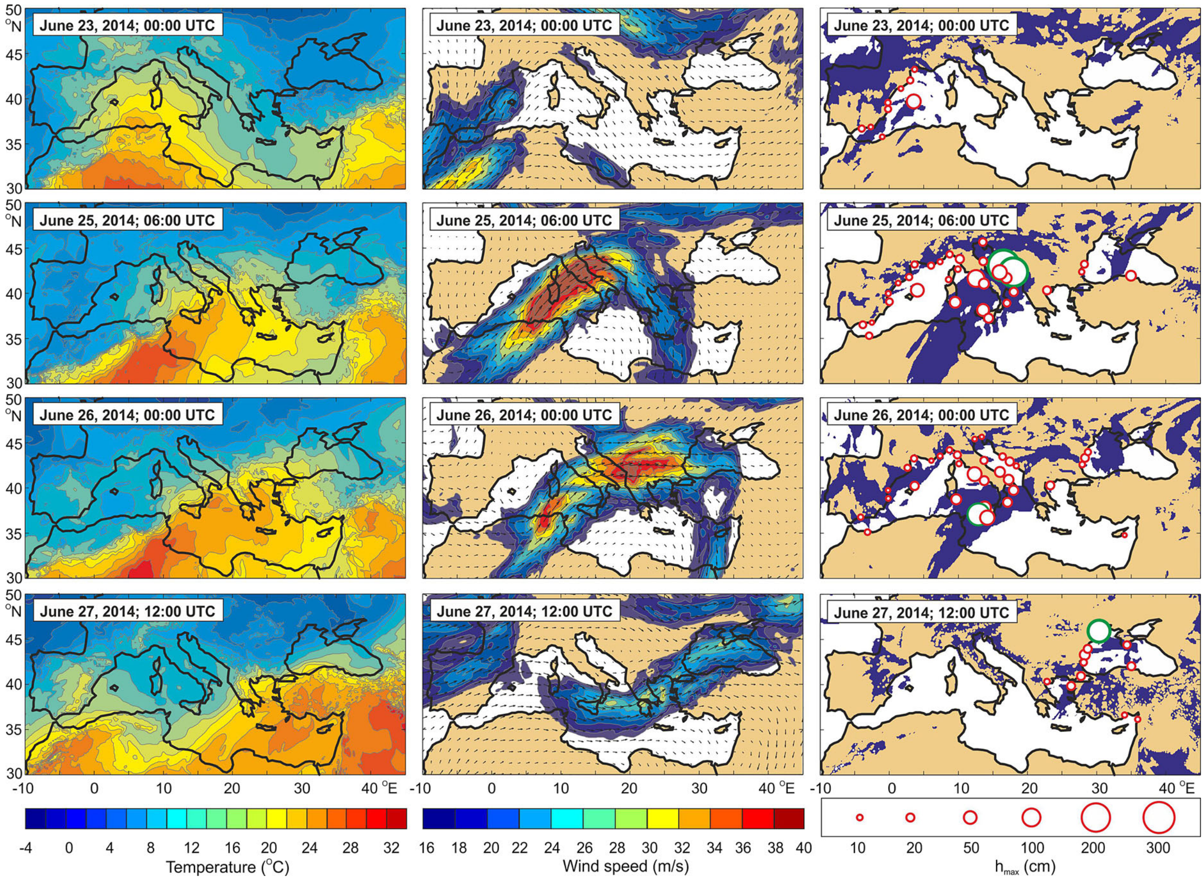


Figure 16
Propagation of the meteotsunamigenic synoptic pattern of June 2014 together with the maximum heights of corresponding sea level oscillations at the times of the meteotsunami events obtained by tide gauge measurements (*red circles*) and eyewitness reports (*green circles*) (after Šepić et al. 2015c)

Mediterranean locations (e.g., the Balearic Islands, Jansà et al. 2007), favour the generation and propagation of ducted atmospheric gravity waves, which are a known source of meteotsunamis. These ducted waves were modelled as the cause of the 2007 Široka Bay meteotsunami (Šepić et al. 2009). However, in their pioneering work on modelling atmospheric pressure disturbances related to meteotsunamis, Belušić et al. (2007a) have shown that Adriatic meteotsunamis can be related to other atmospheric processes as well: the 2003 middle Adriatic meteotsunami was generated by an atmospheric gravity wave supported by the wave-CISK mechanism (which involves positive feedbacks between atmospheric gravity waves and convective clouds). In fact, much important research of the atmospheric processes related to meteotsunamis was first done for the Adriatic Sea: Belušić and Strelec Mahović (2009) were the first to relate the speed of convective clouds determined from atmospheric imagery to the speed of meteotsunami related air pressure disturbances.

Going back to sea level, as air pressure disturbances propagate over the open sea, they generate long ocean waves. If the speed of air pressure disturbances equals the speed of long ocean waves, Proudman resonance occurs, and sea level oscillations can be amplified by several times when compared to the inverse barometric effect (e.g., Hibiya and Kajiura 1982; Vilibić 2008). The larger the rate of air pressure change and the smaller the disturbance width, the larger the amplification will be

(Vilibić 2005). It is interesting to note that the now widely used term Proudman resonance was first introduced by Orlić (1980) in his paper on the Great Vela Luka Flood. Once generated, long ocean waves can be further amplified near the coast due to shoaling, narrowing (in bays), and harbour resonance (e.g., Hibiya and Kajiura 1982; Vilibić et al. 2008). The Adriatic Sea recommends itself as a natural laboratory for studying different aspects of meteotsunami wave growth. The slowly varying northern Adriatic shelf is an almost ideal location for the occurrence of Proudman resonance (Šepić et al. 2015a), whereas the middle and southern Adriatic, with their rapidly changing depths and numerous bays exposed to meteotsunami waves, are more favourable for studying other bathymetric effects, such as amplification in bays, harbour resonance, channel seiches, and other processes. It is thus expected that many more scientific results, as well as advancements in meteotsunami warning system development, might come precisely from scientists investigating meteotsunamis occurring in the Adriatic Sea.

5. Projections, Predictions and Warnings

5.1. Climate Projections

Global sea level rise, as one of the most alarming signals of climate change, has been a focus of public interest over the last two decades. Throughout the twentieth century and especially since the early 1990s, this rise has been accelerating (e.g., Cazenave et al. 2014; Watson et al. 2015). This trend will continue in the future: process-based projections estimate the rise ranging between 44 and 63 cm by the late twenty-first century with respect to the 1986–2005 mean (Church et al. 2013), while semi-empirical projections estimate even higher rates (e.g., Orlić and Pasarić 2013b, 2015). Regionally, the Mediterranean Sea has been recognised as one of the most responsive regions to climate change (Giorgi 2006; Giorgi and Lionello 2008). It experiences large decreases in mean precipitation in summer and a magnitude of warming above the global average. Thus, the Adriatic should experience enhanced evaporation accompanied by reduced precipitation, leading to an overall increase in fresh-water loss to the atmosphere, as well as a reduction in heat loss to the atmosphere (Pasarić and Orlić 2004). These processes may lead to weaker cooling of the ocean or even heat-flux reversal (Dubois et al. 2012). Projections imply warming and salinification of Mediterranean waters from the surface to depths greater than 1000 m (Planton et al. 2012; Tsimplis et al. 2008a), with implications for dense water formation, basin-wide circulation and mass advection through Gibraltar. The changes in the Mediterranean are dominated by those in the Adriatic, where the maximum warming is expected as well as strong salinity increases due to reductions in the outflow of the Po River (Tsimplis et al. 2008a).

The majority of studies have focused either on assessment of steric sea level changes using 3-D models of the Mediterranean (Marcos and Tsimplis 2008; Carillo et al. 2012; Jordà and Gomis 2013; Gualdi et al. 2013; Adloff et al. 2015) or on changes in storm surge statistics estimated by 2-D models applied to both the Mediterranean and Adriatic domains (Marcos et al. 2011; Conte and Lionello 2013; Mel et al. 2013; Androulidakis et al. 2015). Unlike in the open ocean, the halosteric and thermosteric changes in the Mediterranean are of comparable importance. The projected basin-averaged steric sea level change over the twenty-first century equals 13 cm. In the largest part of the Adriatic, however, salinification dominates the warming signal, and the steric change is, thus, close to zero (A2 scenario, Tsimplis et al. 2008a). Multi-model simulations forced by the A1B scenario (Gualdi et al. 2013) yield a 7–12 cm increase of the basin-averaged steric sea level by 2020–2050 with respect to the 1961–1990 period. By contrast, Jordà and Gomis (2013) obtained a lowering of steric sea level (−6.9 cm) over the twenty-first century and under a high emission scenario (A2), as the thermosteric part (+36.1 cm) is exceeded by the halosteric part (−42.9 cm). However, when the contribution of salinity to the change of mass (+56.6 cm) is taken into account, the net effect of temperature and salinity is a sea level rise of 49.7 cm by the year 2100.

The negative sea level trend due to mechanical atmospheric forcing witnessed in the second half of the twentieth century with a maximum in the Adriatic (Gomis et al. 2008) is expected to continue into the future. Due to increases in air pressure by the end of the twenty-first century, a reduction in sea level of up to 2 cm is expected (A2 scenario, Tsimplis et al. 2008a). The combined air pressure and wind forcing during winter impose a negative trend on sea level throughout the Mediterranean, with the maximum (−1 mm/year at A2 scenario) in the Adriatic (Jordà et al. 2012). This trend is related to processes operating at all time scales, from diurnal to planetary scale (Šepić et al. 2012).

Galassi and Spada (2014) took into account the contribution of mass changes and vertical land movements due to glacial isostatic adjustment (GIA) and obtained rates of change in sea level relative to the land. The mass contribution to the Mediterranean-wide sea level rise coming from the melting of terrestrial ice (i.e., the Antarctic and Greenland ice sheets) as well as glaciers and ice caps has been estimated to be 8.5–18.4 cm for the first half of the twenty-first century, while the contribution from terrestrial mass changes excluding ice melting may be neglected. The GIA-induced changes are estimated to be 0.9–1.9 cm. The mass and the GIA contributions are smaller in the Adriatic and are between 7.9–17.1 cm and 0.6–1.5 cm, respectively. When steric changes are included in the estimates (Carillo et al. 2012), the projected relative sea level rise between 2040–2050 and 1990–2000, averaged over the Mediterranean and the Adriatic, equals 9.8–25.6 cm and 11.5–23.8 cm, respectively, with the latter coming largely from terrestrial ice melt. The latter values are significantly higher than what would be expected if secular trends, observed at tide gauges in the north Adriatic, would be prolonged into the future, indicating that the rate of sea level rise might increase by a factor of 2–3 by the year 2050 (Fig. 17). The above total estimates should also be corrected for the direct atmospheric forcing, which may slightly reduce the total sea level rise rates in the Adriatic. Additionally, vertical land movements related to tectonic activity and other processes, rather than GIA, should also be taken into account for proper estimation of relative sea level changes.

Focusing on the Adriatic, Scarascia and Lionello (2013) used existing data to build a linear regression model that they then applied to projected sea temperature and salinity values in order to obtain future sea level in the northern Adriatic. The expected sea level rise by the end of the twenty-first century and under the A1B scenario is between 2.3 and 14.1 cm, with the best estimate at 8.9 cm. The uncertainty comes mainly from the remotely forced sea level rise.

The rise of sea level in the Adriatic during extreme events is of major concern, given that the strongest storm surges in the Mediterranean occur along the coast of the northern Adriatic (e.g., Marcos et al. 2009b). Their occurrence in the future is determined by changes in cyclone activity over the region and by mean sea level changes. Multimodel projections produce an overall decrease in the frequency and intensity of cyclones over the Mediterranean by the middle of the twenty-first century but the northernmost part of Adriatic may expect an increase in the number of extreme-wind storm (Gualdi et al. 2013). Under such conditions, the extreme positive surges will be less frequent and their intensity will be somewhat reduced, with indications that some events would be especially strong (Marcos et al. 2011). The signal is not very strong; several other studies found no significant change in extreme sea levels in Venice (Lionello et al. 2012b; Mel et al. 2013). However, more recent simulations confirm that the predicted weakening of storminess refers more to the frequency, duration and spatial coverage of storm surges, while the trend in the magnitude of annual sea level maxima in the Adriatic changes from negative over the period 2001–2050 to positive over the period 2051–2100 (Androulidakis et al. 2015).

The future projections of extreme sea levels are mainly concerned with storm surges. The evolution of meteotsunamis into the future has not yet been investigated, although they are known to have repeatedly caused considerable damage in some harbours. There are indications that mesoscale activity in the atmosphere, which is responsible for the generation of meteotsunamis, might be further intensified in the future (Gaertner et al. 2007) but this issue should be more closely examined through dedicated climate simulations.

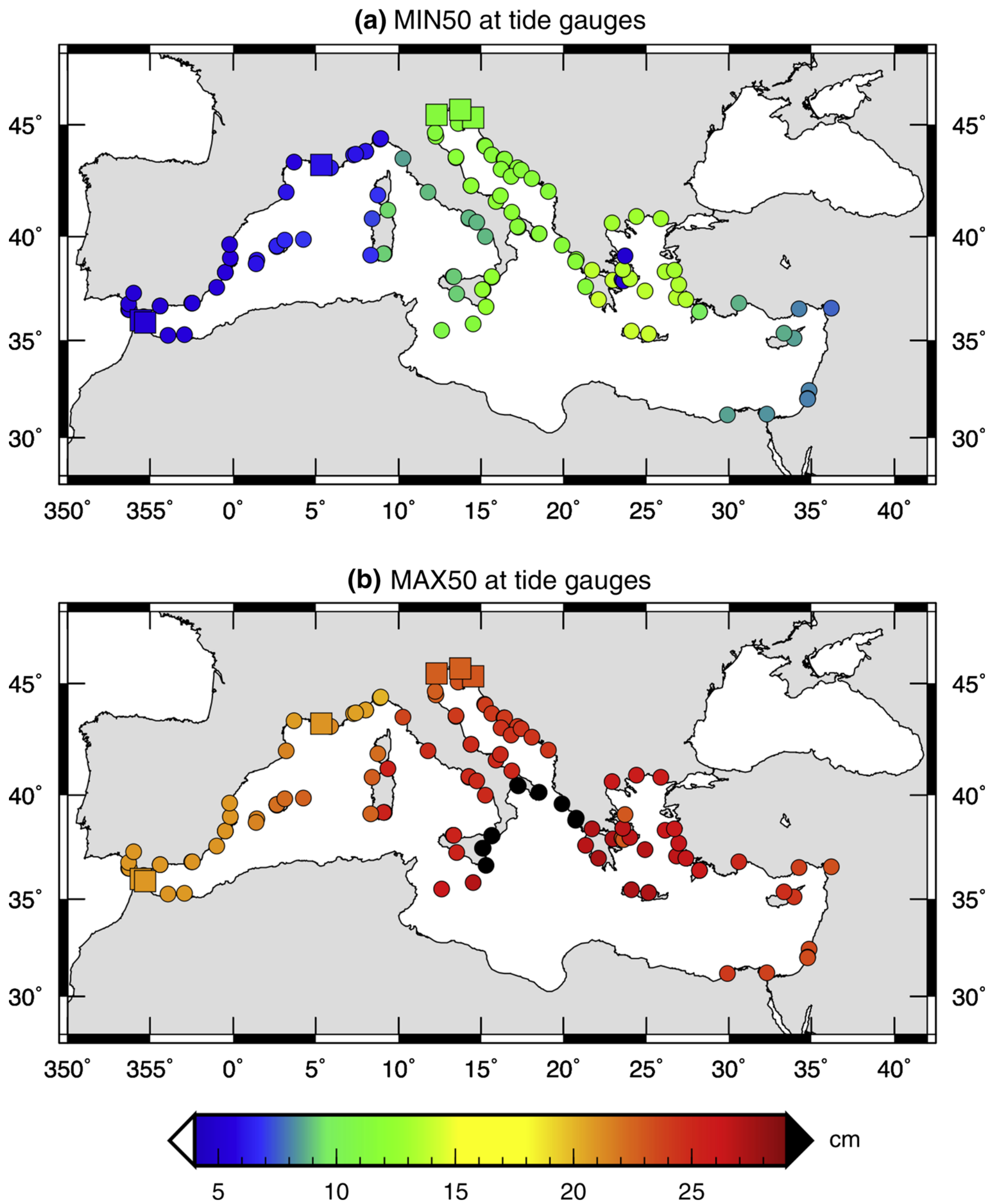


Figure 17

Amount of sea level change at locations of PSMSL tide gauges by 2040–2050, according to (*top*) lower-end and (*bottom*) higher-end scenarios (Galassi and Spada 2014). *Squares* indicate long-term stations where the future change has also been estimated assuming the observed sea level trend

5.2. *Predictions of Storm Surges and Related Flooding Events*

Prolonged floods of the Adriatic coastal area occur on those occasions when sea rises to very high levels. A number of processes contribute to these sea level highs. The most important ones can be divided into tides on the one hand and atmospherically driven phenomena, including planetary-scale sea level variability, storm surges and basin-wide seiches, on the other hand. Contribution of other processes, ranging from seasonal variability to mean sea level rise, is presently relatively small, but this may change in future. Over the greater part of the Adriatic Sea, the tides and the atmospheric contributions to sea level are linearly superimposed, implying that the prediction of the flooding events could concentrate on the atmospheric effects and that the tidal contribution, which can be obtained, for example, from harmonic analysis and synthesis, could simply be added in order to compute the total sea level.

Over the past few decades, statistical and dynamical methods of predicting atmospheric contributions to Adriatic Sea level have been used. Both methods were first employed experimentally and have then been introduced into operational practice. Most operational activities have been carried out at the Istituzione Centro Previsioni e Segnalazioni Maree (ICPSM), which was founded in 1981 as an office of the Venice Municipality.

The statistical method is based on a regression scheme that relates the future sea level in Venice to a number of predictors, with the controlling coefficients being obtained from several decades of simultaneous meteorological and oceanographic measurements. While experimenting with the method, the authors used past sea levels at Venice and past air pressure and wind data recorded at a network of stations as predictors (Tomasin and Frassetto 1979). Subsequent studies also included forecasted meteorological parameters as predictors (Michelato et al. 1983). More recently, nonlinear effects have been considered (Petaccia et al. 2006).

Operational application of the statistical method since 1980s has resulted in an increase of the complexity of the regression scheme used and the number of predictors utilised (Tosoni and Canestrelli 2010/2011). A comparison of published predictions with the observations at Venice has shown that, with lead times of up to 24 h, the standard deviation of the errors ranged from 2 to 8 cm. However, the maximum overestimation amounted to 16–44 cm, whereas the maximum underestimation varied from −13 to −45 cm.

The dynamical method rests on the equations of motion and continuity, which must be solved numerically for a given basin. The atmospheric forcing is supplied by a meteorological model and the open-boundary and initial conditions are defined in an appropriate way. The first experimental attempts at dynamically predicting Adriatic Sea level relied on the Princeton Ocean Model (POM) driven by a mesoscale meteorological model (the Bologna Limited Area Model, BOLAM), with the modelling area being first limited to the Adriatic Sea (Lionello et al. 1998) and then extended to the Mediterranean Sea (Bargagli et al. 2002). In both cases, the models were spun-up over an interval of several days. Comparison of the observed and predicted sea levels for some storm surge episodes pointed to the potential usefulness of the method, thus encouraging its further development.

Today, two variants of the dynamical method are regularly used to produce the Adriatic Sea level predictions. One of them is based on the Shallow Water Hydrodynamic Finite Element Model (SHYFEM), driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) deterministic products. The model domain is the whole Mediterranean, with the Adriatic basin covered by a finer mesh. In experimental applications, simulations are carried out over a month to spin up the model (Zampato et al. 2007; Cavaleri et al. 2010). In operational contexts, two different methods are used to adjust the hindcasted sea levels to the tide gauge records: a post-processing procedure (Bajo et al. 2007) and an artificial-neural-network method (Zampato et al. 2016). By comparing the predictions issued since 2002 with the data collected at Venice, it has been shown that, with lead times of up to 120 h, the standard deviation of the errors ranged from 4 to 11 cm. Moreover, the maximum overestimation amounted to 22–30 cm, whereas the maximum underestimation varied from −32 to −75 cm. Somewhat ironically, the maximum errors were related to extreme sea level events, with the model tending to underestimate the severe storm surges (Fig. 18). The dynamical method performed better than the statistical method for large lead times and was inferior to the statistical method for small lead times.

The other variant of the dynamical method is based on the Hydrostatic Padua Sea Elevation Model (HYPSEM). This model is also forced by ECMWF products, both deterministic (Lionello et al. 2006) and probabilistic (Mel and Lionello 2014a, b). The model is limited to the Adriatic Sea, and a bias removal technique is used in order to allow for the long-period sea level variability forced through the Otranto Strait (Mel and Lionello 2014a, b). Each model run is split into a hindcast interval and a forecast interval, with the observations being assimilated into the model during the hindcast interval in order to identify the optimal initial conditions for the forecast interval (Lionello et al. 2006). A comparison of the predictions produced since 2005 with the observations at Venice has shown that the HYPSEM without assimilation is somewhat inferior to the SHYFEM, whereas the HYPSEM with assimilation is slightly superior to the SHYFEM (Massalin et al. 2007).

An improvement in dynamical forecasting has been achieved by ensembles, instead of single forecasting systems. Based on an analysis of five devastating storms that occurred during the period 1966–2008, Bertotti et al. (2011) compared the ensemble forecasts with the deterministic ones and found that the ensembles extend the reliability of forecasts by about a day or two and can provide forecasts of *acqua alta* up to 6 days in advance. Comparable forecast results to the ones obtained by dynamic forecasting have also been achieved by a combination of a simplified physics modelling corrected by statistical techniques, which has the advantage of low computational time as required for real-time forecasting (Pasquali et al. 2015). Similar approaches have also been used for real-time quantification of storm surge forecast uncertainty (Mel et al. 2014; Mel and Lionello 2016).

To date, experimental and operational predictions of flooding events in the Adriatic have focused on Venice. This activity is expected to intensify in the future, particularly when the building of mobile gates, which could temporarily isolate the Venice Lagoon from the open sea, is completed. Moreover, the activity will most likely expand to other parts of the Adriatic Sea, because some recent events have shown that large sections of both the west and east coasts are prone to flooding.

5.3. Tsunami and Meteotsunami Warnings

Following the catastrophic Indian Ocean 2004 tsunami, the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the Northeastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS) was formed (UNESCO 2009). The countries bordering the Adriatic (Albania, Croatia, Slovenia and Italy) are all

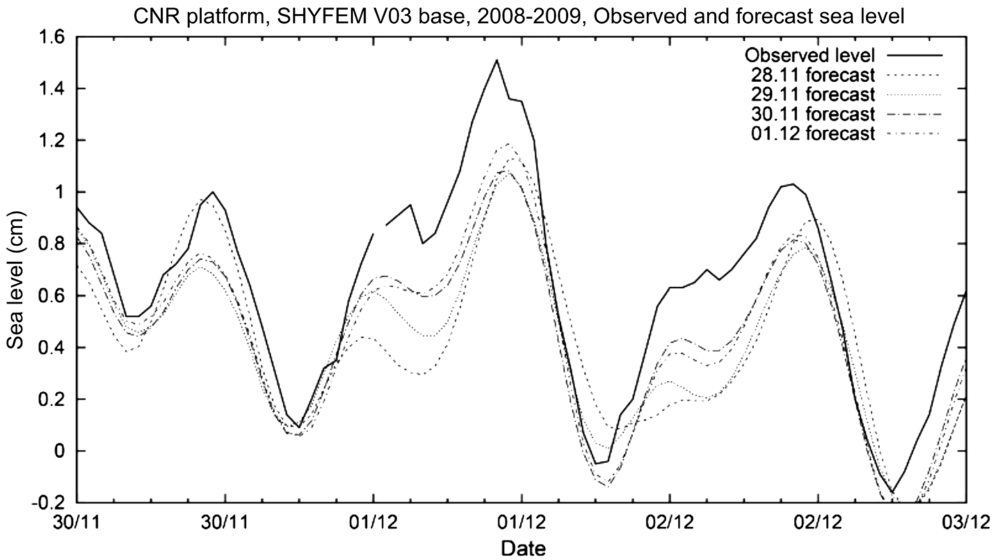


Figure 18
The Adriatic flood of 1 December 2008 (Zampato et al. 2016). The time series represent sea level measured at Venice (*full line*) and sea level forecasted with various lead times (as documented by the legend)

members of ICG/NEAMTWS and are, thus, under its umbrella regarding tsunami warnings.

ICG/NEAMTWS consists of four structural elements: (i) Candidate Tsunami Service Providers (CTSPs); (ii) Tsunami National Contacts; (iii) Tsunami Warning Focal Points (TWFP); and (iv) National Tsunami Warning Centres (NTWCs). CTSPs are responsible for collecting, recording and processing earthquake data to provide rapid initial warnings, computing the arrival time of tsunamis at the national forecast points, collecting, recording and providing sea level data, and disseminating warning messages. Shortly after a potentially tsunamigenic earthquake is detected and its location, depth, magnitude and origin time have been determined (within a few minutes following the earthquake), CTSPs send their first message to the Member State Focal Points and National Warning Centres. Depending on the earthquake parameters, this message can consist of Tsunami Information (no tsunami threat), a Tsunami Advisory (tsunami wave heights less than 0.5 m and larger than 0.2 m and/or tsunami run-up heights less than 1 m, with the potential for local damage), or a Tsunami Watch (tsunami wave heights greater than 0.5 m and/or tsunami run-up heights greater than 1 m, with the potential for considerable damage and loss of life). For more details, see JCOMM (2010) and Tinti et al. (2012). Initial choice of the warning message is based on the Tsunami Decision Matrix (Table 3, also by Tinti et al. 2012). Further messages are based on sea level measurements which serve to either confirm or cancel the warning (the real-time sea level data necessary for tsunami monitoring is available at www.ioc-sealevelmonitoring.org), and, if a tsunami is recorded, include the tsunami travel time, the amplitude and period of the tsunami. Messages from CTSPs are received by national focal points and (if established) National Tsunami Warning Centres. These have an obligation to be available 24/7 to rapidly receive tsunami messages and evaluate and issue national warnings. Within the Adriatic basin, the following TWFPs operate: the National Protection and Rescue Centre (Croatia) and the Istituto Nazionale di Geofisica e Vulcanologia (Italy).

Although meteotsunamis present a non-negligible threat for a number of locations in the Mediterranean (Vilibić et al. 2016) and especially the Adriatic Sea (Orlić 2015, Fig. 15), meteotsunami warnings are currently available only for the area surrounding the Balearic Islands. The Balearic warnings are based either on ocean-atmospheric coupled numerical modelling (Renault et al. 2011; http://www.socib.eu) or on forecasts of general synoptic conditions (issued by La Agencia Estatal de Meteorología). According to Vilibić et al. (2016), an efficient meteotsunami warning system should be based on several elements, including (i) numerical modelling and monitoring of synoptic conditions—in search for potentially meteotsunamigenic situations (Jansà et al. 2007), (ii) coupled ocean–atmospheric high-resolution modelling—to more precisely model the location and strength of potential meteotsunami events (Renault et al. 2011), and (iii) real-time monitoring of atmospheric barometric pressure and sea level at locations far removed from endangered locations (Marcos et al. 2009a; Šepić and Vilibić 2011)—to "catch" meteotsunamigenic air pressure disturbances or meteotsunami ocean waves before they hit endangered locations. A joint Croatian-Italian effort aimed at generating a prototype meteotsunami warning system based on the above elements is currently underway, with the first results expected by the end of 2017 (www.izor.hr/messi).

6. *Research Gaps and Open Issues*

As expected, the synthesis of sea level research in the Adriatic Sea provided in this review generates a number of questions having to do with a range of processes and timescales contributing to overall sea level changes. Some of these research questions are driven by the availability of relevant datasets and observational methods for quantifying a process, while others are related to numerical models, which still require considerable development before they can properly simulate a variety of processes. Additionally, the open research issues regarding Adriatic Sea level cannot be separated from research gaps related to the Mediterranean Sea, which are, according to Gomis et al. (2012):

1. An assessment of the role of straits in determining long-term sea level variability. Particular attention

Table 3

Tsunami decision matrix for the Mediterranean basin (adopted from JCOMM 2010)

Depth	Epicentre location	M_W	Tsunami potential	Tsunami message type		
				Local	Regional	Basin
<100 km	Offshore or close to the coast (≤40 km inland)	>5.5 and ≤6.0	Weak potential for local tsunami	Advisory	Information	Information
		>6.0 and ≤6.5	Potential for a destructive local tsunami (<100 km)	Watch	Advisory	Information
	Offshore or close to the coast (≤100 km inland)	>6.5 and ≤7.0	Potential for a destructive regional tsunami (<400 km)	Watch	Watch	Advisory
		>7.0	Potential for a destructive basin-wide tsunami	Watch	Watch	Watch
≥100 km	Offshore or inland ≤100 km	>5.5	Nil	Information	Information	Information

should be paid to the Strait of Gibraltar, which is also recognised to impact Adriatic Sea level changes over timescales from several weeks to decades.

2. A reduction of high uncertainties in estimates of sea level changes, which are relevant over a span of timescales, from those of Glacial Isostatic Adjustment and vertical land movements, through computation of steric changes, to uncertainties in the assessment of tsunami hazards.
3. A densification of tide gauges along the northern African coast, as the instrumentation gap there directly impacts the quality of Mediterranean Sea level research (Woodworth et al. 2007). More tide gauges should also be installed in straits, like the Strait of Gibraltar and Otranto Strait, in order to precisely monitor the across- and along-slope sea level components and transport through these straits.

These research gaps are also relevant for the Adriatic Sea, in particular those processes that operate on the scale of the Mediterranean. However, there are other topics not addressed by Gomis et al. (2012) or overviewed in this paper, for example sea level changes over paleo-time scales. Additionally, some research issues and gaps are specific to the Adriatic Sea. Although this is not an exhaustive list, we anticipate that the following issues will be relevant for future sea level research:

1. Present sea level monitoring capacities are sufficient for monitoring of the majority of processes and timescales along coastlines, except for those processes that operate at the short timescales, such as tsunamis, meteotsunamis and local seiches. The exception is the eastern shoreline of the southern Adriatic and in the Strait of Otranto (along the Albanian and Greek coastlines), where no operational tide gauges are present. Moreover, no in situ sea level records are available in the open sea; such records might be useful for calibration of a variety of models (simulating ocean circulation, storm surges, and meteotsunamis, among other processes). These data are also necessary for proper calibration of altimeter data in the Adriatic, as coastal tide gauges are biased by the land (Feng and Vandemark 2011). Operational sea level measurements from the open waters of the Adriatic are also necessary for providing more reliable operational tsunami/meteotsunami warnings, which are particularly relevant for the southern and eastern coastlines of the Adriatic.
2. Aside from the existence of tide gauge data, another issue is the availability of the data for research and operational purposes, including the creation of appropriate data sharing policy or policies. The tide gauge data from most of the eastern Adriatic are not readily available to the research community. This gap might be overcome by providing research quality (delayed mode) and operational quality (real-time mode) versions of these data sets to European or world data centres (such as the IOC Sea Level Station Monitoring

Facility and the University of Hawaii Sea Level Centre).

3. The Adriatic Sea is still not properly resolved in climate and paleoclimate ocean models, which are currently being developed for the Mediterranean (e.g., Mikolajewicz 2011; Gualdi et al. 2013). The very first study which verified ocean climate models by in situ data (Dunić et al. 2016) shows that the models are still not capable to resolve large spatial and temporal changes in complex orographically driven ocean forcings in the northern Adriatic. This area in known for a strong air–sea interaction driven by the bora wind (Grisogono and Belušić 2009; Janeković et al. 2014), being the dominant driver of the Adriatic thermohaline circulation through dense water formation. Bora wind is changeable at sub-kilometre spatial scale (Kuzmić et al. 2015) while pulsating over minutes (Belušić et al. 2007b), thus propagation of the model-to-observation error from atmospheric models into ocean models is quite large during dense water formation events. On top of that, the bathymetry in the northern Adriatic is particularly complex, resulting in a bad performance of ocean models, even at 2-km resolution (Vilibić et al. 2017). Therefore, downscaling of these models to higher resolution and improvements in the representation of fine-scale processes in the Adriatic, through statistical downscaling or nesting of the Adriatic model within the Mediterranean, will allow for better assessment of processes operating in the Adriatic at millennial to decadal timescales. That also applies to the sea level issues.
4. An integrated multi-proxy approach in paleo-studies of sea level changes is necessary; these periods still suffer from large uncertainties in the corresponding estimates due to a lack of data (Faivre et al. 2013), and a multi-proxy approach provides much more reliable estimates (Vacchi et al. 2015). Again, the existing data are crucial for these estimates (Dusterhus et al. 2016), which are still much sparser for the eastern than the western and northern Adriatic coasts (Vacchi et al. 2015).
5. A more extensive use of satellite altimetry products in research studies addressing the Adriatic is envisaged, as these series now include more than 20 years of data. Aside from trend assessment (Fenoglio-Marc et al. 2012), these products could be used for assessing seasonal to decadal variability in the Adriatic, for mapping the circulation patterns and, in combination with tide gauges, for closing the sea level budget for the Adriatic.
6. Assessment of hazards posed by nonseismic sea oscillations at tsunami timescales, which may contribute significantly to local sea level extremes, is an open research issue for the Adriatic that is recognised to also be relevant for the whole Mediterranean (Šepić et al. 2015b). As these oscillations are connected with specific synoptic patterns (Jansà et al. 2007; Belušić and Strelec Mahović 2009), establishing a correlation between available atmospheric reanalysis fields and high-frequency sea level oscillations will allow for timely forecasting of these oscillations.
7. A thorough assessment of all components of sea level changes over the Adriatic shorelines through the combined use of long-term sea level records and multi-decadal high-resolution model runs is a long-term goal of sea level research. Such an approach will allow for a proper assessment of processes still neglected in sea level studies, such as the impact of planetary atmospheric waves on extremes and duration of coastal floods (Pasarić and Orlić 1992, 2001), and other.
8. Operational oceanography of the Adriatic Sea that addresses sea level extremes still considers some endangered areas only (such as the Venice Lagoon, Umgiesser et al. 2004); moreover, storm surge forecasts are not available for most of the coastline. This also applies to the forecasting of meteotsunamis for locations where they may occur at destructive levels.

7. *Concluding Remarks*

The paper provides an extensive review of the best available knowledge dealing with sea level changes in the Adriatic Sea, a small Mediterranean basin that exhibits a variety of unique attributes and processes affecting sea levels over a range of spatial and temporal scales. This includes (i) microplate tectonics and subsidence, which induce a high degree of spatial difference in relative sea levels over limited regions; (ii) a large number of ancient natural phenomena and human settlements, which allow for proxy-based reconstruction of sea levels over millennial timescales; (iii) a well-developed orography, which directs synoptically driven winds to follow the orientation of the basin and thereafter induce significant storm surge heights at the basin head; (iv) a basin size that produces a strong near-resonant amplification of tides and free oscillations; and (v) a complex coastline with a number of funnel-shaped bays and elongated channels and a shelf fronting the coastline, representing perfect conditions for the appearance of multi-resonances occurring over time scales ranging from a minute to an hour and the generation of destructive tsunami-like waves with wave heights several times those of tides; and more. This review will surely be of help in future studies of Adriatic Sea level, particularly in that it identifies research gaps and indicates potentially interesting and important research topics. Furthermore, we hope that this review will help in assessing sea level changes in other coastal basins, as well as enclosed and semi-enclosed seas with similar sizes and geographical characteristics, for which the Adriatic Sea may be recognised as a laboratory.

Acknowledgements

This work has been supported by the Croatian Science Foundation through Projects 2831 (CARE) and UKF 25/15 (MESSI).

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(Received January 20, 2017, revised July 10, 2017, accepted July 15, 2017, Published online July 24, 2017)