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Ocean Science
Discussions

Coastal Sea Level Monitoring in the Mediterranean and Black Seas

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Abstract. Spanning over a century, a traditional way to monitor sea level variability by tide gauges is – in combination with modern observational techniques like satellite altimetry – an inevitable ingredient in sea level studies over the climate scales and in coastal seas. The development of the instrumentation, remote data acquisition, processing and archiving in last decades allowed for extending the applications towards a variety of users and coastal hazard managers. The Mediterranean and Black seas are an example for such a transition – while having a long tradition for sea level observations with several records spanning over a century, the number of modern tide gauge stations are growing rapidly, with data available both in real-time and as a research product at different time resolutions. As no comprehensive survey of the tide gauge networks has been carried out recently in these basins, the aim of this paper is to map the existing coastal sea level monitoring infrastructures and the respective data availability. The survey encompasses description of major monitoring networks in the Mediterranean and Black seas and their characteristics, including the type of sea level sensors, measuring resolutions, data availability and existence of ancillary measurements, altogether collecting information about 236 presently operational tide gauge stations. The availability of the Mediterranean and Black seas sea level data in the global and European sea level repositories has been also screened and classified following their sampling interval and level of quality-check, pointing to the necessity of harmonization of the data available with different metadata and series at different repositories. Finally, an assessment of the networks' capabilities for their usage in different sea level applications has been done, with recommendations that might mitigate the bottlenecks and assure further development of the networks in a coordinated way, being that more necessary in the era of the human-induced climate changes and the sea level rise.

1 Introduction

Coastal sea levels have been monitored for decades by networks of tide gauges in ports and harbours, established by a diverse range of institutions to fulfil their specific needs and requirements. Tidal predictions, datum definition and port operations were the original motivation for creating most of these networks. However, tide gauge data are also needed to understand sea level changes at different spatial and temporal scales and are used by experts in fields such as oceanography, hydrography, meteorology, geodesy or seismology. The sea level sensors, which measure water level height relative to land with high accuracy and high temporal resolution (1-60 min), are essential for monitoring and studying coastal sea level hazards that may threat the coastal strip during episodes of extreme sea levels and coastal flooding, the latter being combination of storm surges, tsunamis, meteotsunamis and infragravity waves occurring atop of ongoing sea level rise (Pugh and Woodworth, 2014). Improved knowledge and assessment of sea level changes in magnitude and frequency is essential for coastal planning, as well as for establishing early warning systems, for which tide gauges are a key element along with other *in situ* measurements and forecasting models.

All mentioned hazards are present in the Mediterranean and the Black Sea (M/BS hereafter) and pose a threat to densely populated coastal areas, cultural heritage and historical cities lying near the shore (Fig. 1) (Reimann et al., 2018). This is particularly relevant for some regions exposed to substantial sea level variations spanning over a range of frequencies (Fig. 1), from minutes (like meteotsunamis or tsunamis) through hours, days, weeks (storm surges, or planetary wave forcing) and seasonal oscillations, to interannual variability and decadal trends (Pugh and Woodworth, 2014).

As the Mediterranean and Black seas are microtidal basins (Tsimplis et al., 1995), the atmospherically-driven component of sea level (storm surge) is often the most common cause of extreme coastal sea levels. Conjoined with wind-generated waves and/or intense precipitation (also related to increased river discharge), flood risks during a storm surge may lead to devastating flooding events (Bevacqua et al., 2019). According to Cid et al. (2016), Tunisian (Gulf of Gabes), Aegean and Adriatic coasts undergo the highest number of sea level extreme events per year. In the Black Sea, the western coast is the most exposed to storm surges (Bresson et al., 2018). Low elevation areas, deltas and sinking land areas (e.g. Venice Lagoon and Po Delta in Italy, Nile Delta in Egypt, Ebro Delta in Spain) are also subjected to the high flood risks during extreme events (Ferrarin et al., 2021; El-Fishawi, 1989; Hereher, 2015; Grases et al., 2020). Consequently, coastal zone management and protection bodies are carrying out extensive sea level measurements to support coastal flooding forecasts and issue timely alerts to the population, like The Tide Monitoring and Forecast Centre of the City of Venice that maintains a network comprising tens of tide gauges. From time to time, exceptional high sea levels in the Adriatic Sea threaten particularly the city of Venice (*acqua alta* phenomena), causing severe flooding and disruption of people's lives. As an example, on November 12, 2019, sea level reached 1.89 m (~ 1.3 m surge contribution), the second highest storm surge since 1966 event (1.94 m) (Ferrarin et al., 2021). Occasionally, at other areas, less extreme storm surge events (~ 0.5 m) are also able to cause, in combination with waves, substantial damage to infrastructure, coastal erosion and flooding episodes (e.g. the storm Gloria hitting the Spanish Mediterranean coast in January 2020: Amores et al., 2020; Pérez Gómez et al., 2021).

Tsunamis are amplified coastal sea level oscillations with periods ranging from minutes to hours, mainly generated by strong submarine earthquakes. The convergence of the African and Eurasian plates makes them a likely hazard in the Mediterranean (Tinti and Maramai, 1996; Tinti et al., 2001; Papadopoulos and Papageorgiou, 2012; Papadopoulos et al., 2014, Maramai et al., 2014, 2019; Samaras et al., 2015), where around 10% of all tsunamis worldwide occur, being particularly destructive in the Hellenic Arc area (Fig. 1b). The earthquakes can reach a magnitude of 7.5 to 8 there, triggering > 5-6 m wave heights. The hazard is lower in the Western MS, but tsunami waves over 1 m can reach most of the M/BS locations (Sørensen et al., 2012; Álvarez-Gómez et al., 2011). A well-known ancient tsunami is the one generated by a strong earthquake (magnitude 8 - 8.5) off Crete in 365 A.D., that caused many deaths and damage in the Middle East and all the way up the Adriatic Sea, and the destruction of Alexandria port and library (event t4 in Fig. 1b). Also, in Greece, around 1600 B.C. a giant tsunami triggered by the collapse of Santorini volcano is considered to have caused the end of the Minoan civilization in Crete (event t5 in Figure 1b). Tsunamis can also be generated by landslides and volcanic eruptions, but these events are mostly localised (e.g. Stromboli volcano, Tinti et al., 2005). Recent tsunami events (like the 9 July 1956 Amorgos 12-m high tsunami, Okal et al., 2009, the 21 May 2003 Algerian tsunami reaching the Balearic Islands shores as a 2-m wave, Alasset et al., 2006;

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Vela et al., 2014, the 20 July 2017 Bodrum Peninsula and the 30 October 2020 Samos Island tsunami, Dogan et al., 2017, 2019) have been recorded by tide gauges. These records then became a valuable source of information for improving tsunami models and therefore for establishing and improving tsunami early warning services. As the tsunami consequences for the coastal population might be disastrous in terms of loss of life and economic damage, several regional tsunami service providers and national tsunami warning systems have been established in the area in recent years (e.g. Schindelé et al., 2015). These systems, capable of assessing tsunamis travel time and providing early-warnings to civil-protection authorities on vulnerable coastal populations, make use of real-time tide gauge networks, for which 1 min or less sampling interval is required.

Meteorological tsunamis (also referred to as meteotsunamis) are atmospherically generated long-ocean waves which have spectral properties alike to those of tsunami waves, and which occasionally – at certain locations - reach destructive heights of tsunami waves (Monserrat et al., 2006; Rabinovich, 2020; Gusiakov, 2021). The Mediterranean Sea is considered to be a meteotsunami hot-spot, i.e. a basin where a destructive meteotsunami occurs once in a decade or more often (Vilibić et al., 2021). The most researched Mediterranean meteotsunamis occur in Ciutadella harbour on Menorca Island (Jansà and Ramis, 2021), several locations along the eastern coast of the Adriatic Sea (Orlić, 2015; Orlić and Šepić, 2019), and at Mazara del Vallo on Sicily Island (Zemunik et al., 2021a). The Mediterranean meteotsunamis are commonly generated by high-frequency (T < 1 h) atmospheric gravity waves which, through the Proudman resonance (Proudman, 1929), generate long-ocean waves while travelling over shelves. The strongest Mediterranean events typically occur during summer months (Vilibić et al., 2021) when synoptic situations which favours generation and propagation of atmospheric gravity waves are more common. Several attempts to construct a reliable meteotsunami warning system for the Mediterranean have been made, all for the Balearic Islands and the Adriatic Sea: these warning systems are designed to have at least one of the listed: (i) real-time monitoring of the atmosphere-ocean conditions (Marcos et al., 2009a; Šepić and Vilibić, 2011); (ii) numerical modelling of atmospheric and ocean processes (Denamiel et al., 2019a; Romero et al., 2019), (iii) assessment of forecasted synoptic conditions (Jansà et al., 2007; Šepić et al., 2016b), or (iv) combination of some of the above (Denamiel et al., 2019b).

Sea level rise, a key indicator of ongoing climate changes, is an underlying threat to some coastal areas in the M/BS, particularly to those already exposed to extreme events and low elevation areas (especially if accompanied by subsiding land). Despite the small number of stations with sufficiently long time series for climate studies, historical monthly mean sea levels from tide gauges have been used to compute coastal sea level trends (Zerbini et al., 1996, Tsimplis and Spencer, 1997; Gomis et al., 2012). These data provide relative sea level trends, relevant for assessing flooding risk and improving coastal protection, often differ significantly from one place to another due to local land movements (El-Geziry and Said, 2020). Absolute sea level trends can be obtained for those tide gauge stations that are co-located with permanent Global Navigation Satellite System (GNSS) stations that provide the vertical land motion correction (VLM). Tsimplis et al. (2005) found tide gauge sea level trends of just -0.4 to 0.7 mm/yr between 1958 and 2001 in the Mediterranean, revealing slower sea level rise than is the global average for the period. This appears to be due to a negative trend of the atmospheric (storm surge) component, which in turn was caused by prolonged positive phase of the North Atlantic Oscillation (NAO). However, the Mediterranean sea level trends have increased significantly since the 1990s. Bonaduce et al. (2016) found for the Mediterranean basin a mean sea level positive trend of 2.44 +- 0.5 mm/yr, based on satellite altimetry and tide gauge data for the period 1993-2012. Taibi and Haddad (2019) used 18 tide gauges in the region with data spanning the period of 1993-2015 and found significant trends ranging from 1.48 to 8.72 mm/yr, after VLM correction, pointing to large spatial differences in the sea level rise.

The majority of the quoted research relies strongly on the tide gauge data, either directly or through their usage in calibration of satellite altimeters. Near-real time data transmission, combined with a progressive upgrade to shorter temporal sampling step, have allowed over the last 15 years the integration of tide gauge data in storm surge and tsunami warning systems. Tide gauge data are also required for validation of global, regional and coastal circulation and tsunami models, coastal engineering or altimetry data calibration. Their multi-purpose and multidisciplinary character are an advantage for the sustainability of the system, ensuring a rather permanent funding in some cases. However, it also presents challenges for basin/regional/global scale network coordination initiatives, and for data exchange between existing international programs. This is particularly the case in the M/BS, where in some countries restrictive national data policies, especially along the Mediterranean coast of Africa, have yielded a spatial distribution of stations with available data biased towards the northern countries (Tsimplis and Spencer, 1997, Woodworth et al., 2009). Several attempts and efforts in the past tried to solve this situation: in 1997, the International Commission for the Scientific Exploration of the Mediterranean Sea (CIESM) and the Intergovernmental Oceanographic Commission from UNESCO (IOC/UNESCO) agreed to cooperate in the research on sea level changes in the M/BS by establishing a long-term monitoring network system named MedGLOSS, connected to the Global Sea Level Observing System (GLOSS) (Rosen and Aarup, 2002, http://www.ciesm.org/marine/programs/medgloss.htm). The programme, very active between 2001 and 2005, fostered the establishment of a network in the region, supporting data contribution to international programs, digitization of old chart records, support on quality control, and even installation and calibration of stations in some countries. Despite the fact that the number of stations has increased significantly in recent years, and that the networks in many countries have been modernised (with modernisation mainly driven by new requirements of tsunami warning systems), there is still an important lack of available data along the southern coast of the basin. Other more recent initiatives launched in the framework of MONGOOS or the IOC/UNESCO have also failed, up to now, to fill this gap. Some national sea level networks were substantially upgraded recently following the technological development (e.g. the Spanish networks: Pérez Gómez et al., 2013; 2014, Italian,French and Croatian radar networks, etc.), providing the data to users following FAIR (Findable, Accessible, Interoperable and Reusable) principles recently established as the standard in the science (Wilkinson et al., 2016).

Acknowledging all these developments, it emerged that a cohesive mapping of *in situ* coastal sea level monitoring capacities in the M/BS basins has not been done for a long time, and even sporadically on national levels (e.g. Vilibić et al., 2005), exceeding the time scale of the technological developments that are rapidly changing the observational landscape in geosciences in general (Le Traon, 2013). The aim of this paper is to assess coastal sea level monitoring capacities at national and basin-scale levels, to survey the availability of the sea level data, to address the appropriateness of the networks for the most relevant sea level applications, and to identify required upgrades, maintenance problems and potential fields of regional cooperation. To achieve this, a survey of coastal sea level infrastructure was conducted in 2021, including most of the relevant

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institutions operating tide gauges in the region. Results of the survey are presented, including information on type of technology, ancillary measurements, co-location with GNSS, data sampling and latency, long term data availability, quality control and funding status. The initiative enabled us to access relevant metadata and reach national contacts, and to improve communication and exchange of experiences between national experts in sea level studies and tide gauge operators. The survey has been complemented with an assessment on data availability in different international data portals and programs targeting different applications, and an analysis of the fit-for-purpose status of the network based on data availability at those areas more threatened by storm surges, tsunamis, meteotsunamis and sea level rise. Following introductory section, Section 2 comprises a description of the tide gauge networks or stations operated by the different contributors and presents the main results of the survey. Section 3 is dedicated to data availability in existing international programs, databases and data repositories. Section 4 provides an assessment of the network to fulfil targeted applications, while Section 5 summarizes the work with several conclusions and recommendations.

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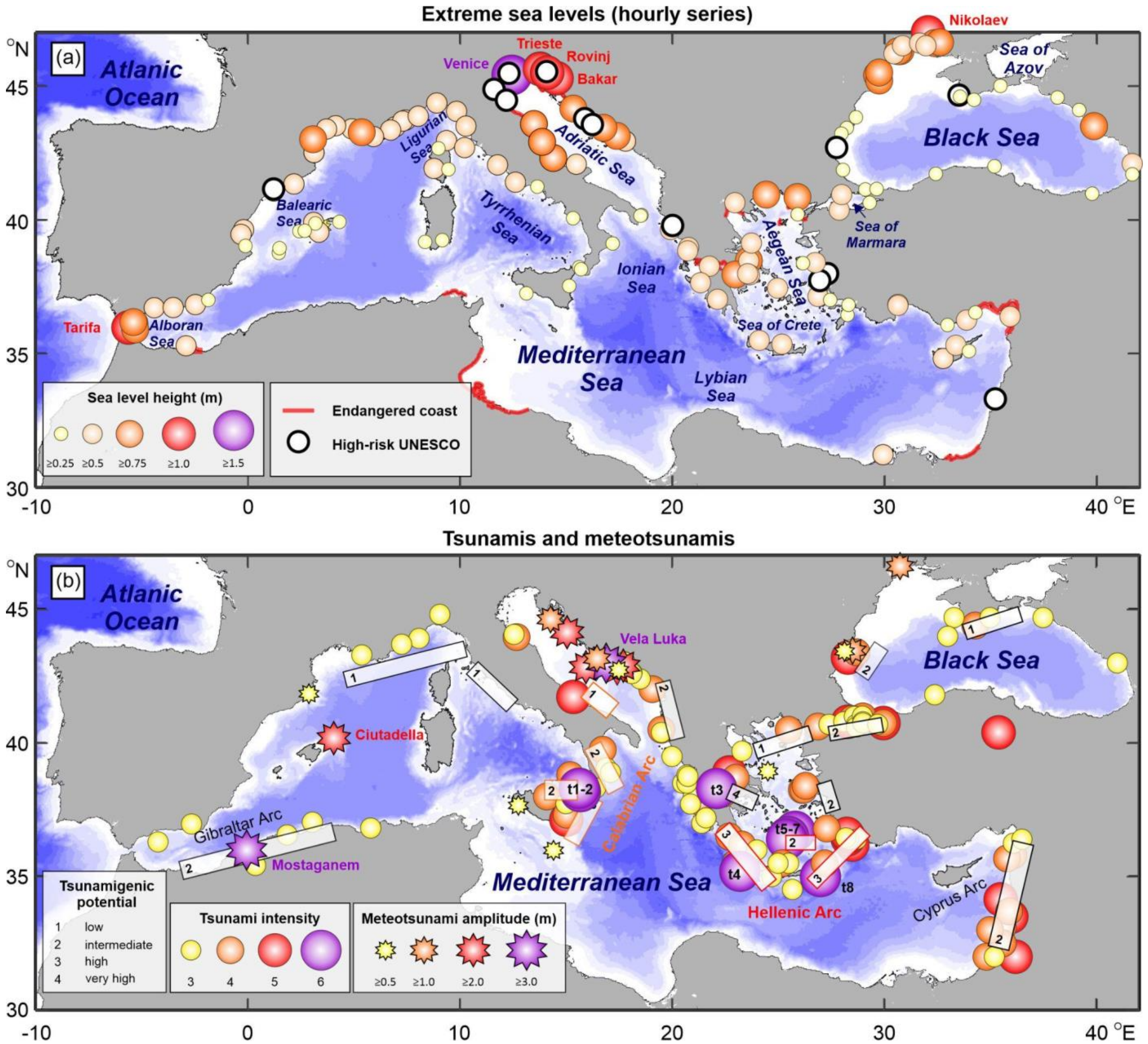

Figure 1. (a) Maximum measured sea levels heights (with respect to a local mean), based on GESLA Version 3 dataset and available national databases, are given (coloured circles); strips of coasts (red lines) and the UNESCO heritage sites (white circles) endangered by present and future-day sea level rise and erosion (after Reimann et al., 2018); (b) Epicentres of earthquakes which resulted with historic tsunamis having intensities of 3 or higher (coloured circles, after Maramai et al., 2014); tsunamigenic fault areas are depicted with white rectangles, and tsunamigenic potential indicated with numbers 1-4 (after Fokaefs and Papadopoulos, 2007, and Oaie et al., 2016); locations of historic meteotsunamis surpassing amplitude of 0.5 m are marked with coloured stars (after Vilibić et al., 2010; 2016; Orlić, 2015; Šepić et al., 2018; Okal, 2021). For extreme hourly sea levels and meteotsunamis, locations at which most extreme events occurred are named; for tsunamis, epicentres of earthquakes leading to the eight most destructive tsunamis are marked with t1-t8.

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2 National tide gauge networks and observations

Operating institutions and operators of tide gauges networks and observing sites in the M/BS region have been identified and contacted throughout 2021. We have received input from 30 different institutions, resulting with brief network descriptions, list of station details (Appendix) and additional questionnaire responses (Supplementary material).

2.1 Networks description

2.1.1 Ports of Spain REDMAR network

The REDMAR network, composed today of 41 multi-purpose radar stations, was established by the Spanish harbour authorities and Puertos del Estado (PdE) in 1992, as an aid to port operations and coastal and harbour engineers. The first three stations in the Mediterranean coast were installed that year at Barcelona, Valencia and Málaga, based on acoustic sensors. Two new stations based on pressure sensors were deployed at Ibiza and Motril in 2003 and 2004, respectively. Ibiza was the first one co-located with a GNSS permanent station, in the framework of ESEAS-RI project, for altimetry calibration (Martínez-Benjamín et al., 2004).

Today, 17 stations are operated along the Spanish Mediterranean coast, including one at Melilla (North of Africa) and 5 at the Balearic Islands. Between 2005 and 2009 all the old stations were upgraded to radar sensors (and 1 min sampling and latency), after an overlapping period of around one year to connect and refer to the same datum the old and the new timeseries (Pérez Gómez et al., 2014). Ancillary atmospheric pressure and wind data (1 min resolution) are measured at 12 of the 17 stations and 7 of the stations are today collocated with a permanent GNSS receiver: Barcelona, Tarragona, Ibiza, Mallorca,Almería, Melilla and Tarifa. Data is displayed through the PdE visualization tool (Portus: https://portus.puertos.es).

All the stations transmit 1 min data with 1 min latency to PdE, the National Geographic Institute (National Tsunami Warning System) and the IOC Sea Level Station Monitoring Facility (SLSMF). Automatic quality control and processing is applied every 15 min for integration in the multi-model sea level forecasting system (Pérez Gómez et al., 2021). In addition, 2 Hz raw data are processed every hour to characterize higher frequency sea level oscillations with periods of minutes (García-Valdecasas et al., 2021). Delayed-mode quality-control and processing is performed annually and monthly mean sea levels are sent to the Permanent Service for Mean Sea Level (PSMSL). The data are also available through CMEMS INS TAC (NRT product), EMODnet and GESLA datasets. Mediterranean stations operated by PdE are listed in Table A1.

2.1.2 SOCIB tide gauge network in the Balearic Islands

The SOCIB tide gauge network (Tintoré et al., 2013; 2019) was established in 2009 and currently consists of six stations around the Balearic Islands, five of which are located on Mallorca and one on Ibiza. The length of the nearly-continuous tide gauge records varies between 5 and 12 years, with the shortest series dating back to 2016. With the exception of the tide gauge in Sant Antoni (Ibiza) that is a radar gauge, the rest are pressure gauges. The sampling frequency is 1 min for all tide gauges. Together with sea level, all stations measure atmospheric pressure, sampled every 30 s, and five of them also monitor water

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temperature every minute. All data are freely distributed in near-real time through the SOCIB website and are also available through the CMEMS INS TAC data portal. Sea level observations are referenced to the tide gauge benchmarks whose positions are controlled on a yearly basis through GNSS surveys. Stations operated by SOCIB are listed in Table A2.

2.1.3 Spanish National Geographic Institute tide gauge network

The tide gauge network of the National Geographic Institute of Spain (IGN) has a set of sensors that gather changes and variations of the mean sea level over the time. It started in the 19th century, when three tide gauges were set up in order to determine the national altimetry datum in Alicante, Santander and Cadiz. The purpose was to establish the required infrastructure to start levelling works. The tide gauge network has been extended and its instruments have been improved since then, including recent upgrades from float to radar sensors. Nowadays the National Geographic Institute has ten tide gauges: five are located in Iberian Peninsula, one in Alboran Island and four in the Canary Islands. Only five are on the Spanish Mediterranean coast. All of them have one or two radar sensors and are linked to GNSS permanent stations. A sea level dataset starting in 1870 has been recently published for Alicante, based on data from historic float gauges and modern radar sensors at this harbour (Marcos et al., 2021). The Mediterranean part of the network is complemented by five IDSL in Cartagena, La Mola de Mahon, Ciutadella, Ceuta.

In addition to maintenance works, network management and connection to High Precision Levelling Network (REDNAP), National Geographic Institute is analysing the historical series of its tide gauges. It is also comparing mean sea level changes with GNSS observations among which a new technique is standing out. It is called GNSS reflectometry (GNSS-R) and it is still under study. Mediterranean stations operated by IGN are listed in Table A3.

2.1.4 Spanish Institute of Oceanography tide gauge network

The sea level data network operated by the Instituto Español de Oceanografía (IEO) consists of 11 stations, six on the Iberian Peninsula, one at Ceuta on the Northern Africa coast, one in the Balearic Islands and 3 in the Canary Archipelago. For historical operative reasons, most of these locations are those in which IEO local headquarters are located. Each tide gauge station is equipped with two sensors: an analogue float-type tide gauge with digital encoder and a radar-based one.

The analogue network is one of the oldest ones in Spain, with some of the measurements dating back to 1943. Historical data are made available through SeaDataNet data portal (www.seadatanet.org). Each of the analogue sensors consist of a float gauge, mechanically connected to an analogue-digital encoder which converts the data to an on-site computer. The radar sensors duplicate the measurements and ensures the measurements continuity when one of the two devices fails. 1 min sampled data are locally stored and recovered via modem by the central data centre once a day, where the data quality is assessed and archived.

The routines for data recovery, quality assessment, detection of high frequency events and data representation are currently being updated, and it is expected that the frequency of data availability will reach 1 per minute by the end of the year 2021. Mediterranean stations operated by IEO are listed in Table A4.

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2.1.5 Spanish Hydrographic Office

Currently, the Spanish Hydrographic Office (IHM) is making a great effort in the installation of a permanent tide gauge network along the national coast. Usually, the IHM installs tide gauges in the hydrographic works area on a temporary basis to be able to calculate the real or reduced probe data. Once the work is finished, the tide gauge is usually removed.

Since 2021, the IHM has installed permanent tide gauges in different ports on the coast: Rosas, Castellón (in the Mediterranean coast) and Huelva (in the Gulf of Cadiz). The intention is to install 8 new tide gauges during 2022, with the objective to further increase density of tide gauges along the Spanish coast. The equipment consists of acoustic sensors with a frequency of 1 Hz and with spatial positioning in real time through a GNSS. At the moment, the web is under development. Mediterranean stations operated by IHM are listed in Table A5.

2.1.6 L'Estartit tide gauge (Meteolestartit, in collaboration with ICM/CSIC-Spain)

The tide gauge is a part of the Meteorological and Oceanographic Station (Meteolestartit) at the harbour of L'Estartit, a coastal town at the Catalan coast, in the NW Mediterranean. It is a float gauge with an analogical record on paper. Recordings are collected every week and digitised with a 2 h resolution. Paper records are preserved for further detailed analyses, if required in some special circumstances, such as seiches. The position of the tide gauge is georeferenced every 5 years by the Catalan Cartographic Institute and sea level data is backwards linearly corrected for each period. Sea level record collection at this point started in January 1990, as part of Meteolestartit, which started in 1969, as a personal initiative of Josep Pascual with the collaboration with the Marine Sciences Research Institute in Barcelona (ICM/CSIC). Data collected included basic meteorological and oceanographic data. More details can be found in Pascual and Salat (2019) and Salat et al. (2019). Details about L'Estartit tide gauge are in Table A6.

2.1.7 SHOM tide gauges network RONIM, France

French Naval Hydrographic and Oceanographic Service (SHOM) has been observing the tides for many years, but the RONIM network, as it exists today, was initiated in 1992, mainly to meet the needs of tide prediction and reduction of bathymetric surveys. It was based on a network which was already in place and which consisted, in 1996, of five tide gauges. It was then densified to reach 23 tide gauges in 2007, including 5 in the Mediterranean (Marseille, Toulon, Nice, Monaco and Ajaccio). Some tide gauges were installed on sites where SHOM already had sea level observations, allowing for continuation of measurements and prolongation of time series. At that time, the Mediterranean tide gauges were equipped with acoustic sensors.

Today, the RONIM network consists of 50 stations of which 14 are currently active in the Mediterranean Sea. All tide gauges are equipped with radar sensors and also have an atmospheric pressure sensor. In the Mediterranean, 3 tide gauges are collocated with a GNSS (Sète, Marseille and Toulon). Most of the tide gauges are equipped with a double real time transmission system: internet and satellite. In the Mediterranean, all tide gauges except Marseille are equipped with satellite

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transmission. The acquisition rate is 1 Hz, and these data are sent directly to SHOM and tsunami warning service by a VPN link.

The 1 min data are computed at SHOM and transmitted in near-real-time to the data.shom.fr website and to the IOC website with a latency of 5 min. The satellite messages are clocked every 6 min. The data transmitted by satellite are also on the IOC website. As there is a double transmission system, on the IOC site, the stations are in double (ex: Toulon (internet transmission) and Toulon2 (satellite transmission)).

The 10 min data is calculated by the tide gauge data logger. They are retrieved once a day and transmitted to the data.shom.fr website.

The RONIM network data are also available on CMEMS INS TAC, EMODNET, GESLA, SONEL, PSMSL data portals.

A major upgrade of the RONIM network is underway (2021/2022). The data logger and the real time transmission process will be replaced, and two additional sensors (webcam + meteo station) will be added at most of tide gauges. A unique supervision system will be implemented for all tide gauges, allowing for a better assessment of real time recording and transmission issues and an improvement of the network reliability. Mediterranean stations operated by SHOM are listed in Table A7.

2.1.8 ISPRA tide gauge networks along the Italian coast

The Italian Institute for Environmental Protection and Research (ISPRA) comprehensively and systematically provides high-resolution estimates for the physical state of the Italian seas as well as real-time monitoring at national and local level. The marine observation system includes two sea level measurement networks: Italian Tide Gauge Network (Rete Mareografica Nazionale - RMN), which continuously monitors the sea level and a number of related meteorological and physical parameters, and the North Adriatic and Venice Lagoon Tide Gauge Network (Rete Mareografica della Laguna di Venezia e del Litorale Nord Adriatico - RMLV) which is used for the real-time storm surge prediction and warning system.

The RMN network is a crucial source of information related to sea level. It provides data useful for analysing sea level variations, predicting storm surges and developing a tsunami early warning system. The RMN consists of 36 measuring stations uniformly distributed along the Italian coast, mainly located within harbours. Some of these stations have been operating since the 1970s. The tidal-wave measurements for the entire network are provided by two different instruments (radar and float) and can be simply configured by a remote command. Each measurement station is also equipped with meteorological sensors: anemometer (wind speed and direction at 10 m above ground level), barometric sensor, multiparametric sensor for humidity and temperature, that are necessary for the real-time evaluation of sea and weather conditions. Four stations (Venezia, Crotone, Gaeta, Carloforte) are collocated with GNSS instruments, to detect the horizontal and vertical displacement of the cabin.

The RMLV network is composed of 26 tide gauge stations equipped for the systematic and widespread measurement of water level and other related parameters, such as wind direction, wind speed, atmospheric pressure, precipitation, and wave-heights in the Lagoon of Venice and along the North Adriatic coastline. Lots of the RMLV stations have been operating for several decades and Venezia - Punta della Salute station for more than 150 years. Real-time data represent one of the main utilities, fundamental for prediction and warnings of exceptional or atypical high tides (storm surges). Two RMLV stations (Venezia Punta della Salute and Grado) are collocated with GNSS in order to detect the continuous vertical shift of the local Zero Tide Level which is the reference benchmark for tide measurements in the Lagoon of Venice (ZMPS). The real-time operability of this network is crucial for several purposes such as: analysis and elaboration of data referring in particular to extreme events (storm surges), signalling and forecasting exceptional high tides. Moreover, data from the Venice Lagoon and North Adriatic tide gauge network (RMLV) is an important source for planning Venice defence from the phenomena of high tides and for scientific studies on sea level variations.

Some IDSL stations were also tested, but the only one still operational is in Marina di Teulada.

Quality-control procedures have been implemented in order to validate sea level historical series and to guarantee data compliance with the international standards. Furthermore, automatic quality control procedures are applied on real-time data. Data are distributed through ISPRA portals (http://dati.isprambiente.it, www.mareografico.it, www.venezia.isprambiente.it and https://tsunami.isprambiente.it/, that is powered by the JRC TAD server software) and through international initiatives (IOC, EMODnet, MONGOOS, EuroGOOS). Stations operated by ISPRA are listed in Table A8.

2.1.9 The Joint Research Center (JRC) IDSL network

Acknowledging the low quantity of sensors deployed on the Mediterranean coasts, the JRC started investigating the adoption of retail technology in 2014, in order to produce a low-cost solution. Since 2014, with the adoption of a few custom components, the reliability of The Inexpensive Device for Sea Level (IDSL) measurements further evolved retaining its best characteristics: low cost (about 2k€), high frequency (5 secs), local intelligence (detection of anomalous sea oscillations through assessing deviation from moving averages).

Funded by the IOC-UNESCO, three campaigns delivered devices throughout the Mediterranean, the Black Sea and the North-East Atlantic. Another collaboration led to providing Indonesia with six IDSL devices. All data collected by the IDSL network are available online through the TAD Server at the JRC web site. Stations operated in Italy by JRC with ISPRA are listed in Table A9.

2.1.10 The tide gauge station of Trieste, Molo Sartorio, Italy

The Italian National Research Council (CNR) operates one station through the Trieste branch of the Institute of Marine Sciences (ISMAR). The station, included in the GLOSS Core Network with No. 340, is located at Molo (Pier) Sartorio, in the harbour of Trieste, and it is equipped with two float instruments with digital encoder, and one 50-year old fully analogue tide gauge. Direct sea level measurements are performed at least twice a month to check the instrument stability. The data quality control is performed in delayed mode at least once a year.

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The tide gauge cabin also hosts two barometers, one of which is digital and one analogue. A GNSS receiver, operated by the University of Bologna, is mounted on top of the building that includes the tide gauge cabin.

The earliest sea level measurements were made in 1859, and since then the tide gauge remained on the same pier; more details can be found in Zerbini et al. (2017). Unfortunately, from 1875 to 1939, only monthly mean sea levels are available (with a few gaps); they can be retrieved from the Permanent Service for Mean Sea Level (PSMSL) data bank. Hourly data are available for 1939-onwards (Raicich, 2019), while 1 min data exist since 2001. Hourly means are available as Fast Delivery data from the University of Hawaii Sea Level Center (UHSLC) since June 2009. The review of pre-1939 data including the digitisation of the available charts is in progress. Details about station Trieste Molo Sartorio are in Table A10.

2.1.11 The mareographic station in Koper, Slovenia

Operational sea level monitoring in Slovenia began in 1958 with the construction of the tide gauge station in Koper, for which hourly sea level measurements are available since 1961. The station is operated by the Slovenian Environment Agency and is collocated with the GNSS station. The existing float-type sensor in a stilling well was upgraded in 2005 with an additional radar sea level sensor, having 1 mm accuracy and 10 min sampling time. It provides sea level data, sea temperature data at 1 m of depth, GNSS data and essential meteorological data (air pressure, wind, air temperature, relative humidity, solar irradiance). The quality-control is automatic, while additional manual controlling of sea level measurements is performed weekly at the station location. Details about station Koper are in Table A11.

2.1.12 Croatian tide gauge network

The Croatian tide gauge network is operated by the Andrija Mohorovičić Geophysical Institute (AMGI), Hydrographic Institute of the Republic of Croatia (HHI), Institute of Oceanography and Fisheries (IOF), National Agency for Water Management Hrvatske vode (Croatian Waters, HV), and by the Ruđer Bošković Institute (RBI). The network consists of permanent stations based on float-type technology installed in stilling wells, established during the 20th century, and of radar-type stations installed from 2004 onward.

Float-type stations: Systematic measurements of sea level in Croatia started in 1929 when the AMGI (Zagreb) established a tide gauge station in Bakar. In the same year, sea level measurements were initiated in Split Harbor by the HHI, but the station was destroyed by bombing in World War II. During the 1950s four long-term coastal stations were installed: Dubrovnik (1955), Split Harbour (1955) and Rovinj (1955) by the HHI, and Split Marjan (1956) by the IOF. The network was again extended when the HHI installed station Zadar in 1990 and Ploče in 2002, and HV installed stations near Mala Neretva river mouth in 1977, at Prosika in 1986 and at Golubinka in 1995. Most of the network was modernized in the early 2000s by mounting a/d (analogue/digital) converters to floats, along with GSM modems for real/near-real-time data acquisition. Modernization was mostly done in the frame of ESEAS-RI project (EU Framework Programme 5). In 2004 an open-air radar sensor was installed at Bakar station and GNSS at Split Harbor station. Ancillary atmospheric pressure (Bakar and Split Marjan) and wind (Split Marjan) measurements are carried out too. Most of the stations locally store 1 min data and transmit them with up to 15 min latency to home institutions. Exceptions are stations Golubinka and Prosika from which data is collected on-site at least once a year. At most stations digital data is automatically quality checked, processed, and displayed (http://geo101.gfz.hr/~bakar/index_files/, https://adriaticsea.hhi.hr, http://vodostaji.voda.hr/) in real-time mode or once a day (Bakar), while analogue data are digitized at hourly resolution, and mostly processed once a year. Maintenance of stations includes regular checks of recorder zero (mainly twice a year), cleaning of the stilling-well and connecting pipe (once in two to five years) and levelling of the contact-point level against tide gauge benchmarks. All stations are levelled towards the national geodetic datum. Most time series have shorter gaps due to various reasons. Monthly and yearly averages from the AMGI, HHI and IOF stations have been sent to the PSMSL since the stations were established.

Since 1950s, additional portable float-type chart-recording tide gauges were occasionally operational along the Croatian coast of the Adriatic, with corresponding sea level measurements spanning over periods from 1 to 18 years, depending on location: Vis and Ušće Neretve (measurements during 1957), Mali Ston (1957-1959), Broce (1957-1959), Ubli (1987-1991), Sućuraj (1987-2005), Žirje (1989-1991), Zlarin (1983-1988), Gaženica (1983-1988) and Rijeka (1998-1999).

Radar-type stations: The Croatian tide gauge network was expanded in 2017-2021 with nine new coastal stations based on radar technology. Stations in Stari Grad (Hvar Island), Sobra (Mljet Island) and Vela Luka (Korčula Island) were installed in 2017 (within the framework of the UKF MESSI and MRRFEU POZOR projects) and are operated by the IOF. Station Šibenik, located in Sv. Ante Channel was established in 2020 and is operated by the RBI. In 2021 the IOF established stations Vis (Vis Island), Mali Lošinj (Lošinj Island), Bistrina (Mali Ston Bay), Raslina (Lake Prokljan - ocean station) as part of the Interreg Italy – Croatia projects ECOSS, CHANGE WE CARE, and RESPONSe. Also, in 2021 the HHI deployed a radar sensor in Rijeka near the traffic port. All instruments are installed in open air providing 1 min data which are averages of 1 s measurements done for 20 s during each minute. All stations locally store these 1 min data and transmit them with up to 10 min latency to home institutions. The exception is Šibenik at which data is stored with a temporal resolution of 55 min. Ancillary atmospheric pressure and wind are measured at Stari Grad, Vela Luka, Mali Lošinj, Vis and Bistrina (1 min data), while surface current and sea temperature (depths 0.5, 1.0, 2.0 and 4.0 m) are measured at Šibenik station (every 55 min). Tide gauges in Rijeka, Stari Grad, Vela Luka and Sobra are leveled to the national geodetic datum. By the end of 2022, stations Rijeka and Sobra are planned to be upgraded with ancillary meteorological sensors. Vela Luka tide gauge was temporarily decommissioned in June 2021, but it should be reinstalled during 2022. All non-quality-controlled sea level and atmospheric data from the IOF stations are available directly through the IOF website (http://faust.izor.hr/autodatapub/mjesustdohvatpod?jezik=eng). In addition, sea level data measured at Sobra, Stari Grad and Vela Luka are also available through the IOC-SLSMF website (since October 2018). Data from Rijeka and Šibenik are visualized on https://adriaticsea.hhi.hr and https://hv.geolux-radars.com/sites/sibenik-svante.html, respectively.

In addition, the HHI plans to install two additional radar-type tide gauges in the following years in the areas of Šibenik and Mali Lošinj. Stations operated by Croatian institutions are listed in Table A12.

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2.1.13 Montenegrin tide gauge Network

The Institute of Hydrometeorology and Seismology, Department of Hydrography, is responsible for monitoring and maintenance of the tide gauges installed in the Montenegrin part of the Adriatic Sea. The network includes two permanent tide gauge stations based on float-type technology. The tide station in Bar was established in 1965 and till 1991 was the part of Former Yugoslavia tide gauge network (Slovenia, Croatia, Montenegro). During the 1990s the tide station in Bar was not fully operational for a long time, but it has been restored, and re-connected to the national geodetic network through levelling. The second Montenegrin tide gauge station was established in Kotor in 2010. For both stations the sea level is measured once every 6 min, with GSM-based data retrieval to the central server. Stations operated by Montenegro are listed in Table A13.

2.1.14 Tide monitoring network in Albania

The Institute of Geoscience, Department of Hydrology, is responsible for monitoring all water resources in Albania, including the sea level. The sea level observations are taken manually, two times a day - at 7 am and 7 pm. These data are stored in a book by the observer and sent every month to the Institute of Geoscience (Tirana, Albania). At the centre, this information is archived and not controlled, unless there is a request for this data. Stations operated by Albania are listed in Table A14.

2.1.15 Sea level observations in the Maltese Islands

The routinely collection of sea level data in the Maltese Islands was initiated in May 1993 by the Physical Oceanography Unit (later Physical Oceanography Research Group) using an ENDECO-type 1029/1150 differential pressure gauge in Mellieha Bay on the northern coast of Malta. The station remained in operation until 2001, measuring in delayed mode every 2 min, supplemented with meteorological measurements collected at a nearby station in Ramla tal-Bir overlooking the southern Comino Channel. This endeavour was mainly intended to assess the sea level variability and to study the phenomenology of strong seiches locally known as the 'milghuba' (Drago, 2000, 2009).

A MedGLOSS station installed in February 2001 in the Portomaso marina at the Malta Hilton in St. Julians constituted the first real-time ocean observing system in Malta. The instrument, donated by the International Commission for the Scientific Exploration of the Mediterranean Sea (CIESM), collected sea level data every 30 s, and also seawater temperature, atmospheric pressure and waves in the marina. Hourly averaged observations were shared in real-time with the MedGLOSS network through the Israel Oceanographic and Limnological Research (IOLR) that coordinated the project. The system comprised an underwater Paroscientific pressure sensor, a type Digiquartz Intelligent sensor, and a Setra atmospheric pressure sensor. In 2010, the system was upgraded with new equipment to enable higher sampling rates, and to enable a first phase towards contributing to the Mediterranean Tsunami Warning System within NEAMTWS (The Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas).

More recently, in collaboration with the Joint Research Commission (JRC), the sea level observing network has been enhanced by two IDSL stations, set up at Delimara (March 2021) and Senglea (June 2021). Data is transmitted in real-time to the University of Malta as well as to the JRC TAD server (https://webcritech.jrc.ec.europa.eu/TAD_server/Device/555) with a temporal frequency of 5 s. Each station is equipped with a radar sensor connected to electronics that also measures air temperature and captures visual images of the sea state every 15 min.

In March 2021, a Radac WaveGuide sensor was installed at the tip of the Marsaxlokk breakwater to measure sea level, wave height and wave period. The instrument was procured through the SIMIT-THARSY project, partially funded by the ERDF through the Operational Programme. This radar sea level gauge is capable of measuring water displacement with a resolution of 3 mm at a frequency of 10 Hz. The wave height is measured with an accuracy of 1 cm at 1 min intervals. In front of it, on the other end of the bay, another IDSL was deployed. The operational data from these stations is linked to other observations and delivered in real-time through the PORTO stations web interface developed through the CALYPSO South project, another INTERREG V-A Italia-Malta project (www.calypsosouth.eu). Tide gauges operated by the Physical Oceanography Research Group of the University of Malta are listed in Table A15.

2.1.16 Greek tide gauge network operated by the Hellenic Navy Hydrographic Service

The Hellenic Navy Hydrographic Service (HNHS) monitors sea level variability over the Aegean and the Ionian Seas through a network of 22 tide gauges. All hydrographic stations consist of analogue float type gauges equipped with rotating drums, rotating with speed of 1 cm/hr. These tidal stations are located within port facilities to record continuously sea level and provide these measurements to the relevant port authorities. The tidal stations at Thessaloniki, Kavala and Piraeus are the oldest of the network, operating continuously since 1933.

Since 1990, HNHS upgraded the network by installing digital water level sensors at seven selected stations (Piraeus, Alexandroupolis, Kalamata, Katakolo, Lefkada, Siros and Chios), operating in parallel to the analogue systems. These stations collect, store and transfer water level data to central servers in near-real-time mode. Digital stations collect additionally a series of ancillary parameters, like the sea surface temperature and meteorological data (air temperature, humidity, barometric pressure and wind speed and direction). In parallel, during that period, the network's tidal data, recorded in paper charts, have been digitized into hourly values, and subsequently organized and stored in the HNHS databases. The water level error is estimated to approximately 1 cm (Tsimplis, 1994).

Data from four stations (Piraeus, Katakolo, Siros and Kalamata) are visualised on-line through the HNHS web page (https://www.hnhs.gr/en/online-2/tide-graphs). Data from all tidal gauges covering the 1969–2020 period are also transferred to the Permanent Service for Mean Sea level (PSMSL) (https://www.psmsl.org/), supported by the International Oceanographic Commission (Bitharis et al., 2017). Sea level data from these four digital stations are also provided and visualized in real-time mode to the IOC -SLSMF (http://www.ioc-sealevelmonitoring.org/). Stations operated by HNHS are listed in Table A16.

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2.1.17 Bulgarian coastal sea level service

Systematic sea level measurements were initiated in Bulgaria in the beginning of the 20th century, with 16 tide gauge stations operational over a certain period of time till 2013. Operators of these sea level stations were: National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences (NIMH) – 6 stations, Cadastre Agency, Ministry of Regional Development and Public Works (CA) – 4 stations, Port Infrastructure (PI) – 5 stations and Institute of Oceanology, Bulgarian Academy of Sciences (IO-BAS) – 1 station. At present, five of these stations are operated jointly by the Institute of Oceanology, National Institute of Geophysics, Geodesy and Geography and the Geodesy, Cartography and Cadastre Agency and are providing data in real-time. The stations are equipped with a high accuracy radar instrument. Active Bulgarian stations are listed in Table A18.

2.1.18 National Institute for Marine Research and Development "Grigore Antipa" coastal sea level monitoring, Romania

Sea level measurements started in Romania in 1856, at the initiative of the European Danube Commission. However, these data have not been preserved, Regular recordings of the sea level started in Romania in 1933, by installing a float gauge. Presently, two methods of measurements are used in Constanta: a pressure sensor and a float gauge, with a hydrometric sight, at which visual measurements are performed three times a day for data quality purpose. The accuracy of the analogue measurements on a paper chart are estimated to 1 mm. At Sulina and Mangalia, the measurements are made using pressure sensors. The sea level data is transmitted to the server via GPRS/GSM method.

In Sulina, Mangalia and Constanta three IDSL were deployed in the last decade. Presently, only the one in Mangalia is operational. Stations operated by NIMRD "Grigore Antipa" are listed in Table A19.

2.1.19 Russian tide gauge network in the Black Sea

Sea level observations on the Russian coast of the Black Sea began in the middle of the 19th century. Systematic measurements of the sea level were initiated in 1873. Since 1944, the sea level network was restored, reconstructed and expanded. Sea level float-type recorders were installed at many tide gauges. Since 1977, all tide gauges have been tuned in a single system of heights (the Baltic Height System). In total, during the years, aat the territory of the USSR on the Black Sea, there were 44 tide gauges, the data from which were saved until 1985. For 23 tide gauges, there are long-term digital series of hourly observations of sea level. Today short-period sea level variations on the Russian coast are measured at five tide gauges: Tuapse, Sochi, Sevastopol, Yalta, and Feodosia. The Russian tide gauge network is owned by The Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) and is operated by the All-Russian Research Institute of Hydrometeorological Information - World Data Center and data availability. Tuapse tide gauge is co-located with a GNSS. Russian tide gauge stations in the Black Sea are listed in Table A20.

2.1.20 Coastal sea level monitoring in Türkiye

Sea level monitoring activities in Türkiye date back to the mid-1930s, when the first float-type tide gauge was installed at Antalya harbour to determine the national vertical datum. Since then, a considerable number of temporary mechanical and analogue tide gauges had been deployed at different spots. In 1999 the Turkish National Sea Level Monitoring System (TUDES) programme was initiated by the General Directorate of Mapping. Up to 2011, under this programme, a network consisting of 20 digital tide gauges with acoustic sounding tubes, for continuous measurements, was established. Due to the significant maintenance problems related to the acoustic gauges and the strong need for the VLM monitoring, all TUDES stations have been replaced with radar gauges after 2015, and most are GNSS collocated. The data averaged at 30 s and 15 min intervals are transmitted to the data center in Ankara in near-real time through GSM and internet. Real-time and delayed mode quality controls, data analysis, database management, and data distribution activities are performed at the data center. Further, TUDES is delivering sea level data to the regional networks (e.g. ICG/NEAMTWS). More information about the TUDES can be found at https://tudes.harita.gov.tr/?lang=us.

In addition, three IDSL stations were deployed in Bozcaada, Samsun and Bodrum. TUDES tide gauge stations are listed in Table A21, while in Table A22 are listed JRC IDSL stations in Türkiye operated by KOERI.

2.1.21 Cyprus tides gauges networks

The systematic monitoring and transmitting real-time sea level data in Cyprus was first initiated in 2001 as part of the MedGLOSS-Mediterranean sea level network. Initially, one tide gauge was deployed at Paphos harbour in 2001 by the Department of Fisheries and Marine Research Oceanography Unit (DFMR) and hourly data were transmitted along with atmospheric pressure and *in situ* sea temperature via internet to a dedicated MedGLOSS web page hosted by the Marine Data Center of the IOLR. Later, this station became part of the MedGLOSS/ESEAS (European Sea Level Service) and continued to transmit data until 2015. After the December 2004 catastrophic Indian Ocean tsunami, the Paphos sea level station was also set to transmit in real-time sea level data to the IOC-SLSMF every 1 min. Moreover, the station was included in the coastal sea level monitoring network of the NEAMTWS-North East Atlantic Mediterranean Tsunami Warning System (UNESCO, 2007).

In the frame of MedGLOSS/ESEAS activities, another three tide gauges were deployed in Cyprus during 2010, at the Zygi and Paralimni fisheries shelters and in the Larnaca marina. The tide gauge deployed at Zygi fisheries shelter was provided by the Cyprus Governmental Department of Lands and Surveys. These tide gauges were operated only for two years, between 2010-2012, the data of which, together with those of the Paphos station (operated between 2001-2015), were used to estimate the Lowest Astronomical Tide and the Lowest Low Tide at the locations of their deployment (Papazachariou, 2014). Furthermore, studies were carried out to examine the trend of the sea level variations at the Paphos station (Loizides et al, 2010), as well as inter-comparison of the Paphos time series data with satellite altimetry time series (Banks et al. 2003; Papazachariou et al., 2014)

The Paphos MedGLOSS/ESEAS tide gauge was equipped with a Paroscientific Digiquartz Intelligent pressure sensor pressure type, while the rest three Cyprus MedGLOSS/ESEAS tide gauges were equipped with AANDERAA pressure sensors. In the frame of the Interreg THALCHOR2 project, a new tides gauge network named PYTHEAS has been deployed in Cyprus during 2018 (Chris et al., 2020). The PYTHEAS tides gauges network consists of four stations (Paralimni and Pomos fisheries shelters and Paphos and Larnaca harbours), all owned by the Cyprus Governmental Department of Lands and Surveys (DLS), while the fifth one (old Limassol harbour) is owned by the Cyprus University of Technology. All the PYTHEAS sea level networks were equipped with radar tide gauge sensors, along with atmospheric sensors, such as pressure, air temperature, humidity, as well as sea temperature. The station at the old Limassol harbour was also set to serve as a GNSS reference. The data from the PYTHEAS tides gauges network are transmitted in real-time to the hydrographic database of the DLS.

In parallel and independent from the PYTHEAS network, an additional acoustic tide gauge station was deployed at the end of March 2018 by the European JRC-Joint Research Center at the Zygi fisheries shelter, next to the location of the Cyprus MedGLOSS/ESEAS Zygi station. The 5 s data from this station are provided in real time also to the IOC-SLSMF (http://www.ioc-sealevelmonitoring.org/station.php?code=zygi1).

In 2019, an offshore station for sea level variation was deployed in the frame of Interreg HERMES project using a bottom mounted AWAC ADCP (Acoustic Current Doppler Profiler) pressure sensor. The ADCP was deployed at the water depth of 40 m in the Larnaca Bay, close to the famous scuba diver shipwreck “Zenobia”. The ADCP measures in addition to the sea level variation, sea currents at 20 water depths, waves, sea temperature and suspended particles. The data are transmitted in real time via cable from the bottom mounted ADCP to a connected surface oceanographic buoy, and then via a GPRS to the ORION NGO server for use in the dedicated HERMES web page (Zhuk et al., 2020). Cyprus stations are listed in Table A23.

2.1.22 Egyptian tide gauge network

Six tide gauges were operational along the Egyptian Mediterranean coast. These gauges were deployed at Port Said, Burullus new harbour, Abu-Qir Bay, Alexandria Western Harbour, Sidi Abdel-Rahman and Mersa Matrouh. The periods of data availability are different for each location, with the longest records (30 years) at Alexandria Western Harbour and the shortest records (4 years) at Mersa Matrouh.

In June 2018, in collaboration with the JRC, the National Institute of Oceanographic and Fisheries deployed an IDSL station in the port of Alexandria. Stations of Egyptian tide gauge network are listed in Table A25.

2.1.23 Algerian tide gauges network

The National Institute of Cartography and Remote Sensing (INCT) is responsible for equipping the national territory with all kinds of geodetic networks: GNSS, gravity and levelling networks. Historically, the altitudes of the Algerian levelling network are reported to several origins generally chosen in an arbitrary manner, level deduced from the indications of the Medimaremeter of La Goulette (Tunisia), altitude of the landmark of Porte De France (Tunisia), or the coast of La Goulette (Tunisia), console placed at Sidi El Hemessi station (Tunisia) in 1914.

Being aware of the significance in providing the national territory with a precise altimetric reference, the INCT put the effort in the installation of automatic tide gauges along the Algerian coasts, first to bring the bathymetric surveys to a stable reference, hydrographic zero or nautical chart zero, and then to predict the tide or define reference levels. In addition, the INCT is in charge for setting up the hydrographic zero as an altimetric reference for water heights, and uses any tidal data as a national referent (official journal): general knowledge of the tide, determination of harmonic constants and extreme levels and tidal prediction.

The installation of six tide gauge stations with automatic acquisitions along the Algerian coasts (Ghazaouet, Oran, Ténès, Algiers, Jijel and Annaba) in the mid-2010s upgraded substantially the network, in particular for monitoring sea level variations and modernization of the national altimetric reference. Currently, the INCT is additionally upgrading the network through setting up permanent GNSS stations in collocation with the tide gauges stations at the ports of Algiers, Jijel, Oran, Annaba, Ghazaouet and Ténès. This approach would constitute an important phase for the creation of a multi-observation observatory for spatial measurements, gravity field, levelling and tide gauge. Upgrade of observatories to have real-time data acquisition is also planned for near future. Stations of Algerian tide gauge network are listed in Table A26.

2.2 Summary of the existing coastal sea level monitoring infrastructure

With the aim of facilitating a more general assessment of the coastal sea level monitoring networks individually described in Section 2.1, a brief questionnaire survey was conducted, resulting with information on: i) institution, country, contact name of a network; ii) number of stations; iii) main purpose of the network; iv) funding mechanism; v) data policy; vi) raw time sampling interval; vii) data latency; viii) number of sea level sensors at each station; ix) type of tide gauge; x) levelling strategy; xi) number of tide gauges collocated with a GNSS; xiii) ancillary measurements; xiv) quality control and processing and xv) public data availability. The survey responses are tabulated and may be found in Supplementary material.

Based on the responses received, 236 active stations have been identified so far in the M/BS. These are operated by 30 agencies, representing all countries in the region except Morocco, Tunisia (both have sea level networks, e.g. Jabnoun and Harzallah, 2020) and Libya. We could also not get information from the Italian Hydrographic Office, that operates Genoa tide gauge, one of the longest-operating Mediterranean tide gauges. In some countries tide gauges are operated by several institutions (e.g. 6 in Spain, 5 in Croatia), while others have one national network managed by a single agency (e.g. SHOM, in France). ISPRA in Italy runs the largest network in terms of number of stations (62), followed by the JRC (24 tsunami stations operated jointly with other institutions), HNHS in Greece (23) and the TUDES Turkish network (20). The majority of respondents are responsible for a smaller number of stations, even for just one single station in several cases.

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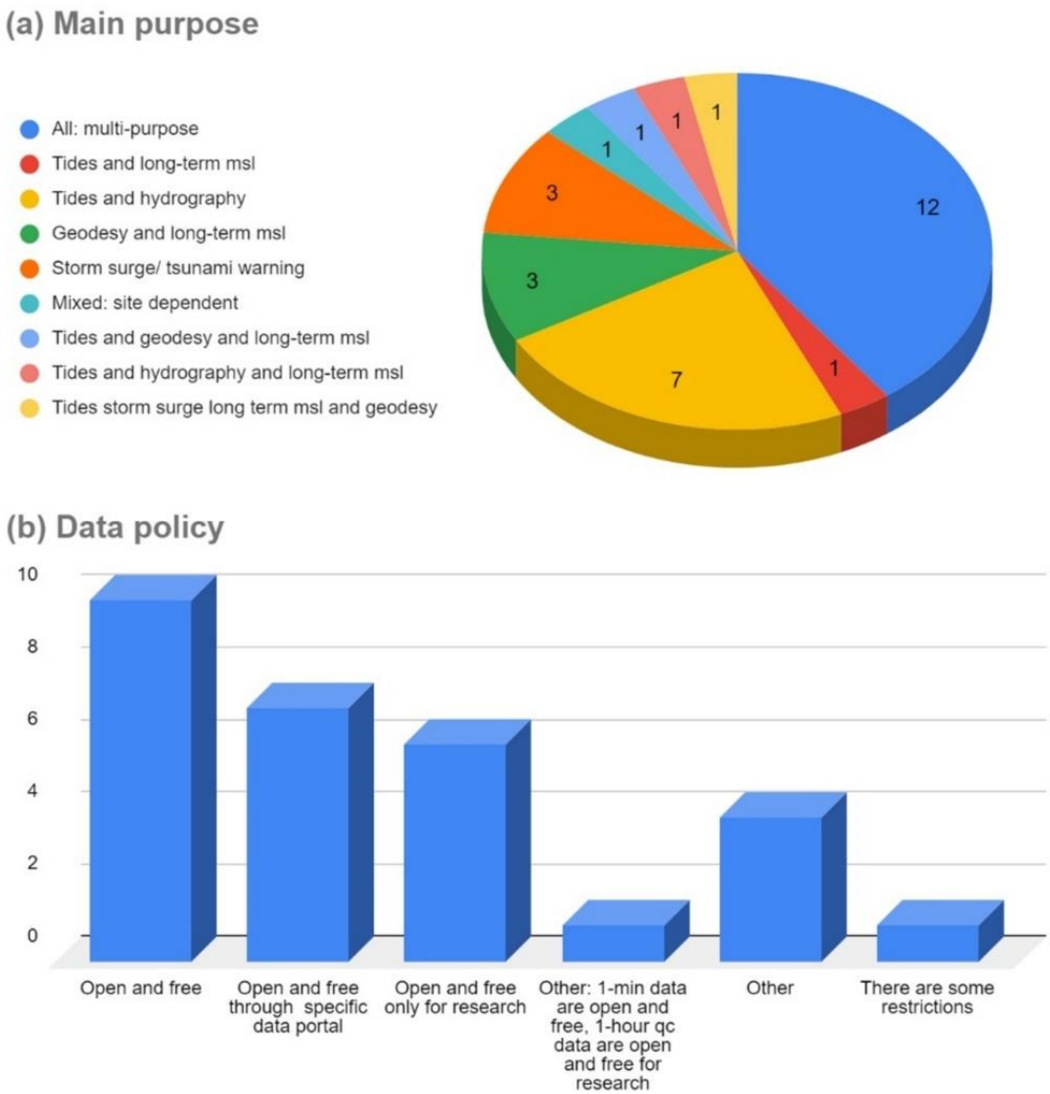

610 **Figure 2. (a) Primary objective of the coastal sea level monitoring networks based on responses to the survey, and (b) data policy of the operating institutions as collected by the survey.**

Figure 2a displays the primary objective of the networks, chosen by operating institutions between the following non -exclusive choices: i) tides and hydrography; ii) storm surge/tsunami warning; iii) geodesy and long-term MSL; iv) tides and long-term mean sea level (MSL); v) altimetry calibration; vi) models validation; vii) harbour operation and aid to navigation; viii) meteotsunamis or xi) multi-purpose (all previous options). Most of the networks, especially the largest ones, are claimed to be multi-purpose (40% of answers:12), followed by those mainly aimed at tides and hydrography applications (23% of the answers: 7), such as the HNHS Greek network, Romania and one of Cyprus networks. Three institutions reported that their stations are focused on storm surge/tsunami warning and another three on geodesy and long-term MSL. None of the stations have been specifically implemented for applications v)-viii). The IOLR network in Israel provided a mixed, site-dependent answer, depending on technology and time sampling and latency (e.g. the 2 radar sensors installed for storm surge/tsunami warning). Despite more than half of the answers claim open and free access to data (altogether 10 agencies, and 7 agencies through specific data portals), there are also some data policy issues (Fig. 2b): open and free only for research were selected by 6 respondents (+1 for 1-h qc data), while 5 institutions mentioned unspecified issues or restrictions on data access.

With respect to network sustainability related to maintenance strategy and status, most of the respondents confirm no problems of funding now or in the near-future. Problems with maintenance are reported by NIOF in Egypt, and for a couple of stations in Croatia (IOF) and Israel (IOLR). Most serious issues are raised by the Albanian network, which is not being maintained at this moment and there are no plans for funding in a short term. JRC also warns that the network funding is guaranteed now, but it might stop anytime. All the agencies rely on their own resources for *in situ* maintenance except PdE (Spain), ISPRA (Italy) and Croatian Waters (Croatia), that subcontract this work.

Raw time sampling interval is 1 min for most of the networks in the region (12 of the respondents). However, a large range of raw sampling options are provided by the rest of contributors, from 6.7 Hz resampled to 5 s (JRC tsunami stations) to 55 min (Ruder Boskovic Institute), 1 h (Croatian Waters) or 2 h (Meteolestartit). Some agencies are more specific in the answer to this question and report several samplings available depending on data portal or application. Latency of data transmission is claimed to be real time (<=1 min) by 9 of the respondents (IOLR only for the two radar sensors), near-real time (minutes, hours or days) by 15 of them and delayed mode access only by 7 agencies.

One of the most challenging aspects of a tide gauge network is datum stability and link to other official references, especially for long-term and mean sea level studies. According to the responses, the majority of networks perform high-precision connection of the tide gauge benchmark (TGBM) to the national geodetic datum, as the basic levelling strategy. In some cases, they provide the date of last levelling campaigns, but in general there is a lack of information about their frequency, apart from periodic levelling near the TGBM during routine maintenance reported by 4 institutions (usually once per year). Connection of all stations to a nearby GNSS station is reported by the Spanish IGN and by the Algerian network.

With respect to quality-control and data processing, the response is also diverse, as shown in Fig. 3. In most cases only delayed-mode quality-control is performed by data originators (17 respondents, 6 of which also generate sea level products). In addition to delayed-mode quality-control and products, automatic quality-control in near-real time is also performed nowadays by 7 agencies in the area, while only 2 agencies do not perform quality-control or processing at all.

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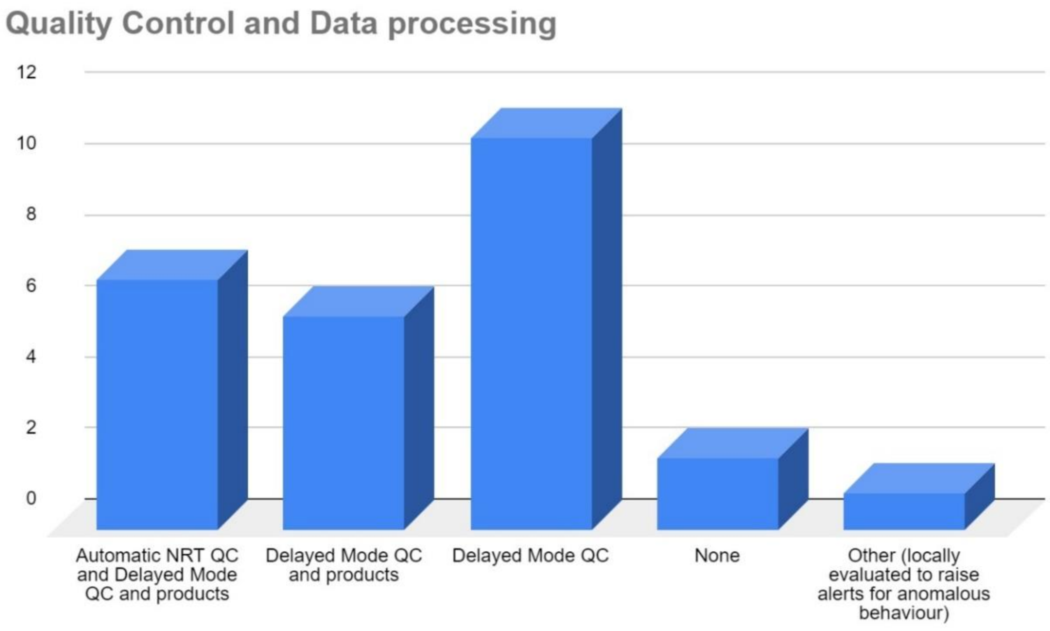

650 **Figure 3. Quality-control and data processing strategies followed by M/BS tide gauge network operating agencies.**

The list of stations including name, coordinates, data period and ancillary measurements is provided in Appendix (Tables A1-A27). This list is the basis for detail mapping of existing sea level infrastructure in the M/BS, composed of 236 active stations, including type of sensor (radar, acoustic, float or pressure sensor), ancillary meteorological or oceanographic data, or collocation with a nearby permanent GNSS station (Figs. 4-6). The data periods on this table reveal that the oldest active stations in the M/BS are: Marseille: 1849 - present (France), Trieste Molo Sartorio: 1875 - 1889; 1901 - present (Italy), Burgas port: 1910 - present (Bulgaria), Varna port: 1919 - present (Bulgaria), Venice Punta della Salute: 1924 - present (Italy), Alicante 1: 1928 - present (Spain) and Bakar: 1929 - present (Croatia). These stations, the most relevant for climate research, started with float gauges and have been upgraded to radar sensors in most cases. Very often, time series from different tide gauges at the same harbour are used to generate a dataset spanning the whole history of the station (e.g. new Alicante dataset by Marcos et al., 2021, starting with first measurements by a tide pole in 1870).

In terms of technology, Figs. 4-6 reveal that today the radar sensors are the most common type of instrument in the network, being sea level sensor at 134 stations (57%), dominating especially in the Western Mediterranean. Further, 62 stations (22%) are still based on, or combined with, traditional float gauges, mainly along the eastern Adriatic coast and in Greece. Acoustic sensors are used at 27 locations (mostly tsunami sensors), while pressure sensors are used at 15 stations (Balearic Islands, Western Black Sea and Israel). At four stations sea level measurements are still performed manually using a tide pole (Albania).

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Only 6 stations that have two different sensors: float and radar (Koper and Bakar), float and pressure (Constanta), float and acoustic (Algiers, Jijel and Oran). GLOSS recommendation for tsunamigenic areas is to use a radar plus a pressure sensor, a combination not found in the M/BS. A promising news is the increasing number of stations collocated with a GNSS, and therefore with potential geocentric reference (TGBM ellipsoidal height) and VLM information: 46 locations (19% of the network): 26 in the Western Mediterranean, 2 in the Central Mediterranean, 9 in the Eastern Mediterranean, 3 in the Marmara Sea and 6 in the Black Sea. At 150 stations (64% of active stations) there are ancillary sensors which provide meteorological data (90 stations, mainly atmospheric pressure and wind), oceanographic data (11 stations) or both (49 stations, many of them in the Central Mediterranean).

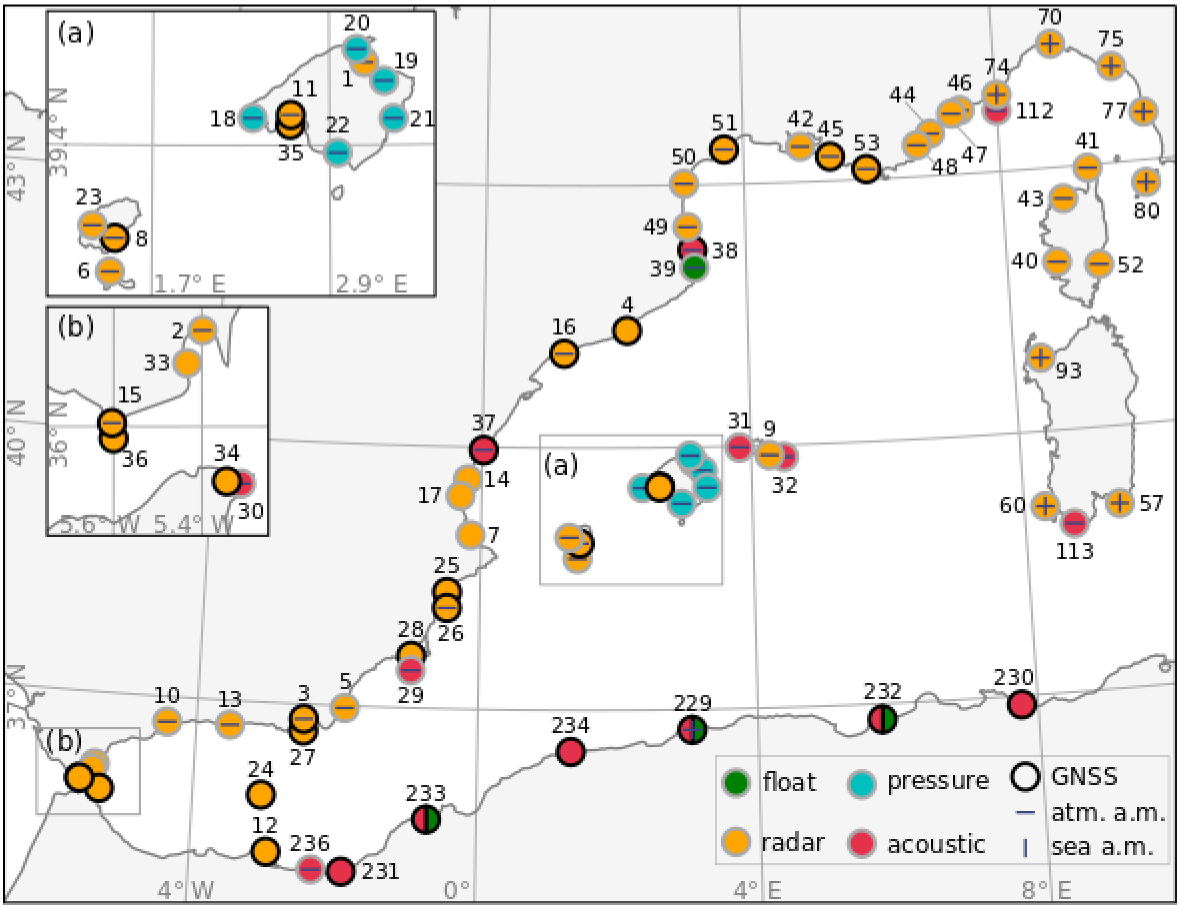

Figure 4: Active tide gauge stations in the Western Mediterranean Sea. Marker colour indicates tide gauge sensor, while black circle indicates collocation with GNSS station. Ancillary measurements, atmospheric or oceanographic, are indicated with navy-blue horizontal and vertical dashes, respectively. Station names are listed in the Appendix tables: Tables A1 -- A9 and Tables A26 -- A27. Stations 26, 27, 29, 32, 34, 35, 36 and 112 are slightly shifted to assure better visibility.

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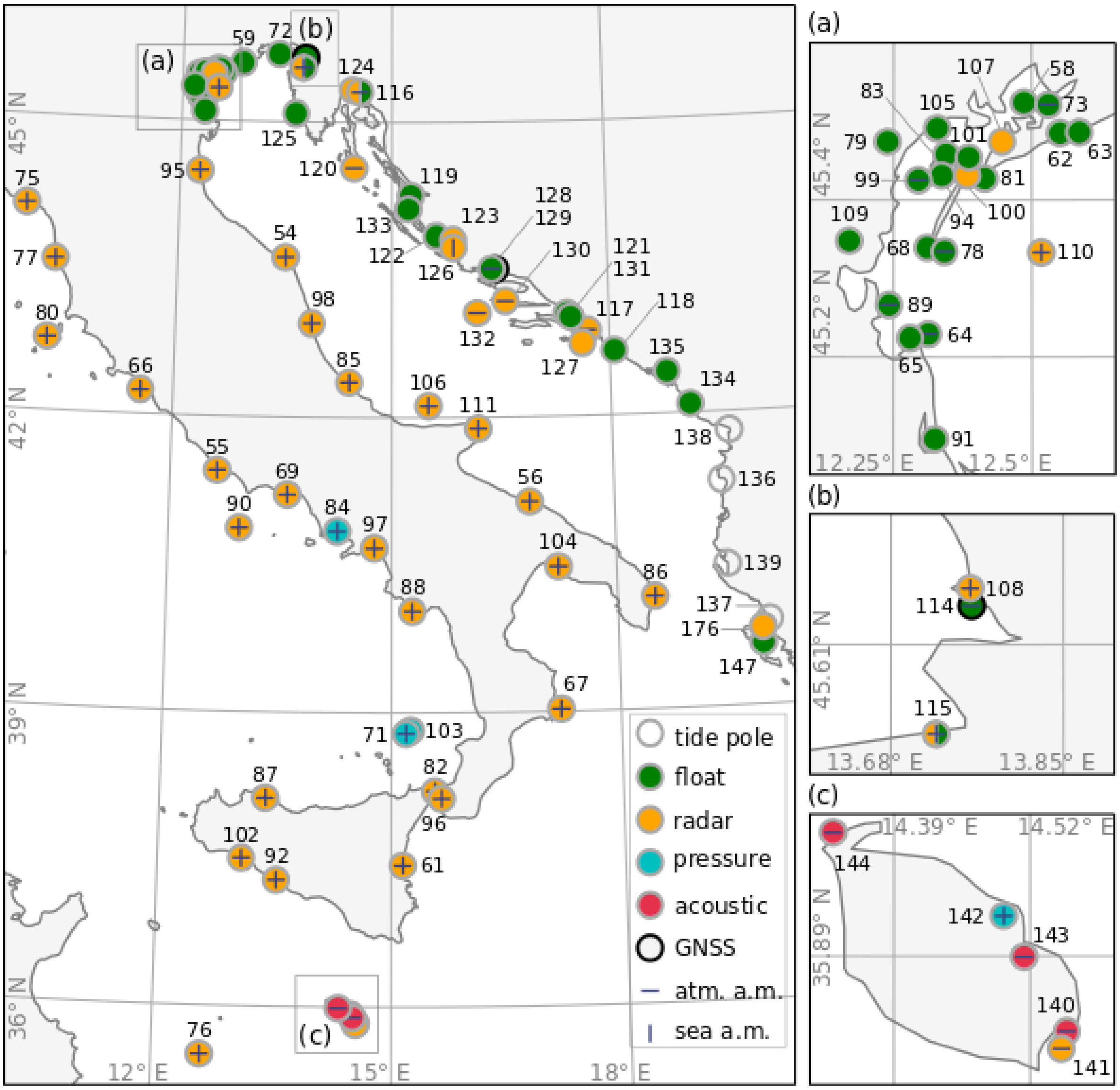

685 **Figure 5: Same as in Figure 4, but for the Central Mediterranean Sea. Station names are listed in the Appendix tables: Table A8 and Tables A10 -- A17. Stations 82, 103, 114, 121, 123, 124, 126, and 128 are slightly shifted to assure better visibility. Some stations appear to be inland due to the relatively coarse resolution of the coastline.**

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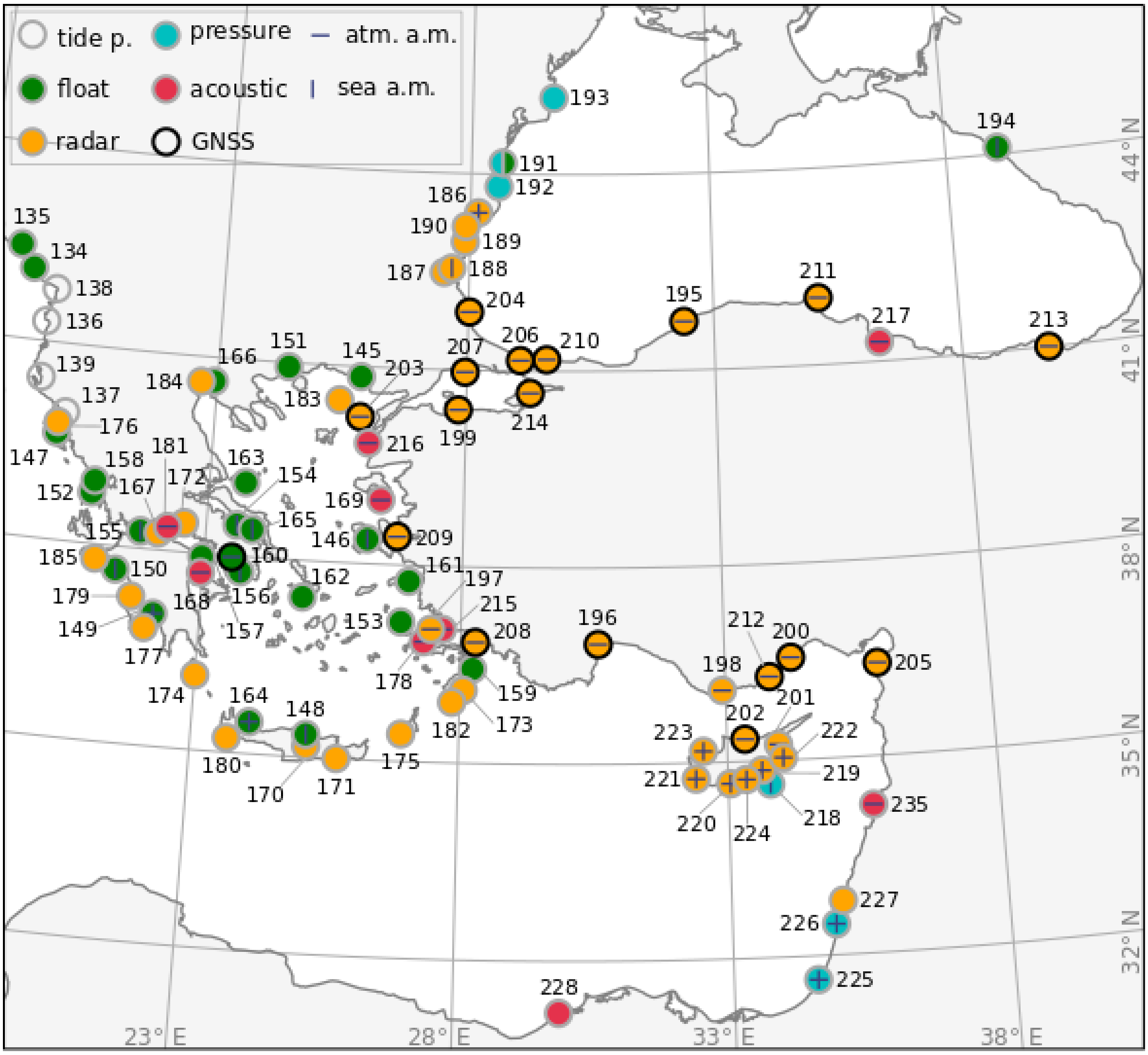

Figure 6: Same as in Figure 4, but for the Eastern Mediterranean Sea and for the Black Sea. Station names are listed in the Appendix tables: Tables A13 -- A14, Tables A16 -- A25, and Table A27. Stations 137, 152, 156, 165, 168, 170, 172, 178, 201 and 218 are slightly shifted to assure better visibility.

3 Data availability in existing international programs

In this chapter, we assess the M/BS sea level data availability. The assessment is primarily based on the public global and European data repositories as of 15 November 2021, which have been established for various applications (from real-time applications to research-quality products) and contain data of different time sampling step (from a minute to a month). Figures 7 and 8 summarize information on the presented data repositories.

3.1. Monthly sea level data repository

The oldest sea level data repository, at which monthly sea level data have been collected for almost a century, is the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org). The PSMSL was established in 1933 by Joseph Proudman, with an aim of collecting, analysing and interpreting monthly sea level data at the global scale (Woodworth and Player, 1993; Holgate et al., 2013). The collected data is of high quality and freely available, thus providing an excellent dataset for mean sea level studies in this era of climate changes (e.g. Spada and Galassi, 2012). In total, there are 158 M/BS data series with a high reliability (classified as revised local reference (RLR) data) (Fig. 8a), with six records spanning over more than 100 years. These stations are Trieste, Marseille and Genova in the Mediterranean, with the respective length of 146, 136 and 114 years and data coverage of 87%, 97% and 78%, then Poti, Batumi and Tuapse stations in the Black Sea (145, 137 and 103 years of length, respectively, and data coverage of 94%, 87% and 99%, respectively). Due to their exceptional length, these series have been thoroughly checked (e.g. Tsimplis and Spencer, 1997; Wöppelmann et al., 2014) and used in numerous long-term sea level assessment studies (e.g. Letetrel et al., 2010; Pashova, 2012).

In the PSMSL repository, there are 38 tide gauge stations with monthly records longer than 50 years, concentrated mostly along the northern coastlines of the M/BS (Fig. 8a). Along the North African coast there are long-term (50+) data from only two stations, Alexandria and Ceuta, making proper quantification of sea level changes along the southern Mediterranean challenging (e.g. Gomis et al., 2012). At a number of sites (24 of them) there are two or more tide gauges collocated, with the long-term data coming from the float-type tide gauges, and with additional sea level series normally coming from the digital instruments (radar, acoustic or pressure tide gauges) and spanning over the last few decades at best. The median data coverage of the M/BS PSMSL series is 92%, while 63 stations have the data coverage higher than 95%. There are 19 sea level records which have 100% data coverage, but all of them are relatively short records (up to 30 years) – these series mostly come from digital instruments. Oppositely, there are 4 sea level records with data coverage less than 50%, with 3 of them containing data from the 1960s and 1970s.

3.2. Hourly sea level data repositories

At hourly resolutions, some of sea level records coming from the PSMSL tide gauges are also available in the Copernicus Marine Service (CMEMS) In Situ Thematic Assembly Centre (http://www.marineinsitu.eu). In general, the CMEMS is a service providing operational data-driven ocean products, plus systematic information on the ocean and sea-ice state (Le Traon et al., 2019). The CMEMS database contains hourly sea level records from 115 tide gauges in the M/BS (Fig. 8b), with the median length of the series of 2 years. Hourly sea level data records can also be found in the EMODnet Physics *in situ* observations repository (Novellino et al., 2015, https://www.emodnet-physics.eu/map), which is developed to be a single point of access to near real time and historical ocean data in Europe. The repository contains hourly sea level observations from 119 tide gauges in the these two basins (Fig. 8b). For some stations, the data is available both from recent observations and from historical periods, sometimes of the same length or even longer than the PSMSL records, but mostly covering shorter periods and sometimes without any data available for download – these "empty" stations are not included here. There are 12 hourly sea level series in the EMODnet repository longer than 30 years, while more than half of stations have records of 4 years long or shorter.

In conjunction with EMODnet Physics and CMEMS, the relevant research product for the M/BS, containing sea level data at hourly resolution, is Global Extreme Sea Level Analysis dataset (GESLA, http://www.gesla.org, Woodworth et al., 2016, 2017) - here version 3 is analysed. GESLA is a research-driven sea level product containing series of hourly or higher sampling resolution, which encompass 1355 sea level records and 39151 station-years all over the world. In the M/BS, GESLA lists 101 stations, most of them spanning over periods much shorter than listed in PSMSL, up to a few decades. The longest GESLA record in the Mediterranean is the one for Marseille (France) tide gauge, 173 years long, while the median length of GESLA records is 15 years.

In addition to the quoted centralized data repositories, some of hourly sea level data can also be accessed through SeaDataNet portal (https://www.seadatanet.org), which is a virtual centre that provides different ocean metadata, data and products archived by data providers. However, the access to the sea level archives is not straight-forward. It is mostly distributed towards data providers, sea level data is often combined with data from other observing platforms (e.g. echosounders, synthetic aperture radars) – data is also provided in different formats and split in small observing intervals – making this portal rather complicated to use. Still, some data not listed in the EMODnet Physics, CMEMS and GESLA dataset may be found there, like sea level records for the Georgian, Ukrainian and Maltese stations.

It is a challenge to a researcher to choose the best database out of the three and to locate research-quality data. In various databases, data originating from the same location frequently have different names, identification numbers and metadata. We thus encourage founders of these data repositories to join their data together, and provide one high-quality dataset for further research, with unique data policies allowing for accessibility of the data and following the FAIR (Findable, Accessible, Interoperable and Reusable) principles (Wilkinson et al., 2016).

3.3. Minute sea level data repositories

Another important sea level data portal is the UNESCO Intergovernmental Oceanographic Commission Sea Level Station Monitoring Facility (IOC SLSMF, http://www.ioc-sealevelmonitoring.org), which – contrary to other sea level data repositories – has not been developed for collection of the research quality data, but for operational purposes (Aarup et al., 2019). The IOC SLSMF has been developed to deliver the information about the status of tide gauges operating in real time, as well as to visualise the data downstreaming to the service (Flanders Marine Institute (VLIZ), 2021). Further, the service provides high-resolution (mostly with a minute resolution) sea level data at global level, following demands of the operational and early warning systems that emerged after the 2004 Indian Ocean tsunami.

As of 15th of November 2021, the IOC SLSMF provides information and data from 143 tide gauge stations in the Mediterranean and Black Sea, most of which (all but 30 for the preceding week) are operational in real-time with data transmitting latency between 1 and 10 min (Fig. 8c). Ten stations have been operational since 2008, when they were installed

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as a result of activities of the IOC Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (IOC ICG NEAMTWS, Amato, 2020), established to coordinate regionally the development of the tsunami early warning system. The most recent additions to the network are from 2019 and 2020, and are related to a few Spanish, Greek and Turkish tide gauges. The availability of the IOC SLSMF data in the Mediterranean is largely dependent on the data providers, which normally upgrade large segments of networks at once. E.g., most of the Italian sea level records have been available from December 2013, which is also the median value for the beginning of data provision of all the Mediterranean IOC SLSMF stations (Zemunik et al., 2021b). Most of the stations from which data are available at the IOC SLSMF database, are equipped with the radar tide gauge technology, sampling rates are normally 1 min, except for Greek and Turkish sea level records that are largely available with the resolutions of 30 s and 20 s.

Recently, European Commission through the Joint Research Centre (JRC) at Ispra established a sea level database (https://webcritech.jrc.ec.europa.eu/, here marked as JRC-SLD, Fig. 7), containing multi-year records on a minute up to a ten minute resolution. The database assembles 105 stations in the M/BS operating in real-time, providing also the estimates of tidal constants for each site. In addition, the companion site at https://webcritech.jrc.ec.europa.eu/tad_server/ is collecting the sea level data at a rate of 5 s, aimed to improve the tsunami hazard monitoring, in particular in the Mediterranean Sea and in the North Atlantic area (NEAMTWS area of UNESCO IOC).

As no global research-quality sea level data repository containing the data at a minute resolution has been developed yet, Zemunik et al. (2021b) applied quality-check procedures on the IOC SLSMF data and provided the Minute Sea level Analysis product (MISELA), to be used for researching of high-frequency sea level phenomena. MISELA dataset contains 331 sea level records and 2303 station-years between 2004 and 2019, with resolution of 1 min and containing only high-frequency part of the signal (cut-off period at 2 h). In the M/BS, MISELA quotes 36 stations, covering a time period from 2008 at the earliest up to 2019, with the longest record coming from Melilla and Barcelona, Spain.

3.4. Data-providers' sea level data repositories

Aside from the listed global sea level data repositories and research products, these sea level data is also accessible through websites of data providers (e.g. PdE, SOCIB, SHOM, ISPRA; see more in Section 2). Further, there are sea level data that are not included in listed repositories, like ISPRA Rete Mareografica Laguna di Venezia, containing sea level records from 24 tide gauge stations, but are available through local repositories (https://www.venezia.isprambiente.it). Last but not least, there are more sea level records, in particular at hourly timescale and the raw data, not easily reachable by users. Some of these tide gauge operators provide the access only to recent sea level data, some are visualised through a graphical interface, while others are available on demand – often only for research purposes, and other have even more restrictive data policies.

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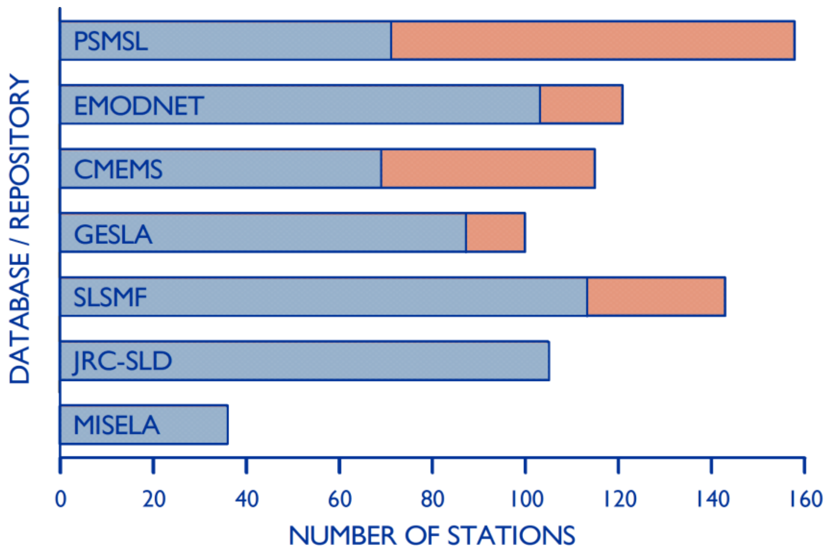

Figure 7. Number of tide gauge stations in the Mediterranean and Black Sea for which the sea level data can be found in the quoted databases or data repositories. As of 15 November 2021, the stations having no data since 2018 for PSMSL, since 2021 for EMODNET and CMEMS, since 2020 for GESLA and being not operational in the preceding 7 days for SLSMF and JRC-SLD are indicated by red. For MISELA data is available up to 2019, at best.

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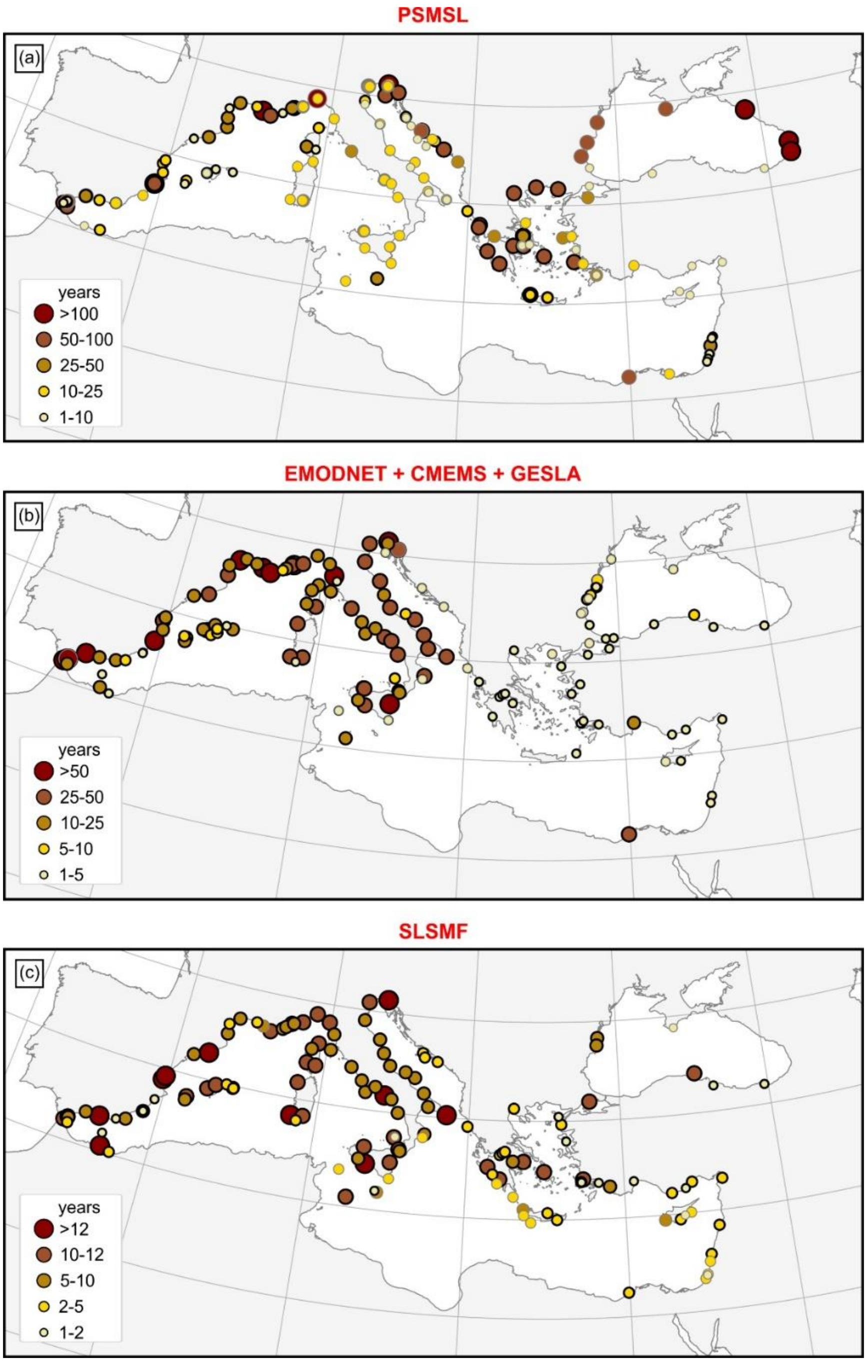

Figure 8. The Mediterranean and Black Sea data accessible as: (a) monthly sea level averages in the PSMSL (the length of series is indicated by the size and colour of the circle; thick border lines denote the series that end in 2018 or later, and grey the series that end earlier, (b) hourly sea level data in either EMODNet Physics, CMEMS and GESLA (the length of series is indicated by the size and colour of the circle; thick and grey lines denote the series that do or do not, contain the data in 2021, respectively), and (c) minute series in the IOC SLSMF (the length of the operability period is indicated by the size and the colour of the circle; thick and gry border lines denote the stations that were or were not, operational on 15 November 2021, respectively).

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4 Assessment of the network to fulfil targeted applications

Based on the information compiled in Sections 2 and 3, an overview of the fit-for-purpose status of the network, to fulfil some specific applications, is presented below. Examples of use of tide gauges in the M/BS are provided, focusing on early warning systems, long-term sea level variability or altimetry calibration, all in order to show the main gaps or lack of information in terms of coastal in-situ measurements.

4.1 Operational, early warning and forecasting systems

4.1.1 Tide tables and port operations

Historically, the first requests for sea level information came from the needs of navigation near the coasts and access to ports with significant tidal ranges. Tide scales or other visual systems quickly gave way to tide gauges, which become a standard in port operations, in particular at these ports with intense traffic and large tidal range (Lemon, 2003). Although the traffic in the M/BS is substantial, the tides are small and ranging normally to a few tens of centimetres, except in the northern Adriatic and Bay of Gabes (Tsimplis et al., 1995). Nonetheless, several countries produce tide tables to predict the astronomical tide.

The tides are normally predicted using harmonic analysis of measured signal. Sea level observations allow for estimation of the harmonic constituents necessary to recompose the tidal signal and provide highly precise estimates of the tidal signal. In the Tide Table, predictions of the times and heights of high and low tides are published for certain points, called reference ports or main ports, for which there are generally long series of observations that allow to obtain an accurate prediction. Each reference port can be linked to one or more secondary ports. For these secondary ports, predictions are obtained by applying time and distance offsets from the reference port.

According to the International Hydrographic Organization (IHO) recommendations, the reference level of the tide/water height observations and predictions for navigators should be the same as the chart datum.

Use of tide gauges for computing tidal harmonic constants and tide predictions, usually done by national hydrographic services, has allowed port authorities along the world to programme their operations well in advance. This is particularly important for those ports that receive large cargo ships with a large draft, for which the time of high or low water is critical. In the M/BS, where the tide is often very small, even negligible, tide tables are only used on those areas with higher tidal ranges. This is the case of the northern Adriatic Sea, where port authorities and pilots in Croatia, Slovenia and Italy use Tide Tables with this purpose. Tide predictions are not used at some other coastlines with smaller tides: as an example, the Spanish Hydrographic Office does not generate Tide Tables for Spanish Mediterranean ports. In these cases, shorter-term sea level forecasts based on storm surge models are the main prediction tool available for harbour operators, as it is the case of Barcelona harbour, that relies on the forecasting system developed by PdE and described in Section 4.1.2. Of course, more precise information can simultaneously be derived from sea level observations transmitted in real time by the tide gauges.

As ships are getting larger and larger, they have more and more drafts, leaving little room for manoeuvre for navigation. The precise knowledge of the water level in real time allows the port authorities to optimize the movement of ships.

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PdE in Spain has developed a harbour visualization tool essential for managing port operations, which integrates real time tide gauge data with other measurements (e.g. wind) and data from models. Sea level is a key component of a local early warning system for each harbour, which issues alert messages whenever sea level or high-frequency sea level oscillations over predetermined thresholds occur. These thresholds can be configured by harbour operators. In Croatia, the Hydrographic Institute also developed a web application with real time and predicted data, so port authorities and pilots can visually see the difference and adjust their operations accordingly.

Real time tide gauge data are also used by the ports during local bathymetric surveys and dredging activities.

The data collected by the sensors all around the world are used by the JRC Sea Level Database (JRC-SLD, https://webcritech.jrc.ec.europa.eu/) to compute the harmonic coefficient needed to forecast the tide in locations of the IDSL sensors and the surrounding areas. Most of the data collected by the JRC-SLD are analysed with the same software used by the IDSL network to assess the behaviour of the sea level rise and decrease. In case of anomaly, this detection disseminates alerting information.

4.1.2 Storm surges and coastal flooding

Apart from high-frequency sea level disturbances (discussed separately in Section 4.1.3), the Mediterranean coastal floods typically occur due to constructive superposition of tides and meteorologically induced storm surges. High local precipitation, increased river discharge and waves may further worsen coastal flood risks and lead to compound flooding episodes (Bevacqua et al., 2019). All these events pose a threat to cultural heritage, and densely populated coastal communities of the M/BS.

Storm surges are most severe along Tunisian, Aegean and Adriatic coasts, at which the highest number of sea level extreme events per year is observed (Cid et al., 2016). Especially critical is the area of the northern Adriatic Sea and Venice Lagoon, exposed to the well-known a*cqua alta* phenomenon. To face these hazards, coastal regions rely on forecasting operational systems (Umgiesser et al., 2021), measurement networks and extreme events research activities (Calafat et al., 2014). In the Venice Lagoon, investment in coastal protection through planning and building of flood barriers has been essential.

These challenges are purely operational: short-term day-to-day flood risk needs to be continuously estimated on synoptic timescales using observation-driven numerical forecasting models and other types of early warning systems (Žust et al., 2021; Makris et al., 2021; Ferrarin et al., 2020; Bajo et al., 2019; Mel and Lionello, 2014; Ferrarin et al., 2013; Pérez Gómez et al., 2012, 2021). Ensemble modelling allows dealing with uncertainties by generating probabilistic envelopes of possible sea levels (Bernier and Thompson, 2015; Bertotti et al., 2011, Ferrarin et al., 2020). Of course, different modelling, ensemble and observation-ingestion paradigms, may be used (Calafat et al. 2014). Panoramically speaking, modelling of sea levels can be classified into numerical physical models on one hand and deep learning approaches on the other. Advantages of the former are typically more extensive spatial coverages - which come at a higher computational cost - and better performance in the extreme tails of sea level distributions. Deep learning systems on the other hand demonstrate rapid progress in their forecasting capabilities at very low computational cost (once trained) (e.g. Žust et al., 2021).

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Operational forecasting sea level models, producing forecasts on the timescales of hours to days, typically cannot resolve low-frequency sea level variability on the timescales of days to weeks (shown to significantly precondition coastal flooding in some parts of the Mediterranean; e.g. Pasarić et al., 2000; Pasarić and Orlić, 2001; Ferrarin et al., 2021) and are further constrained by the limited sea state knowledge at the time of the simulation. Therefore, sea level observations must somehow be introduced into the model during or after runtime. This can be done in several ways. A simple nudging scheme makes use of near-real time tide gauge data from the last 7 days in the Nivmar storm surge forecasting system run by Ports of Spain since 1998 (Álvarez Fanjul et al., 2001). Another reliable approach to do this is tide gauge data assimilation (*e.g.* using ensemble Kalman filtering as in Bajo et al., 2019), followed or complemented by statistical bias corrections with reference to real-time sea level data. Deep-learning approaches (e.g. Žust et al., 2021; Bajo and Umgiesser, 2010) on the other hand offer an alternative way of handling sea level observations: providing near-real-time sea level observations together with tidal model forecasts enables deep networks to learn the biases in tidal models and compensate for this in real time without resorting to numerically expensive schemes like data assimilation.

The Adriatic Sea serves as an example where observation-driven ensemble sea level modelling is absolutely imperative for reliable predictions of cyclone-induced wind driven floods in Venice and other coastal towns along the northern Adriatic coast. Its elongated shape leads to well defined seiche periods and resonant amplification of tides (Medvedev et al., 2020). Its bathymetry on the other hand leads to topographic amplification of sea level signal on the northern Adriatic shelf. Total sea level signal in the northern Adriatic therefore critically depends on the mutual reinforcement between storm surge, tides and seiches, which in turn depends on the temporal phase difference between peak storm surge, peak tide and peak seiche (see e.g. Cavaleri et al., 2010). High sensitivity to the phase difference between these components is the reason that even minor errors in predicting the storm timing or trajectory may lead to substantial errors in the total sea level forecast (Cavaleri et al., 2020), which makes ensemble modelling a clear advantage.

Focusing on short term forecasting of the Venice Lagoon sea level, ISPRA developed and manages an integrated system, made up of *in situ* data coming from the RMN and RMLV networks (see Section 2.1.8) and numerical and statistical models. The sea level forecasting system is mainly based on the deterministic hydrodynamic finite elements numerical model SHYFEM, and it provides sea level forecasts up to 96 h depending on the spatial resolution (40 km in the Mediterranean Sea, 2 km in the Adriatic Sea, 100 m in the Venice Lagoon). It uses ECMWF and BOLAM meteorological fields, as input data, and it assimilates the sea level measured by the 36 RMN tide gauges. This integration and the improvement of both *in situ* observations and modelling system shows a virtuous example of efficiency and functionality to prevent and mitigate the impact of flooding and meteo-marine extreme events on the Italian coastal environment.

Other operational storm surge forecasting systems have been in place in the Mediterranean Sea for the last two decades (Umgiesser et al., 2021). These systems are progressively being improved or combined with existing 3D baroclinic models, new higher resolution models, and ensemble and multi-model statistical techniques that provide sea level forecasts with a confidence interval (probabilistic forecast). In the Western MS, Ports of Spain runs a multi-model storm surge forecast (named ENSURF: Ensemble SURge Forecast: Pérez González et al., 2017, Pérez Gómez et al., 2021) that combines the output of the abovementioned storm surge forecasting system Nivmar with CMEMS circulation models today operational in the region (IBI-MFC (Sotillo et al., 2015) and MED-MFC (Clementi et al., 2019)). The system employs the Bayesian Model Average (BMA) statistical technique, for which near-real-time data from the 17 REDMAR tide gauges in this coast (Section 2.1.1) are used to generate an improved probabilistic forecast at these harbours. This technique is also a valuable tool for operational validation and detailed assessment of the different operational systems.

A multi-model ensemble forecasting system has also been recently developed for the Adriatic Sea combining 10 models predicting sea level height (either storm surge or total water level) and 9 predicting waves characteristics (Ferrarin et al., 2020).

On longer timescales, mid- to long-term coastal management and spatial planning indicates a growing need to understand the impacts of climate change and global mean sea level rise on coastal floods in terms of their intensity and frequency on multi-decadal timescales (Međugorac et al., 2021; Oppenheimer et al., 2019; Bonaldo et al., 2019; Lionello et al., 2017; Androulidakis et al., 2015; Šepić et al., 2012; Marcos et al., 2011). Multi-decadal time series of sea level observations are indispensable in available research since they are the only way of pinning model reanalyses (*e.g.* Escudier et al., 2020) to past sea level variability, thus paving the way for reliable projections.

Several long-term studies (Androulidakis et al., 2015) indicate that different dynamic contributions to the global mean sea level will have to some extent compensat each other, but it can nevertheless be claimed with very high confidence that global mean sea level rise will lead to a substantial overall risk increase in coastal extreme events (Oppenheimer et al., 2019). Consequently, a well-functioning sea level observation network will be more and more imperative for synoptic coastal flood forecasting and mitigation in the M/BS.

4.1.3 Tsunamis and meteotsunamis

A carefully planned network of real-time accessible tide gauge stations is a must for efficient research, monitoring and issuing of tsunami and meteotsunami early warnings. The meteotsunami network should, in addition, be supplemented with air pressure and wind sensors.

Tsunamis, as earthquakes, cannot be predicted. Once they are triggered, mostly by submarine earthquakes, they propagate over thousands of km in the ocean and will reach the coastline in a matter of hours, or even of minutes for those coastal areas which are closer to the tsunami source. As fast detection is essential, tsunami warning systems must rely on real-time seismological networks (real-time information about the earthquake), and real-time information of sea level height oscillations. The latter are provided by shore-based tide gauges and by offshore buoys with bottom pressure sensors (tsunameters, e.g. DART buoys). First alert messages are issued from seismic information. However, assessing the tsunamigenic potential of an earthquake is not easy, so sea level measurements are needed to confirm that a tsunami was generated and to reduce the number of false alarms. Tsunami propagation models are used to forecast the time and amplitude of the wave on arrival at different coastal points, and can also be validated with sea level observations. Adequate

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communications infrastructure allows issuing correct and timely warnings to local emergency management officials, who can decide to activate their emergency protocols to evacuate low-lying coastal areas in advance of the initial tsunami wave.

When the tsunami of 2004 hit the Indian Ocean causing one of the most devastating disasters of our recent history, only the Pacific Ocean had a tsunami warning system in place. Considering how many lives could have been saved, IOC/UNESCO established several intergovernmental working groups for implementation of regional and national tsunami warning systems in other basins, such as the North-Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS) Tsunami Warning System (UNESCO/IOC, 2012a). In 2005, most of the tide gauges in NEAMTWS region were not suitable for tsunami warning. Requirements for this application are less restrictive in terms of accuracy or datum stability than for long-term sea level trends estimates, and consist mainly of improving timeliness and lowering sampling intervals to 1 min or less for adequate measurement of tsunami wave amplitude and arrival time. A basin-wide distribution of stations is needed, with more stations in those areas closer to tsunamigenic sources, as is the case for a significant part of the Mediterranean coast.

Following new NEAMTWS requirements for sea level data exchange, many stations have been upgraded in the M/BS region since 2005, and provide today higher-frequency sea level data in real time to regional and national tsunami warning systems. In addition, the last Global Sea Level Observing System (GLOSS) Implementation Plan (UNESCO/IOC, 2012b) suggests that GLOSS Core stations can be configured to support storm surge and tsunami warning systems. This approach has ensured the multi-purpose character of some of the stations, good for network sustainability, but has raised new challenges on standard quality control and data processing techniques that need to be adapted and the development of automatic tools for tsunami detection (Holgate et al., 2008; Beltrami et al., 2011; Pérez Gómez et al., 2013; UNESCO/IOC, 2020). These stations are handled by national institutions and warning systems, although most of them also contribute to the IOC Sea Level Station Monitoring Facility (http://www.ioc-sealevelmonitoring.org/map.php) and the JRC-SLD https://webcritech.jrc.ec.europa.eu/ portals as well.

Based on data availability on these portals and the response from national institutions to this survey, at least 152 of all active stations in the M/BS are today contributing to tsunami warning systems, including those upgraded and those installed for this purpose (e.g. a total of 24 IDSL stations installed by JRC and 19 radar stations operated by the National Observatory of Athens (NOA) in the Greek coast). However, only three of these stations are located in the North of Africa coast: Melilla, Alexandria and Saidia Marina. The French Tsunami Warning Center (CENALT) developed tools based on tsunami wave modelling to monitor the existing sea level network capacity for tsunami detection (Schindelé et al., 2008, 2015). As an example, they found that the tsunami generated by an earthquake North of Algeria in 2003 would not be confirmed by the tide gauge network in less than 70 min, when the travel time to the most affected zones was 30-40 min. The tool, that provides guidance for the implementation of additional tide gauges, demonstrated that adding four tide gauges, two in the Balearic Islands, one in Sardinia, and one in Sicily, would reduce tsunami detection time by more than 20 min for sources along the North Algeria and Tunisia shoreline. They also recommend implementation of two tsunameters offshore at specific points in that area, to reduce the detection delay to less than 15-25 min along Tunisian coast. However, the high installation and

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maintenance costs, along with the location of tsunamigenic areas so close to the coastline, has prevented the implementation of these offshore instrumentation in the M/BS area so far.

Since 2018, the Tsunami Last Mile project of Joint Research Centre (JRC) explored how to better warn the population during near shore or distant tsunami events. It was demonstrated twice, in Kos (Fall 2019, also presented at the AGU Fall Meeting in 2019) and in Malta (beginning of November 2021), how interconnecting sensing devices with an alerting system may warn the population promptly and allow a safe evacuation. Possibly, the exercise will be repeated in Indonesia during 2022. The two events differ because Kos was a near shore event and thus required the activation before the official alert from service provider was issued, while Malta was a distant shore event so that the first activation was triggered by the information coming from the Tsunami Service Providers. The system is based on a network including IDSLs and seismometers as sensing devices and a long-range siren with two alerting panels to warn the population. As soon as both IDSLs confirmed the anomalous behaviour of the sea level, the alerting devices started alerting the population automatically, providing indications about the countermeasures to be taken. In the case of Kos this was the first triggering information. Specific signages deployed in the streets provided indications about the evacuation routes and the assembly points.

The system allows several degrees of automation, from completely automatic to manual activations only, depending on the standard procedures adopted by the authorities entitled to protect the population. This system is based on the multipurpose platform developed by the JRC and called RIO (Remote InterOperability), that is a complete software platform that allows easy integration of various instruments and analytical computations and activations. The RIO system was also adopted in another project, a low cost GNSS-based buoy that provides sea level data from the open sea. Such a type of device could be therefore naturally integrated in the same network and would provide the alerting information much in advance compared with devices deployed on the coasts: depending on the installation site, the improvement in reaction time could be consistent.

Traditionally, tide gauge stations have not been located at meteotsunami-prone areas, but rather at locations of interest for other sea level processes (e.g. storm surges and sea level rise), and large ports and harbours where sea level data is of utmost importance for safety of navigation or at the well-inhabited coastal towns. Up to the beginning of the 21th century, at the meteotsunami hot spots the measurements have been done only during specific experiments, aimed purely at better understanding of meteotsunamis and other high-frequency sea level phenomena. Such experiments include, but are not limited to: (1) several field experiments with simultaneous air pressure and sea level measurements done during the years 1989-1992 (Monserrat et al., 1991; Rabinovich and Monserrat, 1996), and 1996-1998 (Monserrat et al., 1998; Šepić et al., 2009) in Ciutadella (the Balearic Islands, Spain); (2) field experiments, during which bottom pressure was measured at several locations within the endangered Adriatic bays, conducted through the years 2007-2008 (Orlić and Pasarić, 2008) and 2015 (not published); (3) field experiment with simultaneous air pressure and sea level measurements done in the year 2007 in Mazara del Vallo (Marrobbio Project Report, 2007; Zemunik et al., 2021a). Throughout the last two decades the national agencies and local authorities have, however, recognised a meteotsunami threat and have been making a continuous effort towards operational monitoring and forecasting of meteotsunamis, including installation of permanent tide gauge stations at the most

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endangered coastal locations. These include Ciutadella (Menorca Island, Spain), where a tide gauge station has been operational since 2013, and Vela Luka, Mali Lošinj and Stari Grad (the Adriatic Sea, Croatia), where permanent tide gauge stations have been installed during 2017-2021. Having operational stations at meteotsunami-prone locations is a prerequisite for proper monitoring of destructive events, but more needs to be done for an efficient warning system to be implemented, given that a warning should be issued at least an hour before the meteotsunami occurs at an endangered location.

Vilibić et al. (2016) presented a design of a meteotsunami warning system based on simultaneous numerical modelling of synoptic, mesoscale atmospheric and barotropic sea level conditions, as well as a real-time assessment of atmospheric and ocean data measured a few tens up to a couple of hundreds of kilometres away from the most endangered spots, that is at locations where off-shore meteotsunami generation and growth occur. Denamiel et al. (2019, 2021) further upgraded the concept suggesting that stochastic approaches are more reliable than deterministic numerical modelling – the prototype of such system, which gives estimates of the sea level exceedance probability during meteotsunamis, was tested for the Croatian coast of the Adriatic Sea (Denamiel et al., 2019). Similar modelling and data assessment strategies have been suggested and tested for the Balearic Islands area (Renault et al., 2011; Šepić et al., 2016a; Romero et al., 2019), where a continuously upgraded meteotsunami warning system, with both deterministic and probabilistic component, has been operational since 1985 (Jansà and Ramis, 2021).

In spite of the great efforts invested in development of the meteotsunami warning systems, the results are still not satisfactory, resulting in a loss of trust in the early warning systems. The forecasts are known to be wrong, especially when it comes to estimating the strength and destructiveness of the event (Jansà and Ramis, 2021). The crucial problem is an intrinsic inability of the atmospheric models – related, among else, to coarse resolutions and inadequate physical parameterization at the mesoscale – to reproduce exact properties (spatial outreach and rate of air pressure change, speed, pressure and wind spatial gradient) of the fast changing atmospheric disturbances responsible for the meteotsunami generation (Belušić et al., 2007). Slight changes of any of these properties (e.g. reducing the rate of air pressure change, translating meteotsunamigenic disturbances off their pathways for a few tens of kilometres, changing the propagation speed) may change the modelled sea level response for several times, in particular at the most endangered areas (Vilibić et al., 2008; Orlić et al., 2010; Orfila et al., 2011; Šepić et al., 2016a; Ličer et al., 2017; Mourre et al., 2021).

Nevertheless, a significant densification of the observation network, including the sea level stations, on-shore and off-shore meteorological stations and off-shore bottom pressure recorders would help in real-time monitoring of meteotsunamigenic atmospheric disturbances and ocean conditions and in calibrating operational numerical models – and would likely result in more reliable early warning systems.

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4.2 Climate-related applications

4.2.1 Long-term variability and sea level trends

In order to estimate the long-term variability and trends of the sea level for M/BS, the PSMSL RLR dataset has been used as the primary source of monthly means (see Section 3.1). The analysis is made on a geographical extraction on M/BS of the PSMSL relative sea level trends product (https://www.psmsl.org/products/trends/). This product fits a model composed of linear trend, seasonal component and noise on data which have at least 70% of their annual mean for the given time span. In this section four different time spans were considered all ending in 2019, the shortest one is 30 years - which is the minimum time span of the online PSMSL product and roughly corresponds to the availability of satellite altimetry – while the longest considered time span is 100 year. The number of stations per country spanning the last 30, 50, 70 and 100 years is provided in Table 1.

Table 1: Number of stations per country available for different time spans 30, 50, 70 and 100 years in the PSMSL sea level trend online product.

Time span period	Croatia	Italy	Spain	Greece	France	Georgia	Russia	Ukraine	Egypt	Malta	Total
100 yr : 1920-2019	1	2	0	0	1	1	1	1	0	0	**7**
70 yr : 1950-2019	5	2	3	0	1	1	1	0	1	0	**14**
50 yr : 1970-2019	5	1	3	8	1	1	1	0	1	0	**21**
30 yr : 1990 - 2019	5	1	7	9	2	1	1	0	0	1	**27**

As coming from Table 1, the M/BS has few centennial tide gauge records. If we consider the records spanning the last hundred years 7 stations are available at PSMSL: 4 in the Mediterranean (Trieste and Venice in Italy, Bakar in Croatia, Marseille in France) and 3 in the Black Sea (Poti in Georgia, Tuapse in Russia and Sevastopol in Ukraine). Some stations that appear in the PSMSL database for the 1920-2019 period are not present in the shorter time spans period because they stopped with work in the second half of the twentieth century. This is the case for Sevastopol in Ukraine that had 97% of its annual record for the period 1910 to 1994 and then stopped, so it does not show up anymore in our 70, 50 and 30 time spans.

For the sea level records spanning the last 70 years (1950-2019), 14 stations are available in the PSMSL data bank (2 times more than the centennial records). Four of these new long tide gauge records are located along the coast of Croatia (2 are located in Split, 1 in Dubrovnik and 1 in Rovinj) making the Adriatic Sea the most populated in terms of historical sea level records with half of the fourteen 70 years long records. For Italy, France and the Black Sea, the 70 and 100 years long stations remain the same (except for Sevastopol discussed above), while Spain comprises 3 long records at the entrance of the Mediterranean Sea near Gibraltar straits (Ceuta, Malaga and Tarifa). The Alexandria station in Egypt also fits to the 70 year time span, but disappears in the shorter time span because it ended in 2006 in the PSMSL database. It is noticeable that

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Alexandria is present up to 2016 in the UHSLC and that 5 of the new stations in the 70 year time span have not been updated in PSMSL since 2017, highlighting the importance of updating records within the PSMSL. Although they do not appear yet in the PSMSL RLR dataset, some long-term records can be found from external sources. This is the case for Alicante station in Spain that has been recently digitized by Marcos et al. (2021), the Venezia station in Italy that has been updated recently (Zanchettin et al., 2021) and the data from Koper in Slovenia that has been provided by the co-authors of this paper. We have decided to add these stations in our analysis (represented in blue in Fig. 9).

If the last 30 years (1990-2019) are considered, the situation is a bit better with 27 stations available. It is noticeable that no long-term records are available for the south of the Mediterranean Sea (North African coast). These long-term records are the only means to compute robust estimation of sea level rise.

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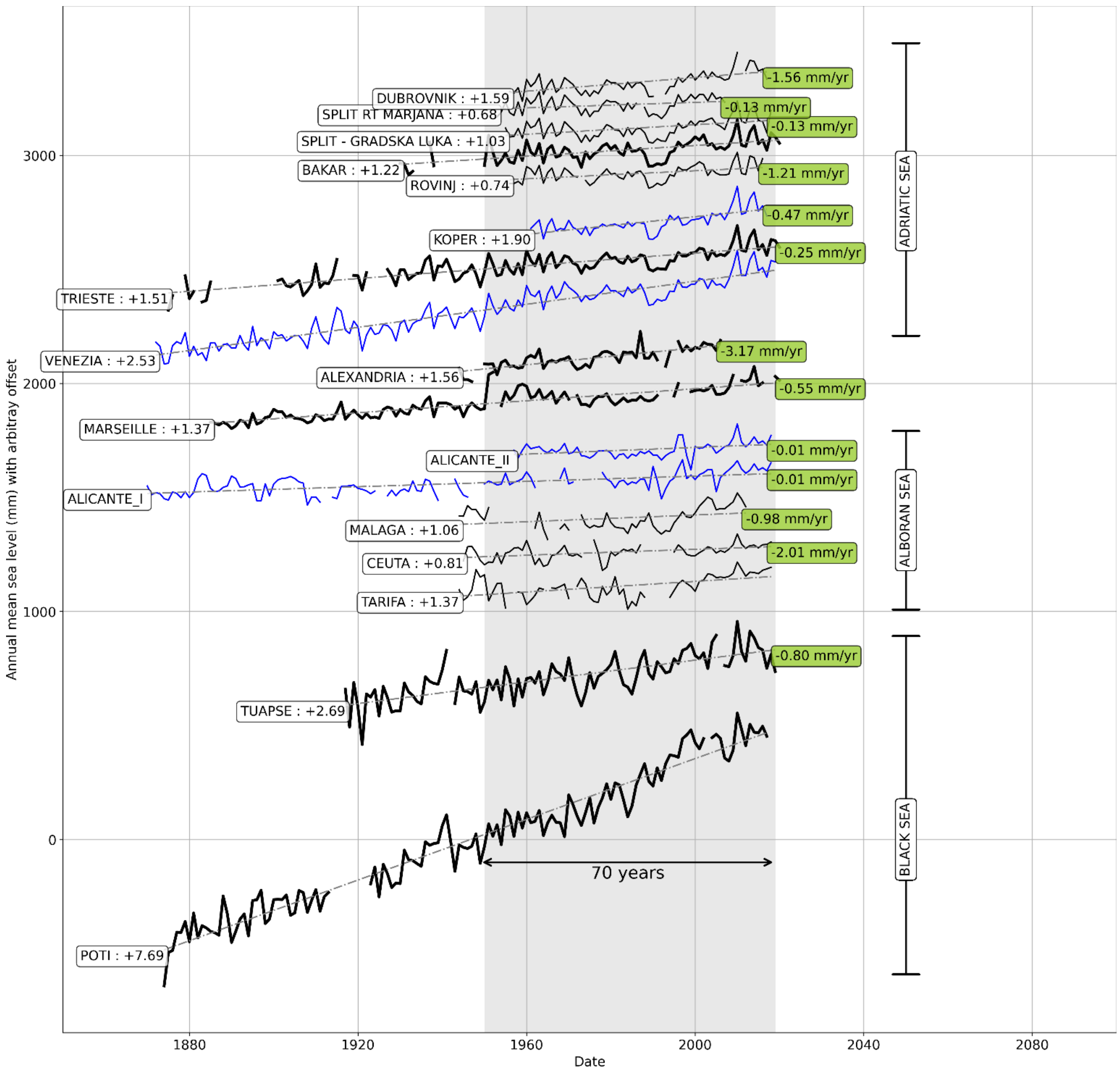

Figure 9: 70 years long sea level records. The curves in black are for data from PSMSL, bold are the 100 year long records, and in blue the updated or new records, not available in the PSMSL. The name of the station is followed by the relative sea level trend estimates in mm/yr and in the green boxes on the right of the curve are the vertical land motion estimates.

In Fig. 9 the vertical land movement (VLM) rates for each station is estimated from a combination of the different GNSS solutions provided by the SONEL data center (www.sonel.org). These estimates are based on the mean of the different VLM solution from the collocated GNSS stations, and they have been supported by an update on co-location between GNSS and tide gauges in Europe. The update has been recently released by the EuroGOOS Tide Gauge Task Team and SONEL, in the framework of a contract of EuroGOOS with the European Environmental Agency, to increase *in situ* sea level data provision to Copernicus Marine Service (https://insitu.copernicus.eu/library/reports/coins-coastal-sea level-stations). It can be seen that all long-term records in the M/BS show relative sea level rise with values ranging from 0.68 mm/yr in Split RT Marjana in the Adriatic Sea to 7.69 mm/yr in Poti in the Black Sea. The high sea level rise at this last station suggests that it is probably prone to significant VLM (Avşar et al., 2017). One can see also the high correlation of the sea level variation in the Adriatic Sea.

4.2.2 Evolution of extreme sea levels

Long-term changes, at interannual and longer time scales, in extreme sea levels are primarily driven by changes in mean sea level (MSL, Woodworth et al., 2019). However, variations in extremes unrelated to MSL variability have also been identified in tide gauge records at hourly scale worldwide (Wahl and Chambers 2015; Marcos and Woodworth, 2017) and linked to changes in storminess. In the Mediterranean Sea, long-term multidecadal fluctuations in sea level extremes have been noticed in long tide gauge records, such as those in Trieste since the 1930s (Raicich, 2003) and other stations in the northern Adriatic (Masina and Lamberti, 2013), and in Marseille since the early 20th century (Letetrel et al., 2010; Marcos et al., 2015). These variations are regionally coherent as they normally originate from large-scale atmospheric forcing (Calafat et al. 2014; Marcos et al., 2015; Lionello et al 2021). Given the variability at such low frequencies, the estimation of linear trends is highly dependent on the selected period. For example, Raicich (2003) identified a decrease in the frequency of extremes in Trieste tide gauge record during the period 1940-2000, with no clear trend in their intensity. In contrast, Masina and Lamberti (2013) identified a small increase in the magnitude of sea level extremes in the northern Adriatic that was associated with an intensification of the bora wind in the 1990s. In Venice, Lionello et al (2021) reported that the frequency of flooding resulting from storm surges has increased since the mid-20th century, although they linked this effect to relative sea level rise rather than to a sustained trend in storminess. At interannual time scales changes in extreme sea levels are correlated with the North Atlantic Oscillation (Marcos et al., 2009b; Masina and Lamberti, 2013), even after the removal of the yearly MSL signal.

4.3 Satellite altimetry calibration

Satellite altimetry is nowadays an inevitable tool for mapping sea level changes over the ocean basins (Ablain et al., 2017). However, their measurements are biased by a number of processes (Fu and Haines, 2013) and therefore a proper calibration of these data is the prerequisite (Andersen and Cheng, 2013; Woodworth et al., 2017), in particular when approaching the coastal zone (Vignudelli et al., 2019). The tide gauge data is normally used for satellite altimetry calibration, yet the problem is that the altimetry measurements are not reliable close to land, while large differences in mean sea level may occur at the coastal distances (e.g. in the last 4-5 km to the coast, as observed for the Senetosa calibration site at Corsica for both TOPEX/Poseidon and Jason altimetry missions, Gouzenes et al., 2020). Indeed, a careful examination should be conducted to verify nonexistence of all potential errors that could explain the increased rate of sea level rise close to the coast - like spurious trends in the geophysical corrections, imperfect inter-mission bias estimate, decrease of valid data close to the coast and errors in waveform retracking - before ascribing a finding to the real physical. Here, for the Sanatosa calibration site, it has been proven that the steric sea level component is responsible for such changes (Dieng et al., 2021).

These problems are even more amplified in enclosed seas, such as the M/BS, where the impact of a basin topography and a complex coastline is more pronounced than at the oceans. Orbit-related sea level errors are an example, as found to be prominent in the Mediterranean (Esselborn et al., 2020). For that reason, calibration of satellite altimeters has a long history there. This particularly applies to some selected tide gauge sites in the Mediterranean locations, like Ibiza (Martinez-Benjamin et al., 2004; Frappart et al., 2015) or Corsica (Bonnefond et al., 2003, 2021; Cancet et al., 2013). Recently, advanced learning methods (such as deep learning networks) have been used to improve calibrations of altimeter data (Yang et al., 2021).

4.4. Definition of vertical frames of reference

The precise information on vertical references, which strongly relies on tide gauge measurements, is also a major issue, for both ocean and land charts. Vertical reference surfaces can be categorized under three general headings:

- tidal datum, also called chart datum which should, according to the IHO recommendations, correspond to the lowest astronomical sea level (LAT) or an equivalent reference level considered by the hydrographic services as being as close as possible to the LAT;
- vertical reference datum which is a surface of zero elevation to which heights of various points at land are referred, being a base for defining height systems (e.g. European Vertical Reference System, EVRF2019)
- ellipsoidal reference datum, which allows to define the ellipsoidal height important for satellite altimetry measurements and GNSS receivers at tide gauges (e.g. Adebisi et al., 2021), such as Global Reference System 1980 (GRS80) or World Geodetic System 1984 (WGS84).

At tide gauges, the referencing of one with respect to another is essential to allow tidal observations to serve all possible applications (e.g. the analysis of the tidal observations allows to define the characteristics of the tide at the tide gauges (LAT, MSL, HAT...) and consequently to determine the tidal/chart datum.

Traditionally, bathymetric data has been collected and stored relative to a tidal datum and topographic data relative to a geodetic datum. Close to a tide gauge, bathymetric data can be referenced to the chart datum by subtracting the observations of the tide gauge directly or associated with models. One of the most significant challenges in traditional hydrography is establishing the relationship between the instantaneous water surface and chart datum away from water level gauge locations. In this case, to obtain the chart depths, the vertical positions of the bottom are referred to the so-called Vertical Reference Surface for Hydrography (VRSH), which, following the recommendations of the IHO, is identified with the development of a 3D separation model between Chart Datum (LAT) and the geodetic datum (geoid and/or respect to the ellipsoid).

In modern times, the hydrographic surveying community is using high-accuracy Global Navigation Satellite System (GNSS) positioning techniques for vertical positioning of survey platforms, the sea surface and the sea floor. This method of hydrographic surveying, which is known as Ellipsoidal Referenced Surveying (Hamden and Din, 2018), provides a direct

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measurement of the seafloor to the ellipsoid, as established by GNSS observations, and a translation of the reference from the ellipsoid to the geoid and/or a chart datum (VRSH).

In Spain, the orthometric and ellipsoidal heights of the LAT have been established for the Iberian Peninsula and Canary Islands domains from model-reanalysis sea level data fields, which were first validated and then adjusted to experimental data from 119 tide gauge stations. The sea level height with respect to the geoid was obtained from the modelling-reanalysis service provided by the Iberia-Biscay-Ireland Monitoring and Forecasting Center (IBI MFC), in the framework of the EU Copernicus Marine Environment Monitoring System (Sotillo et al., 2015). Away from water level gauge locations the model will be adjusted in the future by GNSS water level buoys, to establish chart datum at offshore locations.

5 Summary and conclusions

An overview of existing coastal sea level infrastructure in the M/BS has been presented, based on the contribution from 30 institutions/sea level scientists operating tide gauges in the region. These stations are essential to monitor and study sea level variations that pose a hazard in these basins, such as storm surges, tsunamis, meteotsunamis and sea level rise, by providing accurate sea level data at all frequency ranges along the coastline. The initiative gives an insight into the status of the *in situ* sea level network in both basins and confirms several challenging aspects such as the diversity of national strategies, sea level technology, funding or data availability, often linked to differences on the primary and evolving objectives of these installations, and their unbalanced spatial distribution. National contacts and relevant basic metadata are provided, as a starting point for improving coordination across the region. In most countries tide gauges are operated by several agencies, usually targeting different purposes. Only 7 of these institutions are in charge of more than 15 stations, while the majority operate a smaller number of stations, sometimes one single station.

We have identified 236 active stations covering nearly all the country's coastlines in the M/BS. Several stations in Morocco and Tunisia could not be added to this inventory, and no information was obtained from Libya. confirming the lack of information along the southern Mediterranean coast from previous initiatives.

There are still many float gauges as the ones installed since the end of the XIXth century for tides and hydrography applications, still being the second most important application, especially along the northern and eastern Adriatic and the Greek coasts. However, tides in the M/BS are generally small, so tide predictions are not computed nor needed for port operations everywhere. Therefore, an increasing number of stations are becoming multi-purpose, a term we apply here to tide gauges upgraded to be used as well in tsunami, storm surge and other early warning systems. A significant part of the network is based on radar sensors (134, 57% of the stations) providing 1 min time sampling data, with real or near-real time data transmission. This has been mainly driven by new requirements for tsunami warning systems since 2005, that yielded to the upgrade of existing networks in several countries (e.g. Spain, France, Italy, Türkiye) and the installation of new sensors in several areas (15 new radar sensors since 2012 along the Greek coast (NOA), 24 inexpensive acoustic sensors by JRC, in collaboration with several national operators, all around the Mediterranean). In fact, about 152 of the active stations are contributing nowadays to regional or national tsunami warning systems in this region. In addition, lower time samplings have allowed, as for the global network, an improved dataset for understanding and warning meteotsunami events, more frequent than tsunamis at several spots in the M/BS. While 1 min sampling is sufficient for detection of most of these sea level oscillations, access to even higher frequency raw data from modern sensors would be desirable in the future, for a better characterization of all periods above 30 s. As an example, PdE in Spain has recently developed a tool for operational characterization of 2 Hz raw data from the REDMAR network, that provides these data and derived data products including waves through PdE OpenDap server. In addition, at least 4 more institutions participating in this survey compute wind wave parameters from tide gauge raw data.

In terms of length of the sea level records, the numbers decrease significantly: only 10 stations have been identified with enough valid data covering the last 100 years (7 with data in the PSMSL), while 27 would have data for the last 30 years (the altimetry period). This reflects the limitations of the network to provide reliable sea level trends and their spatial variability along the coastline. Apart from the smaller number of tide gauges in the past, this is perhaps the most challenging application, as it requires a precise knowledge of the station history, data archaeology efforts and often the careful combination of data from different technologies/locations inside a harbour. Fortunately, access to VLM information has also improved in recent years, with up to 46 stations now collocated with a permanent GNSS in the M/BS.

Some of these stations are contributing, with different time sampling, latency and quality control to one or more of the seven international data integrators or portals described in Section 3, where a detailed assessment of data accessibility in the M/BS is presented. The most populated portal, PSMSL, contains data from 158 stations in the region, which means that there is still a significant number of M/BS stations focused on local or national services and not included in international programs. This is a problem for basin scale applications and research studies and it is often related to data policy issues: not all tide gauges provide open and free data to users, and some claim data availability only for research applications. It must be emphasized that most of national operators rely on their own personnel and resources, including in situ maintenance as well as quality control, data processing and product generation, and international programs have traditionally relied on these national efforts. This requires enough funding of the networks from the Member States, not always guaranteed, and it could also explain the lack of access to data, or the delays in updating the time series with recent records.

On the contrary, in other cases, the same sea level time series can be found at different repositories, as well as at national data portals, with different name, metadata, or quality control, which may be confusing for end-users. These problems are not exclusive to the M/BS, and are partly linked to the lack of unique identifiers and adequate and standard metadata information for tide gauges. Data integrators should collaborate between them and work more closely with original data providers, to ensure interoperability and homogeneous and good quality datasets, according to FAIR principles. These issues are being tackled by GLOSS and by the EuroGOOS Tide Gauge Task Team in the framework of the EuroSea project (see EuroSea Deliverable 3.3: New tide gauge data flow strategy, https://doi.org/10.3289/eurosea_d3.3).

This work shows the evolution of sea level sensors technology through the decades, for tide gauges typically installed on a pier in a harbour. These are relatively easy to install and maintain, and the main source of in situ sea level data along the coast. Apart from float, acoustic, pressure and radar sensors, a novel technique based on GNSS Interferometric Reflectometry (GNSS-IR) has recently emerged and revealed its potential as the number of satellite constellations increased (Peng et al., 2021). GNSS receivers have the advantage of providing both sea level and land motion information. Some institutions in the M/BS (e.g. Spanish Geographic Institute) are already exploring this technique. In the framework of the EuroSea project and the EuroGOOS Tide Gauge Task Team activities, the UK National Oceanographic Center (NOC) has recently developed a global GNSS-IR data portal, hosted at the PSMSL (https://eurosea.eu/new/a-global-sea-level-data-portal-using-global-navigation-satellite-system-interferometric-reflectometry/).

The use of GNSS receivers for sea level is becoming a reality and it is going even further. For many applications, in situ sea level measurements offshore would be a significant improvement of the coastal sea level network. One example is tsunami warning, where detection of the wave before reaching the coast is a clear advantage. GNSS receivers on buoys (GNSS-buoys) have been used for years in Japan's tsunami warning system. Despite this inventory is not including this type of stations in the M/BS, we know that several countries and agencies are now planning their implementation by adding GNSS receivers to existing or new buoys. These data would be also valuable for calibration of coastal altimetry or, as described in Section 2, for determination of offshore chart datum.

This survey has also revealed that at least 64% of active stations in the M/BS (150) have some kind of ancillary sensor providing meteorological and/or oceanographic data. Atmospheric pressure and wind are the most traditional and frequent additional parameters, very often with time samplings of 1 min, useful for meteotsunami studies. But a number of stations in the Appendix are in fact multi-sensor platforms providing a large range of parameters, as do meteorological stations (humidity, air temperature, precipitation, etc) and even ocean data like water temperature, salinity or currents. Several agencies have already or plan to install cameras (e.g. webcams planned by SHOM, in France). Multi-sensor platforms deployment seems a reasonable approach for ensuring sustainability of the networks by expanding even more their range of applications.

In summary, the assessment of the coastal sea level monitoring capacities in the M/BS exposed several important issues that are a prerequisite for making sea level operations and science over a variety of timescales and applications in these enclosed basins comprehensive: (1) a longevity of calibrated measurements is threatened at some monitoring sites, which may lower the confidence of the sea level rise estimates in the era of climate change – this should be immediately bypassed by putting again in operations all inoperable tide gauges that have multi-decadal time series; (2) the gaps in monitoring systems or their inadequacy that exist in some coastlines (e.g. Libya, Albania) should be bridged, by upgrading the existing stations or installing new ones; (3) the quoted activities should be done through collaboration and knowledge-transfer from more experienced tide gauge networks, in particular towards North Africa countries, preferably within the umbrella of existing international programmes (IOC, MONGOOS), agencies (e.g. through extending the IDSL network of JRC) or joint projects; (4) the data should be available for research and follow the open science policies, in particular of the FAIR principles (Wilkinson et al., 2016); and (5) the cacophony of sea level data repositories should be minimized, with the clear and unique provision of data for real-time and research purposes through one-stop shop service, including harmonized quality-check procedures. We hope that the next decade of coastal sea level monitoring will be as dynamic as the last decade, in which substantial progress in some of the quoted issues has been achieved in some tide gauge networks, thus with a potential to be spilled over the whole Mediterranean and Black seas.

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Author Contributions

BPG lead this work as chair of the MONGOOS Tide Gauge Task Team and was in charge of the overall direction and planning, based on discussions with team members (IV, JS, LT, FR, MM, CF, ML, SM, GZ) for definition of the final scope and structure of the manuscript. Several authors took the lead in writing specific sections: BPG (Sect. 1, 2 and 5), IV (Abstract, Sect. 3 and 4.3), CF (Sect. 4.1.1 and 4.4), ML (Sect. 4.1.2), JŠ (Sect. 4.1.3), LT (Sect. 4.2.1) and MM (Sect. 4.2.2). The following authors provided relevant contribution to Sect. 2, including network description, answer to the survey and stations information for their respective institutions in: Spain (BPG, EAF, MM, JT, BC, ET, AC, VMG, MAF, JMQB, MLR, JP and JS), France (CF), Italy (SM, MP, FR), Malta (AD, AG), Slovenia (MJ), Croatia (HM, SČ, DB, IM, JŠ, IV), Montenegro (BG), Albania (KZ), Greece (GS, DAG), Cyprus (GZ), Egypt (MS), Israel (AL), Türkiye (MS, ES, HK), Bulgaria (AP), Romania (DN), Russia (IM), Algeria (HA, AM, MAM) and those from JRC, including Lebanon IDSL station (DAG). BPG designed and launched the survey to identified contacts, prepared Figs. 2 and 3, and contributed to writing in Sect. 4.1.1, 4.1.2, 4.1.3 and 4.2.1. JŠ provided meteotsunamis description in Sect. 1 and prepared Fig. 1. Maximum hourly values for Fig. 1a were provided by MM (for those stations in GESLA dataset), MS (stations in Türkiye), GS (Greek stations) and IM and SČ (Croatian stations). IM designed and prepared Figs. 4, 5 and 6 with detailed mapping of existing infrastructure, based on the stations list in the Appendix, and IV and JŠ prepared Figs. 7 and 8 on data availability in data portals. LT compiled monthly mean sea levels from PSMSL and

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several agencies, and prepared Fig. 9. JMQB and MLR contributed to Sect. 4.1.1 and 4.4, SM and MP to Sect. 4.1.2 and DAG to Sect. 5. JŠ, SČ, DB, MJ and ML helped with contacting authors from Algeria, Russia, Montenegro and Albania. Finally, IV, JS, IM and BPG helped shape the final version of the manuscript during the internal review process. All authors have read and agreed to the submission of the manuscript for publication.

Competing interests

The authors declare that they have no conflict of interest.

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Table A1: Stations operated by Puertos del Estado (REDMAR network) and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
1	**Alcudia**	Radar	39.83456	3.13898	Sep 2009 - present	Atm. pressure, wind	
2	**Algeciras**	Radar	36.17700	-5.39838	Jul 2009 - present	Atm. pressure, wind	
3	**Almería**	Radar	36.83002	-2.47835	Jul 2006 - present	Atm. pressure, wind, GNSS	
	Barcelona	Acoustic	41.34936	2.16023	Aug 1992 - Dec 2007		Upgraded and relocated
4	**Barcelona2**	Radar	41.34177	2.16570	Jan 2008 - present	GNSS	
5	**Carboneras**	Radar	36.97430	-1.89959	Jun 2013 - present	Atm. pressure, wind	
6	**Formentera**	Radar	38.73466	1.41903	Sep 2009 - present	Atm.pressure, wind	
7	**Gandía**	Radar	38.99521	-0.15139	Sep 2007 - present		
	Ibiza	Pressure	38.91123	1.44984	Jan 2003 – Dec 2009		Upgraded
8	**Ibiza2**	Radar	38.91123	1.44984	Jan 2010 - present	Atm. pressure, wind, GNSS	
9	**Mahón**	Radar	39.89304	4.27056	Nov 2009 - present	Atm. pressure, wind	
	Málaga	Acoustic	36.71269	-4.41545	Jul 1992 - Jan 2010		Upgraded and relocated
10	**Málaga3**	Radar	36.71184	-4.41709	Feb 2010 - present	Atm. pressure	
11	**Mallorca**	Radar	39.56015	2.63748	Sep 2009 - present	Atm. pressure, wind, GNSS	
12	**Melilla**	Radar	35.29061	-2.92853	Oct 2007 - present	GNSS	
	Motril	Pressure	36.72297	-3.52922	Jan 2005 - May 2007		Upgraded and relocated
13	**Motril2**	Radar	36.72024	-3.52360	Jun 2007 - present	Atm. pressure, wind	
14	**Sagunto**	Radar	39.63392	-0.20624	Sep 2007 - present		
15	**Tarifa**	Radar	36.00646	-5.60351	Jul 2009 - present	Atm. pressure, GNSS	
16	**Tarragona**	Radar	41.07897	1.21325	May 2011 - present	Atm. pressure, wind, GNSS	
	Valencia	Acoustic	39.46167	-0.32583	Jul 1992 – Oct 2006		Upgraded and relocated
17	**Valencia3**	Radar	39.44203	-0.31128	Nov 2006 - present		

Table A2: Tide gauge stations in the Balearic Islands operated by SOCIB.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
18	**Andratx**	Pressure	39.544189	2.378460	Jun 2011 - present	Atm. pressure	
19	**Col. Sant Pere**	Pressure	39.737317	3.273358	Apr 2016 - present	Atm. pressure	
20	**Pollença**	Pressure	39.904701	3.088516	Jul 2009 - present	Atm. pressure	
21	**Porto Cristo**	Pressure	39.539174	3.335090	Mar 2016 - present	Atm. pressure	
22	**Sa Rapita**	Pressure	39.360062	2.953671	May 2011 - present	Atm. pressure	
23	**Sant Antoni**	Radar	38.977001	1.298762	Mar 2015 - present	Atm. pressure	

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Table A3: Stations operated by National Geographic Institute of Spain in the Mediterranean Sea and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
24	**Alborán**	Radar	35.93890	-3.03373	Oct 2016 - present	GNSS	
25	**Alicante 1**	Radar	38.33827	-0.47787	May 1928 - present	GNSS	1999: upgraded from mechanical recorder to angle encoder. 2010: upgraded from float to radar.
26	**Alicante 2**	Radar	38.33890	-0.48123	Mar 1957- present	Atm. pressure, GNSS	1996: upgraded from mechanical recorder to angle encoder. 2010: upgraded from float to radar.
27	**Almería**	Radar	36.83224	-2.48499	Jan 1990 - present	GNSS	2010: upgraded from float to radar.
28	**Cartagena**	Radar	37.59661	-0.97385	Jul 2002 - present	GNSS	2010: upgraded from float to radar.
29	**Cartagena**	Acoustic (IDSL)	37.567146	-0.978958	Jun 2018 - present	Air temperature	
30	**Ceuta**	Acoustic (IDSL)	35.895837	-5.311531	Sep 2017 - present	Air temperature	
31	**Ciutadella**	Acoustic (IDSL)	39.987588	3.828154	Oct 2017- present	Air temperature	
32	**La Mola de Mahon Menorca**	Acoustic (IDSL)	39.872305	4.308363	Oct 2017 - present	Air temperature	

Table A4: Stations operated by Spanish Institute of Oceanography in the Mediterranean Sea and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
33	**Algeciras**	Radar	36.11667	-5.43333	1943 - present		2002: upgraded from float to radar
34	**Ceuta**	Radar	35.9	-5.31666	1943 - present	GNSS	2002: upgraded from float to radar
35	**Palma de Mallorca**	Radar	39.55	2.63333	1997 - present	GNSS	2002: upgraded from float to radar
36	**Tarifa**	Radar	36	-5.6	1943 - present	GNSS	2002: upgraded from float to radar

Table A5: Stations operated by Spanish Hydrographic Office in the Mediterranean Sea and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
37	**Castellón**	Acoustic	39.96823	0.01988	Sep 2021 - present	Atm. pressure, air temperature, humidity, GNSS	
38	**Rosas**	Acoustic	42.25531	3.17819	Sep 2021 - present	Atm. pressure, air temperature, humidity, GNSS	

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Table A6: Station operated by Josep Pascual (meteorological observer, Meteolestartit/CSIC).

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
39	**L'Estartit**	Float	42.05338	3.20601	1990 - present	Atm. pressure and other meteorological data	

Table A7: Stations operated by Shom (RONIM network) and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
40	**Ajaccio**	Radar	41.9227982	8.7628498	1981 - present with discontinuities	Atm. pressure	link to DATA Shom
41	**Centuri**	Radar	42.965775	9.349833	2010 - present	Atm. pressure	link to DATA Shom
42	**Fos Sur Mer**	Radar	43.404935	4.892935	2006 - present with discontinuities	Atm. pressure	link to DATA Shom
43	**Ile Rousse**	Radar	42.6396	8.93524	2012 - present with discontinuities	Atm. pressure	link to DATA Shom
44	**La Figueirette**	Radar	43.4835	6.93494	2011 - present	Atm. pressure	link to DATA Shom
45	**Marseille**	Radar	43.278814	5.353758	1849 - present with discontinuities	Atm. pressure, GNSS	link to DATA Shom
46	**Monaco - Fontvieille**	Radar	43.728847	7.421497	1960 - present with discontinuities	Atm. pressure	link to DATA Shom
47	**Nice**	Radar	43.695508	7.285257	1981 - present with discontinuities	Atm. pressure	link to DATA Shom
48	**Port Ferreol**	Radar	43.359072	6.717606	2012 - present	Atm. pressure	link to DATA Shom
49	**Port Vendres**	Radar	42.519922	3.107450	1981 – present with discontinuities	Atm. pressure	link to DATA Shom
50	**Port-La-Nouvelle**	Radar	43.014705	3.064097	2009 - present with discontinuities	Atm. pressure	link to DATA Shom
51	**Sete**	Radar	43.397633	3.699105	1956 - present with discontinuities	Atm. pressure, GNSS	link to DATA Shom
52	**Solenzara**	Radar	41.856856	9.40383	1977 - present with discontinuities	Atm. pressure	link to DATA Shom
53	**Toulon**	Radar	43.11722	5.91306	1961 - present with discontinuities	Atm. pressure, GNSS	link to DATA Shom

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Table A8: Stations operated by ISPRA - Italian Institute for Environmental Protection and Research (RMN - National tide gauge Network; RMLV - Venice Lagoon and North Adriatic Tide Gauge Network).

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
54	Ancona	Radar	43.624	13.513	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
55	Anzio	Radar	41.447	12.635	2011 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
56	Bari	Radar	41.137	16.861	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
57	Cagliari	Radar	39.115	9.405	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
58	Canale dell'Ancora	Float	45.524	12.486	2006 - present		RMLV
59	Caorle	Float	45.592	12.862	2000 - present		RMLV
60	Carloforte	Radar	39.148	8.309	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
61	Catania	Radar	37.44	15.147	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
62	Cavallino Centro	Float	45.485	12.551	1992 - present		RMLV
63	Cavallino Darsena	Float	45.486	12.586	2000 - present		RMLV
64	Chioggia Diga Sud	Float	45.229	12.313	2000 - present	Wind	RMLV
65	Chioggia Vigo	Float	45.224	12.28	1989 - present		RMLV
66	Civitavecchia	Radar	42.244	11.554	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
67	Crotone	Radar	39.023	17.22	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
68	Faro Rocchetta	Float	45.339	12.311	1989 - present		RMLV
69	Gaeta	Radar	41.21	13.59	2010 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
70	Genova	Radar	44.41	8.925	1998 - present	Atm. pressure, air temperature, wind,	RMN

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						relative humidity, sea temperature	
71	Ginostra	Pressure	38.785	15.191	2010 - present	Atm. pressure, air temperature, relative humidity, sea temperature	RMN
72	Grado	Float	45.683	13.383	1991 - present		RMLV
73	Grassabò	Float	45.521	12.53	1989 - present	Wind, Rain	RMLV
74	Imperia	Radar	43.878	8.019	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
75	La Spezia	Radar	44.097	9.858	2007 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
76	Lampedusa	Radar	35.5	12.604	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
77	Livorno	Radar	43.546	10.299	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
78	Malamocco Diga Nord	Float	45.334	12.342	2000 - present	Wind	RMLV
79	Marghera	Float	45.474	12.239	1989 - present		RMLV
80	Marina di Campo	Radar	42.743	10.238	2011 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
81	Meda Bocca Lido	Float	45.427	12.415	1989 - present		RMLV
82	Messina	Radar	38.196	15.564	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
83	Murano	Float	45.458	12.345	1995 - present		RMLV
84	Napoli	Pressure	40.841	14.269	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
85	Ortona	Radar	42.356	14.415	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
86	Otranto	Radar	40.147	18.497	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
87	Palermo	Radar	38.121	13.371	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
88	Palinuro	Radar	40.031	15.275	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN

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89	Petta de Bò	Float	45.266	12.242	1992 - present	Wind, Rain	RMLV
90	Ponza	Radar	40.867	12.95	2011 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
91	Porto Caleri	Float	45.095	12.325	2000 - present		RMLV
92	Porto Empedocle	Radar	37.286	13.527	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
93	Porto Torres	Radar	40.842	8.404	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
94	Punta della Salute	Float	45.431	12.337	1924 - present		RMLV
95	Ravenna	Radar	44.492	12.283	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
96	Reggio Calabria	Radar	38.121	15.649	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
97	Salerno	Radar	40.672	14.768	1999 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
98	San Benedetto del Tronto	Radar	42.955	13.89	2010 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
99	San Giorgio in Alga	Float	45.425	12.295	2000 - present	Wind, Rain	RMLV
100	San Nicolò	Radar	45.431	12.383	1989 - present		RMLV
101	Sant'Erasmo	Float	45.454	12.386	1996 - present		RMLV
102	Sciacca	Radar	37.505	13.076	2012 - present	Atm. pressure, air temperature, relative humidity, sea temperature	RMN
103	Strombolicchio	Pressure	38.817	15.252	2013 - present	Atm. pressure, air temperature, wind, relative humidity	RMN
104	Taranto	Radar	40.475	17.225	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
105	Tessera	Float	45.491	12.329	1994 - present		RMLV
106	Tremiti	Radar	42.119	15.502	2013 - present	Atm. pressure, air temperature, relative humidity, sea temperature	RMN
107	Treporti	Radar	45.474	12.446	1989 - present		RMLV

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108	Trieste	Radar	45.649	13.758	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
109	Valle Averto	Float	45.348	12.17	1989 - present		RMLV
110	Venezia	Radar	45.333	12.517	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN
111	Vieste	Radar	41.887	16.179	1998 - present	Atm. pressure, air temperature, wind, relative humidity, sea temperature	RMN

Table A9: IDSL Stations operated in Italy by JRC with ISPRA.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
112	**Imperia**	Acoustic (IDSL)	43.87834	8.0188	Nov 2014 - present	Air temperature	
113	**Marina di Teulada**	Acoustic (IDSL)	38.927535	8.719503	May 2018 - present	Air temperature	

Table A10: Station operated by CNR-ISMAR at Trieste, Italy, and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
114	**Trieste Molo Sartorio**	Float	45.64725	13.75947	1875-1889 1901 - present	Atm. pressure, GNSS	Variable sampling frequency

Table 11: Slovenian tide gauge station operated by the Slovenian Environment Agency, and sea level data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
115	**Koper**	One radar, one float type sensor	45.5481	13.7245	1961 - present	Atm. pressure, air temperature, wind, relative humidity, solar irradiance, sea temperature	1961-2005: hourly 2005 - present: 10 min

Table A12: Croatian tide gauge stations operated by the Andrija Mohorovičić Geophysical Institute (AMGI), Hrvatske Vode (HV), Hydrographic Institute of the Republic of Croatia (HHI), Institute of Oceanography and Fisheries (IOF), and Ruđer Bošković Institute (RBI), and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
116	**Bakar**	Float Radar	45.3050	14.5400	Dec 1929 - present	Atm. pressure	AMGI; Larger gap during World War II and a few shorter gaps
117	**Bistrina**	Radar	42.8719	17.7007	Sep 2019 - present	Atm. pressure, wind	HV
118	**Dubrovnik**	Float	42.6579	18.0608	1955 - present		HHI
119	**Golubinka**	Float	44.2565	15.2654	1995 - present		HV; Station code: 7356; No data for 2000
120	**Mali Lošinj**	Radar	44.53385	14.46358	Jun 2021 - present	Atm. pressure, wind	IOF
121	**Ploče**	Float	43.0481	17.4241	2003 - present		HHI
122	**Prosinka**	Float	43.8440	15.6226	1986 - present		HV; Station code: 7270; Data gaps till 1994
123	**Raslina**	Radar	43.8073	15.8560	Sep 2019 - present	Atm. pressure, wind	HV
124	**Rijeka**	Radar	45.3241	14.4381	Jun 2021 - present		HHI; Plan to upgrade with meteorological station
125	**Rovinj**	Float	45.0837	13.6291	1955 - present		HHI

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126	**Šibenik**	Radar	43.7243	15.8587	2020 - present	Waves, surface current, sea temperature	RBI; https://hv.geolux-radars.com/sites/sibenik-svante.html
127	**Sobra**	Radar	42.73952	17.62005	May 2017 - present		IOF
128	**Split Harbor**	Float	43.5067	16.4386	1955 - present	GNSS	HHI
129	**Split Marjan**	Float	43.50833	16.39167	Apr 1952 - present	Atm. pressure, wind	IOF
130	**Stari Grad**	Radar	43.18101	16.57590	Jun 2017 - present	Atm. pressure, wind	IOF
131	**Ustava ušće nizvodno**	Float	43.0073	17.4698	1990 - present		HV; Station code: 7499; At mala Neretva River mouth; Hourly data from 1990
	Vela Luka	Radar	42.96027	16.70334	May 2017- Jun 2021	Atm. pressure, wind	IOF; Station is temporarily removed from the location; it will re-installed as soon as possible
132	**Vis**	Radar	43.0619	16.1841	Jun 2021 - present	Atm. pressure, wind	IOF
133	**Zadar**	Float	44.1192	15.2304	1990 - present		HHI; Larger gap during the war in Croatia

Table A13: National tide gauge network of Montenegro operated by the Institute for Hydrometeorology and Seismology.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
134	**Bar**	Float	42.0878	19.0755	1965 - present		Larger GAP during 90s
135	**Kotor**	Float	42.4239	18.7698	2010 - present		

Table A14: Tide gauge stations in Albania, operated by the Institute of Geoscience.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
136	**Durrës**	Tide pole	41.302542	19.452575	1950 - present		
137	**Sarandë**	Tide pole	39.870519	20.003483	1950 - present		
138	**Shëngjin**	Tide pole	41.807364	19.586865	1950 - present		
139	**Vlorë**	Tide pole	40.450147	19.481039	1950 - present		

Table A15: Stations operated by the Physical Oceanography Research Group of the University of Malta.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
140	**Delimara**	Acoustic (IDSL)	35.831567	14.554759	Mar 2021 - present	Air temperature	Data sent in real-time to the JRC TAD Server
141	**Marsaxlokk**	Radar (RADAC)	35.818083	14.549409	Mar 2021 - present	Air temperature	Data sent in real-time to the JRC TAD Server
	Mellieha	ENDECO-type differential pressure gauge	35.974444	14.351389	May 1993 - Dec 2000	Sea temperature	
142	**Portomaso**	Pressure	35.921103	14.494667	Feb 2001 - present	Atm. pressure, sea temperature	Currently offline and undergoing maintenance

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143	**Senglea**	Acoustic (IDSL)	35.889343	14.514121	Jun 2021 - present	Air temperature	Data sent in real-time to the JRC TAD Server
144	**Paradise Bay**	Acoustic (IDSL)	35.985778	14.331861	2019 - present	Air temperature	Data sent in real-time to the JRC TAD Server

Table A16: Network of stations operated by the Hellenic Navy - Hydrographic Service, Greece.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
145	Alexandroupolis	Float type / digital recording	40.84414	25.87827	1981 - present		Upgraded to digital/GSM connection
146	Chios	Float type / analogue and digital recording	38.37151	26.14119	1978 - present	Sea surface temperature	Upgraded to digital/GSM connection
147	Corfu	Float type / analogue recording	39.6282	19.90532	2004 - present		
148	Iraklio	Float type / analogue and digital recording	35.34848	25.15269	1951 - present	Sea surface temperature	
149	Kalamata	Float type / analogue and digital recording	37.02368	22.11584	1936 - present	Sea surface temperature, air temperature, barometric pressure, wind, humidity	Upgraded to digital/GPRS connection
150	Katakolo	Float type / analogue and digital recording	37.64482	21.31968	1981 - present	Sea surface temperature	Upgraded to digital/GPRS connection
151	Kavala	Float type / analogue recording	40.93464	24.41213	1933 - present		
152	Lefkada	Float type / analogue and digital recording	38.83454	20.71211	1979 - present		Upgraded to digital/GSM connection
153	Leros	Float type / analogue recording	37.12967	26.84799	1981 - present		
154	North Chalkida	Float type / digital recording	38.47229	23.59263	1977 - present	Sea surface temperature	
155	Patras	Float type / analogue and digital recording	38.25937	21.73654	1975-2009 (old location), 2011 - present (new location)	Sea surface temperature	Upgraded to digital and relocated/GSM connection
156	Piraeus	Float type / analogue and	37.93738	23.62671	1933 - present	Sea surface temperature	Upgraded to digital/GPRS

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		digital recording					connection
157	Posidonia	Float type / analogue recording	37.95116	22.9601	1975 - present		
158	Preveza	Float type / analogue recording	38.95908	20.75663	1981 - present		
159	Rhodos	Float type / digital and analogue recording	36.44172	28.23644	1981-2009 (old location), 2010 - present (new location)		Upgraded to digital and relocated/GSM connection
160	Salamina	Float type / digital recording	37.97961	23.53664	1956-2004 (old location), 2009 - present (new location)	Air temperature, barometric pressure, wind, humidity, GNSS	Upgraded and relocated
161	Samos	Float type / digital recording	37.75512	26.97644	2005 - present		Upgraded to digital/GSM connection
162	Siros	Float type / analogue and digital recording	37.43997	24.94581	1979 - present		Upgraded to digital/GPRS connection
163	Skopelos	Float type / analogue recording	39.12364	23.71281	1999 - present		
164	Souda	Float type / digital recording	35.48745	24.08248	1973 - present	Sea surface temperature, air temperature, barometric pressure, wind, humidity	
165	South Chalkida	Float type / digital recording	38.46089	23.58946	1977 - present	Sea surface temperature	
166	Thessaloniki	Float type / analogue recording	40.63254	22.93493	1933 - present		

Table A17. Network of stations operated by NOA in collaboration with JRC.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
167	Aigio	Radar	38.25714	22.07685	Oct 2013 – present		
168	Corinth	Acoustic (IDSL)	37.94539	22.93525	Dec 2015 – present	Air temperature	
169	Greece (Lesvos Is.)	Acoustic (IDSL)	38.97188	26.37055	Nov 2019 – present	Air temperature	
170	Hrakleio	Radar	35.3484	25.15254	Oct 2013 – present		

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171	Ierapetra	Radar	35.00374	25.73852	Oct 2013 – present		
172	Itea	Radar	38.43035	22.42277	Oct 2013 – present		
173	Kalathos	Radar	36.1139	28.0696	Oct 2013 – present		
174	Kapsali	Radar	36.1418	23.0037	Jan 2012 – present		
175	Kasos	Radar	35.4186	26.92184	Oct 2013 - present		
176	Kerkyra	Radar	39.79	19.91	Oct 2013 - present		
177	Koroni	Radar	36.7974	21.9602	Jan 2012 – present		
178	Kos	Acoustic (IDSL)	36.898362	27.287792	Jul 2018 – present	Air temperature	
179	Kyparissia	Radar	37.2596	21.66436	Oct 2013 – present		
180	Paleochora	Radar	35.224	23.6786	Jan 2012 – present		
181	Panormos	Acoustic (IDSL)	38.359995	22.253942	Nov 2017 – present	Air temperature	
182	Plimiri	Radar	35.9273	27.8575	Oct 2013 – present		
183	Samothraki	Radar	40.4746	25.46797	Oct 2013 – present		
184	Thessaloniki	Radar	40.63	22.91	Oct 2013 - present		
185	Zakynthos	Radar	37.78142	20.9052	Oct 2013 - present		

Table A18: Stations operated by the Bulgarian Coastal Sea Level Service (IO-BAS).

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
186	**Balchick port**	Radar	43.404162	28.165389	2009 - present	Atm. pressure, air temperature relative humidity, wind, visibility, sea temperature, salinity	
187	**Burgas port**	Radar	42.483606	27.481925	1910 - present		
188	**Pmorie port**	Radar	42.551405	27.639129	2009 - present	Sea temperature, salinity	
189	**Shkorpilovtci**	Radar	42.958128	27.900861	2010 - present		
190	**Varna port**	Radar	43.192504	27.911421	1919 - present		

Table A19: Stations operated by NIMRD "Grigore Antipa", Romania, and data availability.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
191	**Constanta**	Float and	44.168842	28.658165	1993 - present		The pressure sensor will be

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		pressure	44.160805	28.657206		replaced by a radar sensor
192	**Mangalia**	Pressure	43.806973	28.582088	Dec 2017 - present	The pressure sensor will be replaced by a radar sensor
193	**Sulina**	Pressure	45.162296	29.726634	May 2020 - present	

Table A20: Russian and Soviet tide gauge stations operated by the All-Russian Research Institute of Hydrometeorological Information - World Data Center and data availability.

ID	**Station**	**Technology**	**Latitude**	**Longitude**	**Data Period**	**Ancillary meas.**	**Comments**
	Batumi	Float	41.7	41.6	1977–1991	Sea temperature, salinity, wind waves	
	Belgorod-Dnestrovskiy	Float	46.2	30.4	1977–1995	Sea temperature, salinity, wind waves	
	Bolshoe	Float	45.2	29.7	1977–1984	Sea temperature, salinity, wind waves	
	Feodosia	Float	45.01666	35.23333	1977 - present	Sea temperature, salinity, wind waves	
	Gelendzhik	Float	44.6	38.1	1977–1992	Sea temperature, salinity, wind waves	
	Heroyskoe	Float	46.5	31.9	1985–1995	Sea temperature, salinity, wind waves	
	Illichivsk	Float	46.3	30.7	1977–1995	Sea temperature, salinity, wind waves	
	Kasperovka	Float	46.6	32.3	1977–1995	Sea temperature, salinity, wind waves	
	Kherson	Float	46.6	32.6	1977–1995	Sea temperature, salinity, wind waves	
	Kulevi	Float	42.3	41.7	1977–1979	Sea temperature, salinity, wind waves	
	Nikolaev	Float	47.0	32.0	1977–1995	Sea temperature, salinity, wind waves	
	Ochakov	Float	46.6	31.6	1977–1995	Sea temperature, salinity, wind waves	
	Odessa	Float	46.5	30.8	1977–1995	Sea temperature, salinity, wind waves	
	Paromnaja Pereprava	Float	46.3	30.6	1980–1995	Sea temperature, salinity, wind waves	
	Poti	Float	42.1	41.6	1977–1991	Sea temperature, salinity, wind waves	

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	Poti (Rioni)	Float	42.2	41.7	1977–1979	Sea temperature, salinity, wind waves	
	Prorva	Float	45.5	29.7	1977–1984	Sea temperature, salinity, wind waves	
	Sevastopol	Float	44.61	33.529	1977 - present	Sea temperature, salinity, wind waves	
	Sochi	Float	43.56510	39.74222	1977 - present	Sea temperature, salinity, wind waves	
	Stanislav	Float	46.6	32.2	1989–1991	Sea temperature, salinity, wind waves	
194	**Tuapse**	Float	44.1	39.06666	1977 - present	Sea temperature, salinity, wind waves, GNSS	
	Vilkovo	Float	45.4	29.6	1977–1984	Sea temperature, salinity, wind waves	
	Yalta	Float	44.48	34.16	1977 - present	Sea temperature, salinity, wind waves	

Table A21: Turkish Sea Level Monitoring System (TUDES) tide gauge stations operated by the General Directorate of Mapping and data availability.

ID	**Station**	**Technology**	**Latitude**	**Longitude**	**Data Period**	**Ancillary Meas.**	**Comments**
195	**Amasra**	Radar	41.74399	32.39033	Jun 2001 - present	Atm. pressure, GNSS	Relocated
196	**Antalya**	Radar	36.83042	30.60868	Dec 1998 - present	Atm. pressure, GNSS	
197	**Bodrum**	Radar	37.03218	27.42346	Dec 1998 - present	Atm. pressure	
198	**Bozyazı**	Radar	36.09619	32.94012	Aug 2008 - present	Atm. pressure	
199	**Erdek**	Radar	40.38988	27.84518	Apr 1999 - present	Atm. pressure, GNSS	
200	**Erdemli**	Radar	36.56372	34.25539	May 2003 - present	Atm. pressure, GNSS	
201	**Gazimağusa**	Radar	35.12343	33.95015	Oct 2008 - present	Atm. pressure	
202	**Girne**	Radar	35.34080	33.33406	Oct 2008 - present	Atm. pressure, GNSS	
203	**Gökçeada**	Radar	40.23171	25.89349	Jan 2008 - present	Atm. pressure, GNSS	
204	**İğneada**	Radar	41.88890	28.02352	Jun 2002 - present	Atm. pressure, GNSS	

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205	**İskenderun**	Radar	36.41559	35.88520	Dec 2004 - present	Atm. pressure, GNSS	Relocated
206	**İstanbul**	Radar	41.15984	29.07413	Feb 2011 - present	Atm. pressure, GNSS	
207	**Marmara Ereğlisi**	Radar	40.96897	27.96215	Jul 2004 - present	Atm. pressure, GNSS	
208	**Marmaris**	Radar	36.84867	28.28240	Jan 2008 - present	Atm. pressure, GNSS	Relocated
209	**Menteş**	Radar	38.42961	26.72215	Apr 1999 - present	Atm. pressure, GNSS	
210	**Şile**	Radar	41.17637	29.60538	Jan 2008 - present	Atm. pressure, GNSS	Relocated
211	**Sinop**	Radar	42.02307	35.14946	Jun 2005 - present	Atm. pressure, GNSS	
212	**Taşucu**	Radar	36.28146	33.83623	Aug 2008 - present	Atm. pressure, GNSS	
213	**Trabzon**	Radar	41.00198	39.74455	Jul 2002 - present	Atm. pressure, GNSS	
214	**Yalova**	Radar	40.66197	29.27761	Jan 2008 - present	Atm. pressure, GNSS	Relocated

1340 **Table A22**: JRC IDSL stations in Türkiye operated by KOERI.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
215	**Bozcaada**	Acoustic	39.835741	26.075859	Nov 2016 - present	Air temperature	
216	**Samsun**	Acoustic	41.2949	36.33746	Sep 2018 - present	Air temperature	
217	**Bodrum**	Acoustic	37.031054	27.42477	May 2018 - present	Air temperature	

Table A23: Cyprus sea level/tide gauge stations deployed/operated by DFMR, OC-UCY, DLS, CUT, JRC, ORION

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
218	**Larnaca ORION**	Pressure (ADCP)	34.8836	33.65	Oct 2019 - present	Waves, sea temperature, currents, susp. particles	Operational
	Larnaca OC-UCY	Pressure	34.916	33.641	2010-2012	Atm. pressure, sea temperature	Interrupted
219	**Larnaca DLS**	Radar	34.928	33.645	2018 - present	Atm. pressure, sea temperature, wind, humidity	Operational
220	**Limassol CUT**	Radar	34.669	33.042	2018 - present	Atm. pressure, sea temperature, wind, humidity	Operational

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	Paphos DFMR	Pressure	34.755	32.4087	Sept 2001 - Jan 2013	Atm. pressure, sea temperature	Interrupted
221	**Paphos DLS**	Radar	34.7549	32.4075	2018 - present	Atm. pressure, sea temperature, wind,humidity	Operational
	Paralimni OC-UCY	Pressure	35.0383	34.0364	2010-2012	Atm. pressure, sea temperature	Interrupted
222	**Paralimni DLS**	Radar	35.0384	34.0364	Ma 2018 - present	Atm. pressure, sea temperature, wind, humidity	Operational
223	**Pomos DLS**	Radar	35.1754	32.5556	2018 - present	Atm. pressure, sea temperature, wind, humidity	Operational
224	**Zygi JRC**	Radar	34.7263	33.34	2017 - Jun 2021	Atm.pressure, sea temperature, wind	Operational
	Zygi DLS	Pressure	34.7268	33.34	2010-2012	Atm. pressure, sea temperature	Interrupted

Table A24: Tide gauge stations in Israel, operated by the National Institute of Oceanography, Israel Oceanographic and Limnological Research.

ID	**Station**	**Technology**	**Latitude**	**Longitude**	**Data Period**	**Ancillary meas.**	**Comments**
	Ashdod IDSL	Radar	31.79633	34.62635	Feb 2018 - 2020		
225	**Ashkelon**	Pressure	31.634879	34.494176	Jul 2012 - present	Atm. pressure, sea temperature, wave height and period, current, temperature, salinity, fluorescence, turbidity, oxygen	Near real time and delayed mode: https://isramar.ocean.org.il/isramar_data/TimeSeries.aspx (under Ashkelon RDI)
226	**Hadera**	Pressure	32.470533	34.863051	Apr 1992 - present	Atm. pressure, sea temperature, wave height and period, current, temperature, salinity, fluorescence, turbidity, oxygen	Gloss St. #80 near real time and delayed mode: https://isramar.ocean.org.il/isramar_data/TimeSeries.aspx(under Hadera RDI)
	Hadera IDSL	Radar	32.47313	34.88207	Feb 2018 - 2020		
227	**Haifa IDSL**	Radar	32.822454	35.007042	Feb 2018 - present		

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Table A25: Stations operated by Egypt.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
	Abu Qir Bay	Float gauge	31.3250	30.0750	1990-2010		
228	**Alexandria Eastern Harbor**	Radar	31.2124	29.8849	2018 - present		IOC Station, near real time
	Alexandria Western Harbour	Float gauge	31.2001	29.8783	1979-2011		
	Burullus new harbour	Float gauge	31.6017	30.9672	2004-2008		
	Mersa Matrouh	Float gauge	31.3600	27.1833	2003-2006		
	Port Said	Float gauge	31.2567	32.3050	2002-2010		
	Sidi Abdel_Raman	Float gauge	30.9330	28.8360	2003-2010		

Table A26: Stations operated by Algeria (National Institute of Cartography & Remote Sensing).

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
229	**Algiers**	Analog and acoustic	36.7681	3.0597	1985 - present 2011 - present	Atm. pressure, sea temperature, wind, air temperature, relative humidity, absolute gravity, GNSS	Upgraded to digital VPN/3G connection (Being deployed)
230	**Annaba**	Acoustic	36.9000	7.7666	2016 - present	Absolute gravity, GNSS (being deployed)	Upgraded to digital VPN/3G connection (Being deployed)
231	**Ghazaouet**	Acoustic	35.1000	-1.8700	2015 - present	Absolute gravity, GNSS (being deployed)	Upgraded to digital VPN/3G connection (Being deployed)
232	**Jijel**	Analog and acoustic	36.8209	5.7724	2004 - present 2012 - present	Absolute gravity, GNSS (being deployed)	Upgraded to digital VPN/3G connection (Being deployed)
233	**Oran**	Analog and acoustic	35.7275	-0.7012	2006 - present 2013 - present	Absolute gravity, GNSS (being deployed)	Upgraded to digital VPN/3G connection (Being deployed)
234	**Ténès**	Acoustic	36.5233	1.3294	2014 - present	Absolute gravity, GNSS (being deployed)	Upgraded to digital VPN/3G connection (Being deployed)

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Table A27: Additional IDSL based stations.

ID	Station	Technology	Latitude	Longitude	Data Period	Ancillary meas.	Comments
235	**Batroun (Lebanon)**	Acoustic (IDSL)	34.25848	35.65678	Jun 2016 - present	Air temperature	
236	**Saïdia Marina (Morocco)**	Acoustic (IDSL)	35.111863	-2.292942	Apr 2016 - present	Air temperature	

Supplementary material

Response to the survey from the different networks is provided as supplementary material (Excel file).

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References

Aarup, T., Wöppelmann, G., Woodworth, P.L., Hernandez, F., Vanhoorne, B., Schöne, T., and Thompson, P.R.: Comments on the article "Uncertainty and bias in electronic tide-gauge records: evidence from collocated sensors" by Stella Pytharouli, Spyros Chaikalis, Stathis C. Stiros in Measurement (Volume 125, September 2018), Measurement, 135, 613-616, https://doi.org/10.1016/j.measurement.2018.12.007, 2019.

Ablain, M., Legeais, J.F., Prandi, P., Marcos, M., Fenoglio-Marc, L., Dieng, H.B., Benveniste, J., and Cazenave, A.: Satellite altimetry-based sea level at global and regional scales, Surv. Geophys., 38, 7-31, https://doi.org/10.1007/s10712-016-9389-8, 2017.

Adebisi, N., Balogun, A.L., Min, T.H., and Tella, A: Advances in estimating Sea Level Rise: A review of tide gauge, satellite altimetry and spatial data science approaches, Ocean Coast. Manag., 208, 105632, https://doi.org/10.1016/j.ocecoaman.2021.105632, 2021.

Alasset, P.J., Hébert, H., Maouche, S., Calbini, V., and Meghraoui, M.: The tsunami induced by the 2003 Zemmouri earthquake (MW=6.9, Algeria): modelling and results, Geophys. J. Int., 166, 213–226, https://doi.org/10.1111/j.1365-246X.2006.02912.x, 2006.

Álvarez-Fanjul, E., Pérez-Gómez, B., and Rodríguez, I.: Nivmar: a storm surge forecasting system for Spanish waters, Sci. Mar., 65, 145–154, https://doi.org/10.3989/scimar.2001.65s1145, 2001.

Álvarez-Gómez, J.A., Aniel-Quiroga, L., González, M., and Otero, L.: Tsunami hazard at the Western Mediterranean Spanish coast from seismic sources, Nat. Hazards Earth Syst. Sci., 11, 227-240. https://doi.org/10.5194/nhess-11-227-2011, 2011.

Amato, A.: Some reflections on tsunami Early Warning Systems and their impact, with a look at the NEAMTWS, Boll. Geof. Teor. Appl., 61, 403-420, https://doi.org/10.4430/bgta0329, 2020.

Amores, A., Marcos, M., Carrió, D. S., and Gómez-Pujol, L.: Coastal impacts of Storm Gloria (January 2020) over the northwestern Mediterranean. Nat. Hazards Earth Syst. Sci., 20, 1955–1968, https://doi.org/10.5194/nhess-20-1955-2020, 2020.

Andersen, O.B., and Cheng, Y.: Long term changes of altimeter range and geophysical corrections at altimetry calibration sites, Adv. Space Res., 51, 1468–1477, https://doi.org/10.1016/j.asr.2012.11.027, 2013.

Androulidakis, Y.S., Kombiadou, K.D., Makris, C.V., Baltikas, V.N., and Krestenitis,Y.N.: Storm surges in the Mediterranean Sea: variability and trends under future climatic conditions, Dyn. Atm. Oceans, 71, 56-82, https://doi.org/10.1016/j.dynatmoce.2015.06.001, 2015.

Avsar, N.B., Jin, S.G., Kutoglu, S.H., and Gurbuz, G.: Vertical land motion along the Black Sea coast from satellite altimetry, tide gauges and GPS. Adv. Space Res., 60, 2871-2881, https://doi.org/10.1016/j.asr.2017.08.012, 2017.

Bajo, M, Međugorac, I, Umgiesser, G., and Orlić, M.: Storm surge and seiche modelling in the Adriatic Sea and the impact of data assimilation, Q. J. Roy. Meteorol. Soc., 145, 2070–2084, https://doi.org/10.1002/qj.3544, 2019.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Ocean Science Discussions

Bajo, M., and Umgiesser, G.: Storm surge forecast through a combination of dynamic and neural network models, Ocean Model., 33, 1–9, https://doi.org/10.1016/j.ocemod.2009.12.007, 2010.

Banks, A., Drakopoulos, P., and Zodiatis, G.: A comparison of tide gauge and satellite altimetry derived sea-level for two eastern Mediterranean islands. Geophys. Res. Abstracts, 5, European Geophysical Society - American Geophysical Union – European Union of Geophysicists Joint Assembly, Nice, France, 06–11 April, 2003.

Beltrami, G. M., Di Risio, M., and De Girolamo, P.: Algorithms for automatic, real-time tsunami detection in sea level measurements, in: The Tsunami Threat - Research and Technology, edited by: Morner, N.-A., InTech Open, 549-574, https://doi.org/10.5772/13908, 2011.

Belušić, D., Grisogono, B., and Klaić, Z. B.: Atmospheric origin of the devastating coupled air–sea event in the east Adriatic, J. Geophys. Res., 112, D17111, https://doi.org/10.1029/2006JD008204, 2007.

Bernier, N. B., and Thompson, K. R.: Deterministic and ensemble storm surge prediction for Atlantic Canada with lead times of hours to ten days, Ocean Model., 86, 114–127, https://doi.org/10.1016/j.ocemod.2014.12.002, 2015.

Bertotti, L., Bidlot, J.-R., Buizza, R., Cavaleri, L., and Janousek, M.: Deterministic and ensemble-based prediction of Adriatic Sea sirocco storms leading to “acqua alta” in Venice, Q. J. Roy. Meteor. Soc., 137, 1446–1466, https://doi.org/10.1002/qj.861, 2011.

Bevacqua, E., Maraun, D., Vousdoukas, M.I., Voukouvalas, E., Vrac, M., Mentaschi, L., and Widmann, M.: Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change, Sci. Adv., 5, eaaw5531, https://doi.org/10.1126/sciadv.aaw5531, 2019.

Bitharis, S., Ampatzidis, D., Pikridas, C., Fotiou, A., Rossikoppoulos, D., and Schuh, H.: The role of GNSS vertical velocities to correct estimates of sea level rise from tide gauge measurements in Greece, Mar. Geodesy, 40, 297-314, https://doi.org/10.1080/01490419.2017.1322646, 2017.

Bonaduce, A., Pinardi, N., Oddo, P., Spada, G., and Larnicol, G.: Sea-level variability in the Mediterranean Sea from altimetry and tide gauges, Clim. Dyn., 47, 2851–2866, https://doi.org/10.1007/s00382-016-3001-2, 2016.

Bonaldo, D., Antonioli, F., Archetti, R., Bezzi, A., Correggiari, A., Davolio, S., De Falco, G., Fantini, M., Fontolan, G., Furlani, S., Gaeta, M.G., Leoni, G., Lo Presti, V., Mastronuzzi, G., Pillon, S., Ricchi, A., Stocchi, P., Samaras, A.G., Scicchitano, G., and Carniel, S.: Integrating multidisciplinary instruments for assessing coastal vulnerability to erosion and sea level rise: lessons and challenges from the Adriatic Sea, Italy, J. Coast. Conserv., 23, 19–37, https://doi.org/10.1007/s11852-018-0633-x, 2019.

Bonnefond, P., Exertier, P., Laurain, O.,Ménard, Y., Orsoni, A., Jan, G., and Jeansou, E.: Absolute calibration of Jason-1 and TOPEX/Poseidon altimeters in Corsica. Mar. Geodesy, 26, 261-284, https://doi.org/10.1080/714044521, 2003.

Bonnefond, P., Exertier, P., Laurain, O., Guinle, T., and Féménias, P.: Corsica: A 20-yr multi-mission absolute altimeter calibration site, Adv. Space Res., 68, 1171-1186, https://doi.org/10.1016/j.asr.2019.09.049, 2021.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Ocean Science Discussions
Open Access

Bresson, É., Arbogast, P., Aouf, L., Paradis, D., Kortcheva, A., Bogatchev, A., Galabov, V., Dimitrova, M., Morvan, G., Ohl, P., Tsenova, B., and Rabier, F.: On the improvement of wave and storm surge hindcasts by downscaled atmospheric forcing: application to historical storms, Nat. Hazards Earth Syst. Sci., 18, 997–1012, https://doi.org/10.5194/nhess-18-997-2018, 2018.

Calafat, F.M, Avgoustoglou, E., Jordà, G., Flocas, H., Zodiatis, G., Tsimplis, M.N., and Kouroutzoglou, J.: The ability of a barotropic model to simulate sea level extremes of meteorological origin in the Mediterranean Sea, including those caused by explosive cyclones, J. Geophys. Res. Oceans, 119, 7840-7853, https://doi.org/10.1002/2014JC010360, 2014.

Cancet, M., Bijac, S., Chimot, J., Bonnefond, P., Jeansou, E., Laurain, O., Lyard, F., Bronner, E., and Féménias, P.: Regional in situ validation of satellite altimeters: calibration and cross-calibration results at the Corsican sites, Adv. Space Res., 51, 1400-1417, https://doi.org/10.1016/j.asr.2012.06.017, 2013.

Cavaleri, L., Bertotti, L., Buizza, R., Buzzi, A., Masato, V., Umgiesser, G., and Zampieri, M.: Predictability of extreme meteo-oceanographic events in the Adriatic Sea, Q. J. Roy. Meteorol. Soc., 136, 400-413, https://doi.org/10.1002/qj.567, 2010.

Cavaleri, L., Bajo, M., Barbariol, F., Bastianini, M., Benetazzo, A., Bertotti, L., Chiggiato, J., Ferrarin, C., Umgiesser, G, and Trincardi, F..: The 2019 flooding of Venice and its implications for future predictions, Oceanography, 33, 42–49, https://doi.org/10.5670/oceanog.2020.105, 2020.

Cid, A., Menéndez, M., Castanedo, S., Abascal, A.J., Méndez, F.J., and Medina, R.: Long-term changes in the frequency, intensity and duration of extreme storm surge events in southern Europe, Clim Dyn, 46, 1503–1516, https://doi.org/10.1007/s00382-015-2659-1, 2016.

Clementi, E., Pistoia, J., Escudier, R., Delrosso, D., Drudi, M., Grandi, A., *et al.*: Mediterranean Sea analysis and forecast (CMEMS MED-Currents, EAS5 system) [Data set]. London: Copernicus Monitoring Environment Marine Service (CMEMS), 2019.

Chris, D., Nikolaidis, M., Mettas, C., Hadjimitsis, D.G., Kokosis, G., and Kleanthous, C.: Establishing an integrated permanent sea-level monitoring infrastructure towards the implementation of maritime spatial planning in Cyprus, J. Mar. Sci. Eng., 8, 861, https://doi.org/10.3390/jmse8110861, 2020.

Denamiel, C., Šepić, J., Ivanković, D., and Vilibić, I.: The Adriatic Sea and coast modelling suite: evaluation of the meteotsunami forecast component, Ocean Model., 135, 71–93, https://doi.org/10.1016/j.ocemod.2019.02.003, 2019a.

Denamiel, C., Šepić, J., Huan, X., Bolzer, C., and Vilibić, I.: Stochastic surrogate model for meteotsunami early warning system in the eastern Adriatic Sea, J. Geophys. Res. Oceans, 124, 8485-8499, https://doi.org/10.1029/2019JC015574, 2019b.

Denamiel, C., Huan, X., and Vilibić, I.: Conceptual design of extreme sea-level early warning systems based on uncertainty quantification and engineering optimization methods, Front. Mar. Sci., 8, 650279, https://doi.org/10.3389/fmars.2021.650279, 2021.

Dieng, H.B., Cazenave, A., Gouzenes, Y., and Sowd, B.A.: Trends and inter-annual variability of altimetry-based coastal sea level in the Mediterranean Sea: Comparison with tide gauges and models. Adv. Space Res., 68, 3279-3290, https://doi.org/10.1016/j.asr.2021.06.022, 2021.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Dogan, G. G., Annunziato, A., Papadopoulos, G. A., Guler, H. G., Yalciner, A. C., Cakir, T. E., Sozdinler, C. O., Ulutas, E., Arikawa, T., Suzen, M. L., Guler, I., Probst, P., Kânoğlu, U., and Synolakis, C.: The 20th July 2017 Bodrum–Kos Tsunami field survey, Pure Appl. Geophys., 176, 2925–2949, https://doi.org/10.1007/s00024-019-02151-1, 2019.

Dogan, G. G., Yalciner, A. C., Yuksel, Y., Ulutaş, E., Polat, O., Güler, I., Şahin, C., Tarih, A., and Kânoğlu, U.: Correction to: The 30 October 2020 Aegean Sea Tsunami: Post-event field survey along Turkish coast, Pure Appl. Geophys., 178, 2393, https://doi.org/10.1007/s00024-021-02753-8, 2021.

Drago, A.: Sea level measurements in Malta, in IOC Workshop Report no.176 "MedGLOSS Workshop and Coordination Meeting for the Pilot Monitoring Network System of Systematic Sea Level Measurements in the Mediterranean and Black Seas", IOLR, Haifa, Israel 15-17May2000, Annex IVb, pp. 8-11, 2000.

Drago, A.: Sea level variability and the 'Milghuba' seiche oscillations in the northern coast of Malta, Central Mediterranean, Phys. Chem. Earth, 34, 948-970, https://doi.org/10.1016/j.pce.2009.10.0022009, 2009.

El-Fishawi, N. M.: Coastal erosion in relation to sea level changes, subsidence and river discharge, Nile Delta coast, Acta Mineral Petrogr., 30, 161–171, 1989.

El-Geziry, T. M., and Said, M. A.: Spatial variations of sea level along the Egyptian Mediterranean coast. Athens J. Medit. Studies, 6, 141-154, 2020.

Escudier, R., Clementi, E., Omar, M., Cipollone, A., Pistoia, J., Aydogdu, A., Drudi, M., Grandi, A., Lyubartsev, V., Lecci, R., Cretí, S., Masina, S., Coppini, G., and Pinardi, N.: Mediterranean Sea Physical Reanalysis (CMEMS MED-Currents) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1, 2020.

Esselborn, S., Rudenko, S., and Schöne, T.: Orbit-related sea level errors for TOPEX altimetry at seasonal to decadal timescales, Ocean Sci., 14, 205–223, https://doi.org/10.5194/os-14-205-2018, 2018.

Ferrarin, C., Valentini, A., Vodopivec, M., Klaric, D., Massaro, G., Bajo, M., De Pascalis, F., Fadini, A., Ghezzo, M., Menegon, S., Bressan, L., Unguendoli, S., Fettich, A., Jerman, J., Ličer, M., Fustar, L., Papa, A., and Carraro, E.: Integrated sea storm management strategy: the 29 October 2018 event in the Adriatic Sea, Nat. Hazards Earth Syst. Sci., 20, 73–93, https://doi.org/10.5194/nhess-20-73-2020, 2020.

Ferrarin, C., Bajo, M., Benetazzo, A., Cavaleri, L., Chiggiato, J., Davison, S., Davolio, S., Lionello, P., Orlić, M., and Umgiesser, G.: Local and large-scale controls of the exceptional Venice floods of November 2019, Prog. Oceanogr., 197, 102628, https://doi.org/10.1016/j.pocean.2021.102628, 2021.

Flanders Marine Institute (VLIZ): Intergovernmental Oceanographic Commission (IOC) Sea level station monitoring facility. Accessed at http://www.ioc-sealevelmonitoring.org on 14 December 2021 at VLIZ, https://doi.org/10.14284/482, 2021.

Fokaefs, A., and Papadopoulos, G: Tsunami hazard in the eastern Mediterranean: strong earthquakes in Cyprus and the Levantine Sea, Nat. Hazards, 40, 503–526, https://doi.org/10.1007/s11069-006-9011-3, 2007.

Frappart, F., Roussel, N., Biancale, R., Benjamin, J.J.M., Mercier, F., Perosanz, F., Pasquin, J.G., Davila, J.M., Gomez, B.P., Gomez, C.G., Bravo, R.L., Gomez, A.T., Ripoll, J.G., Pajares, M.H., Lino, M.S., Bonnefond, P., and Casanova, I.V.: The 2013

Ibiza calibration campaign of Jason-2 and SARAL altimeters, Mar. Geodesy, 38, 219-232. https://doi.org/10.1080/01490419.2015.1008711, 2015.

Fu, L.L., and Haines, B.J.: The challenges in long-term altimetry calibration for addressing the problem of global sea level change. Adv. Space Res., 51, 1284-1300, https://doi.org/10.1016/j.asr.2012.06.005, 2013.

García-Valdecasas, J., Pérez Gómez, B., Molina, R., Rodríguez, A., Rodríguez, D., Pérez, S., Campos, A., Rodríguez Rubio, P., Gracia, S., Ripollés, L., Terrés Nicoli, J.M., de los Santos, F.J., and Álvarez Fanjul, E.: Operational tool for characterizing high-frequency sea level oscillations, Nat. Hazards, 106, 1149–1167, https://doi.org/10.1007/s11069-020-04316-x, 2021.

Gomis, D., Tsimplis, M., Marcos, M., Fenoglio-Marc, L., Pérez Gómez, B., Raicich, F., Vilibic, I., Wöppelmann, G., and Monserrat, S.: Mediterranean sea-level variability and trends, in: Climate of the Mediterranean region: From the Past to the Future, edited by Lionello, P., Elsevier Insights, 257-299, https://doi.org/10.1016/B978-0-12-416042-2.00004-5, 2012.

Gouzenes, Y., Léger, F., Cazenave, A., Birol, F., Bonnefond, P., Passaro, M., Nino, F., Almar, R., Laurain, O., Schwatke, C., Legeais, J.-F., and Benveniste, J.: Coastal sea level rise at Senetosa (Corsica) during the Jason altimetry missions, Ocean Sci., 16, 1165–1182, https://doi.org/10.5194/os-16-1165-2020, 2020.

Grases, A., Gracia, V., García-León, M., Lin-Ye, J., and Sierra, J.P.: Coastal flooding and erosion under a changing climate: Implications at a low-lying coast (Ebro Delta), Water, 12, 346, https://doi.org/10.3390/w12020346, 2020.

Gusiakov, V.K.: Meteotsunamis at global scale: problem of event identification, parametrization and cataloguing, Nat. Hazards, 106, 1105-1123, https://doi.org/10.1007/s11069-020-04230-2, 2021.

Hamden, M. H., and Md Din, A. H.: A review of advancement of hydrographic surveying towards ellipsoidal referenced surveying technique, IOP Conf. Ser.: Earth Environ. Sci., 169, 012019, https://doi.org/10.1088/1755-1315/169/1/012019, 2018.

Hereher, M.E.: Coastal vulnerability assessment for Egypt's Mediterranean coast, Geomatics, Natural Hazards and Risk, 6, 342-355, https://doi.org/10.1080/19475705.2013.845115, 2015.

Holgate, S., Foden, P., Pugh, J., and Woodworth, P.: Real time sea-level data transmission from tide gauges for tsunami monitoring and long-term sea level rise observations, J. Oper. Oceanogr, 1, 3–8, https://doi.org/10.1080/1755876X.2008.11081883, 2008.

Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M.E., Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S., and Pugh, J.: New data systems and products at the Permanent Service for Mean Sea Level, J. Coastal Res., 29, 493-504, https://doi.org/10.2112/JCOASTRES-D-12-00175.1, 2013.

Jabnoun, R., and Harzallah, A.: An estimate of the sea level trend along the Tunisia coast, Bulletin de l'Institut National des Sciences et Technologies de la Mer de Salammbô, 47, 165-171, http://hdl.handle.net/1834/41476, 2020.

Jansà, A., Monserrat, S., and Gomis, D.: The rissaga of 15 June 2006 in Ciutadella (Menorca), a meteorological tsunami, Adv. Geosci., 12, 1–4, https://doi.org/10.5194/adgeo-12-1-2007, 2007.

Jansà, A., and Ramis, C.: The Balearic rissaga: from pioneering research to present-day knowledge, Nat Hazards, 106, 1269-1297, https://doi.org/10.1007/s11069-020-04221-3, 2021.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Le Traon, P. Y.: From satellite altimetry to Argo and operational oceanography: three revolutions in oceanography, Ocean Sci., 9, 901–915, https://doi.org/10.5194/os-9-901-2013, 2013.

Le Traon, P.Y., Reppucci, A., Alvarez Fanjul, E., Aouf, L., Behrens, A., Belmonte, M., Bentamy, A., Bertino, L., Brando, V.E., Kreiner, M.B., Benkiran, M., Carval, T., Ciliberti, S.A., Claustre, H., Clementi, E., Coppini, G., Cossarini, G., De Alfonso Alonso Muñoyerro, M., Delamarche, A., Dibarboure, G., Dinessen, F., Drevillon, M., Drillet, Y., Faugere, Y., Fernández, V., Fleming, A., Garcia-Hermosa, M.I., Sotillo, M.G., Garric, G., Gasparin, F., Giordan, C., Gehlen, M., Gregoire, M.L., Guinehut, S., Hamon, M., Harris, C., Hernandez, F., Hinkler, J.B., Hoyer, J., Karvonen, J., Kay, S., King, R., Lavergne, T., Lemieux-Dudon, B., Lima, L., Mao, C., Martin, M.J., Masina, S., Melet, A., Buongiorno Nardelli, B., Nolan, G., Pascual, A., Pistoia, J., Palazov, A., Piolle, J.F., Pujol, M.I., Pequignet, A.C., Peneva, E., Pérez Gómez, B., Petit de la Villeon, L., Pinardi, N., Pisano, A., Pouliquen, S., Reid, R., Remy, E., Santoleri, R., Siddorn, J., She, J., Staneva, J., Stoffelen, A., Tonani, M., Vandenbulcke, L., von Schuckmann, K., Volpe, G., Wettre, C., and Zacharioudaki, A.: From observation to information and users: The Copernicus Marine Service perspective, Front. Mar. Sci., 6, 234, https://doi.org/10.3389/fmars.2019.00234, 2019.

Lemon, D.D., Chave, R.A.J., Clarke, M.R., Curran, T.A., Hinds, A., Thorn, A., Thomson, A., and Badger, C.J.: Real-time monitoring of currents and water level at second narrows to improve port efficiency in Vancouver harbour, Oceans 2003. Celebrating the Past ... Teaming Toward the Future (IEEE Cat. No.03CH37492), pp. 231-237, https://doi.org/10.1109/OCEANS.2003.178559, 2003.

Letetrel, C., Marcos, M., Miguez, B.M., and Wöppelmann, G.: Sea level extremes in Marseille (NW Mediterranean) during 1885-2008, Cont. Shelf Res., 30, 1267-1274, https://doi.org/10.1016/j.csr.2010.04.003, 2010.

Ličer, M., Mourre, B., Troupin, C., Krietemeyer, A., Jansá, A., and Tintoré, J.: Numerical study of Balearic meteotsunami generation and propagation under synthetic gravity wave forcing. Ocean Model, 111, 38–45, https://doi.org/10.1016/j.ocemod.2017.02.001, 2017.

Lionello, P., Conte, D., Marzo, L., and Scarascia, L.: The contrasting effect of increasing mean sea level and decreasing storminess on the maximum water level during storms along the coast of the Mediterranean Sea in the mid 21st century, Global Planet. Change, 151, 80-91, https://doi.org/10.1016/j.gloplacha.2016.06.012, 2017.

Lionello, P., Barriopedro, D., Ferrarin, C., Nicholls, R. J., Orlić, M., Raicich, F., Reale, M., Umgiesser, G., Vousdoukas, M., and Zanchettin, D.: Extreme floods of Venice: characteristics, dynamics, past and future evolution (review article), Nat. Hazards Earth Syst. Sci., 21, 2705–2731, https://doi.org/10.5194/nhess-21-2705-2021, 2021.

Loizides, G., Papazachariou, D., and Zodiatis, G.: Data analysis of the CYCOFOS Paphos Sea Level Station-MedGloss Network 2001-2010. internal report, Oceanography Center, University of Cyprus, 23 August, 2010.

Makris, C., Androulidakis, Y., Karambas, T., Papadimitriou, A., Metallinos, A., Kontos, Y., Baltikas, V., Chondros, M., Krestenitis, Y., Tsoukala, V., and Memos, C.: Integrated modelling of sea-state forecasts for safe navigation and operational management in ports: Application in the Mediterranean Sea, Applied Mathematical Modelling, 89, 1206-1234, https://doi.org/10.1016/j.apm.2020.08.015, 2021.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Maramai, A., Brizuela, B., and Graziani, L.: The Euro-Mediterranean Tsunami Catalogue, Ann. Geophys., 57, https://doi.org/10.4401/ag-6437, 2014.

Maramai, A., Graziani L., and Brizuela B.: Euro-Mediterranean Tsunami Catalogue (EMTC), version 2.0. Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/tsunami/emtc.2.0, 2019.

Marcos, M., Jordà, G., Gomis, D., and Pérez Gómez, B.: Changes in storm surges in southern Europe from a regional model under climate change scenarios, Global Planet. Change, 77, 116-128, https://doi.org/10.1016/j.gloplacha.2011.04.002, 2011.

Marcos, M., Monserrat, S., Medina, R., Orfila, A., and Olabarrieta, M.: External forcing of meteorological tsunamis at the coast of the Balearic Islands, Phys. Chem. Earth, 34, 838–947, https://doi.org/10.1016/j.pce.2009.10.001, 2009a.

Marcos, M., Tsimplis, M.N., and Shaw, A.G.P.: Sea level extremes in southern Europe, J. Geophys. Res., 114, C01007, https://doi.org/10.1029/2008JC004912, 2009b.

Marcos, M., Calafat, F.M., Berihuete, A., and Dangendorf, S.: Long-term variations in global sea level extremes, J. Geophys. Res. Oceans, 120, 8115-8134, https://doi.org/10.1002/2015JC011173, 2015.

Marcos, M., and Woodworth, P.L.: Spatiotemporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico, J. Geophys. Res. Oceans, 122, 7031-7048, https://doi.org/10.1002/2017JC013065, 2017.

Marcos, M., Puyol, B., Amores, A., Pérez Gómez, B., Fraile, M.A., and Talke, A.: Historical tide gauge sea-level observations in Alicante and Santander (Spain) since the 19th century. Geosci. Data J., 8, 144-153, https://doi.org/10.1002/gdj3.112, 2021.

Marrobbio Project Report: Creation of a prediction station for Marrobbio events to be installed in the fishing port of Mazara del Vallo, funded by SFOP 2004 – Mis. 4.17b (Cod. 1999.IT.16.1.PO.011/4.17b/8.3.7/0082), 2007.

Martinez-Benjamin, J. J., Martinez-Garcia, M., Lopez, S. G., Andres, A. N., Pozuelo, F. B., Infantes, M. E., Lopez-Marco, J., Davila, J. M., Pasquin, J. G., Silva, C. G., Bonnefond, P., Laurain, O., Isanta, A. M. B., Castellon, M. A. O., Lopez, J. T., Pérez Gomez, B., Álvarez Fanjul, E., Velasco, G. R., Gomis, D., Marcos, M., Menard, Y., Jan, G., Jeansou, E., Lyard, F., and Roblou, L.: Ibiza absolute calibration experiment: Survey and preliminary results, Mar. Geodesy, 27, 657-681. https://doi.org/10.1080/01490410490883342, 2004.

Masina, M., and Lamberti, A.: A nonstationary analysis for the Northern Adriatic extreme sea levels, J. Geophys. Res. Oceans, 118, 3999–4016, https://doi.org/10.1002/jgrc.20313, 2013.

Mel, R., and Lionello, P.: Verification of an ensemble prediction system for storm surge forecast in the Adriatic Sea. Ocean Dyn., 64, 1803–1814, https://doi.org/10.1007/s10236-014-0782-x, 2014.

Međugorac, I., Pasarić, M., and Güttler, I.: Will the wind associated with the Adriatic storm surges change in future climate?, Theor. Appl. Climatol., 143, 1–18, https://doi.org/10.1007/s00704-020-03379-x, 2021.

Medvedev, I. P., Vilibić, I., and Rabinovich, A. B.: Tidal resonance in the Adriatic Sea: Observational evidence, J. Geophys. Res. Oceans, 125, e2020JC016168, https://doi.org/10.1029/2020JC016168, 2020.

Monserrat, S., Ramis, C., and Thorpe, A.J.: Large-amplitude pressure oscillations in the Western Mediterranean, Geophys. Res. Lett., 18, 183–186, https://doi.org/10.1029/91GL00234, 1991.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Monserrat, S., Rabinovich, A. B., and Casas, B.: On the reconstruction of the transfer function for atmospherically generated seiches, Geophys. Res. Lett., 25, 2197–2200, https://doi.org/10.1029/98GL01506, 1998.

Monserrat, S.., Vilibić, I., and Rabinovich, A.B.: Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band, Nat. Hazards Earth Syst. Sci., 6, 1035–1051, https://doi.org/10.5194/nhess-6-1035-2006, 2006.

Mourre, B., Santana, A., Buils, A., Gautreau, L., Ličer, M., Jansà, A., Casas, B., Amengual, B., and Tintoré, J.: On the potential of ensemble forecasting for the prediction of meteotsunamis in the Balearic Islands: sensitivity to atmospheric model parameterizations, Nat. Hazards Earth Syst. Sci., 106**,** 1315–1336, https://doi.org/10.1007/s11069-020-03908-x, 2021.

Novellino, A., D'Angelo, P., Benedetti, G., Manzella, G., Gorringe, P., Schaap, D., Pouliquen, S., and Rickards, L.: European Marine Observation Data Network - EMODnet Physics. OCEANS 2015 - Genova, 1-6, https://doi.org/10.1109/OCEANS-Genova.2015.7271548, 2015.

Oaie, G., Seghedi, A., and Radulescu, V.: Natural marine hazards in the Black Sea and the system of their monitoring and real-time warning, Geo-Eco-Marina, 22, https://doi.org/10.5281/zenodo.889593, 2016.

Okal, E.A., Synolakis, C.E., Uslu, B., Kalligeris, N., and Voukouvalas, E.: The 1956 earthquake and tsunami in Amorgos, Greece, Geophys. J. Int., 178, 1533–1554, https://doi.org/10.1111/j.1365-246X.2009.04237.x, 2009.

Okal, E. A.: On the possibility of seismic recording of meteotsunamis, Nat. Hazards, 106, 1125-1147, https://doi.org/10.1007/s11069-020-04146-x, 2021.

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R. M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., and Sebesvari, Z.: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., in press, 2019.

Orfila, A., Balle, S., and Simarro, G.: Topographic enhancement of long waves generated by an idealized moving pressure system. Science, 75, 595–693, https://doi.org/10.3989/scimar.2011.75n3595, 2011.

Orlić, M.: The first attempt at cataloguing tsunami-like waves of meteorological origin in Croatian coastal waters, Acta Adriat., 56, 83–96, 2015.

Orlić, M., and Pasarić, M: Recent data on high-frequency sea-level variability in Vela Luka and Stari Grad Bays. International Symposium on Meteotsunamis, 30th Anniversary of the Great Flood of Vela Luka (21 June 1978), Book of Abstracts, Vela Luka, Croatia, p. 36, 2008.

Orlić, M., and Šepić, J.: Meteorological tsunamis in the Adriatic Sea – catalogue of meteorological tsunamis in Croatian coastal waters. Online, http://jadran.izor.hr/~sepic/meteotsunami_catalogue/, accessed: 21 September 2021, 2019.

Orlić, M., Belušić, D., Janeković, I., and Pasarić, M.: Fresh evidence relating the great Adriatic surge of 21 June 1978 to mesoscale atmospheric forcing, J. Geophys. Res., 115, C06011. https://doi.org/10.1029/2009JC005777, 2010.

Pascual, J., and Salat, J.: Monthly sea level anomaly based on 2h data from L'Estartit meteorological station II (NW Mediterranean) since 1990. PANGAEA, https://doi.org/10.1594/PANGAEA.902604, 2019

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Papadopoulos, G., and Papageorgiou, A.: Large earthquakes and tsunamis in the Mediterranean region and its connected seas. In: Extreme Natural Hazards, Disaster Risks and Societal Implications, Cambridge University Press, Cambridge, 252-266, https://doi.org/10.1017/CBO9781139523905.025, 2012.

Papadopoulos, G., Gràcia, E., Urgeles, R., Sallares, V., De Martini, P.M., Pantosti, D., González, M., Yalciner, A., Mascle, J., Sakellariou, D., Salamon, A., Tinti, S., Fokaefs, A., Camerlenghi, A., Novikova, T., and Papageorgiou, A.: Historic and pre-historic tsunamis in the Mediterranean and its connected seas: a review on documentation, geological signatures, generation mechanisms and coastal impacts. Mar. Geol., 354, 81-109, https://doi.org/10.1016/j.margeo.2014.04.014, 2014.

Papazachariou, D.: Estimation of the lowest astronomical tide and the lowest low tide at tide-gauge stations in Cyprus. Internal Report, Oceanography Center, University of Cyprus, 10 October, 2014.

Papazachariou, D., Zodiatis, G., Nikolaidis, A., Stylianou, S., and Arabelos, D.: Satellite altimetry and tide gauge data for monitoring sea level changes in the Eastern Mediterranean, Geophys. Res. Abstracts, 16, EGU2014-9582, 2014.

Pasarić, M., Pasarić, Z., and Orlić, M.: Response of the Adriatic Sea level to the air pressure and wind forcing at low frequencies (0.01–0.1 cpd), J. Geophys. Res., 105, 11423-11439, https://doi.org/10.1029/2000JC900023, 2000.

Pashova, L.: Assessment of the sea level change on different timescales from Varna and Burgas tide gauge data, C. R. Acad. Bulg. Sci., 65, 193-202, 2012.

Peng, D., Feng, L., Larson, K.M., and Hill, E.M.: Measuring coastal absolute sea-level changes using GNSS interferometric reflectometry, Remote Sens., 13, 4319, https:// doi.org/10.3390/rs13214319, 2021.

Pérez Gómez, B., Brouwer, R., Beckers, J., Paradis, D., Balseiro, C.,Lyons, K., Cure, M., Sotillo, M. G., Hackett, B., Verlaan, M., and Fanjul, E. A.: ENSURF: multi-model sea level forecast: implementation and validation results for the IBIROOS and Western Mediterranean regions. Ocean Sci., 8, 211–226, https://doi.org/10.5194/os-8-211-2012, 2012.

Pérez Gómez, B., Alvarez Fanjul, E., Pérez Rubio, S., de Alfonso, M., and Vela, J.: Use of tide gauge data in operational oceanography and sea level hazard warning systems, J. Oper. Oceanogr., 6, 1–18, https://doi.org/10.1080/1755876X.2013.11020147, 2013.

Pérez Gómez, B. Payo, A., López, D., Woodworth, P.L., and Alvarez-Fanjul, E.. Overlapping sea level time series measured using different technologies: an example from the REDMAR Spanish network. Nat. Hazards Earth Syst. Sci., 14, 589-610, https://doi.org/10.5194/nhess-14-589-2014, 2014.

Pérez Gómez, B., García-León M., García-Valdecasas, J., Clementi, E., Mösso Aranda, C., Pérez-Rubio, S., Masina, S., Coppini, G., Molina-Sánchez, R., Muñoz-Cubillo, A., García Fletcher, A., Sánchez González, J.F., Sánchez-Arcilla, A., and Álvarez-Fanjul, E.: Understanding sea level processes during Western Mediterranean storm Gloria, Front. Mar. Sci., 8, 647437, https://doi.org/10.3389/fmars.2021.647437, 2021.

Pérez González, I., Pérez Gómez, B., Sotillo, M. G., and Álvarez Fanjul, E.: Towards a new sea level forecast system in Puertos del Estado. Extended proceedings, in Proceedings of the 8th EuroGOOS Conference, Bergen, 2017.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Ocean Science Discussions

Pasarić, M., and Orlić, M.: Long-term meteorological preconditioning of the North Adriatic coastal floods, Cont. Shelf Res., 21, 263-278, https://doi.org/10.1016/S0278-4343(00)00078-9, 2001.

Proudman, J.: The effects on the sea of changes in atmospheric pressure, Geophys. Suppl. Mon. Not. R. Astron. Soc., 2, 197–209, https://doi.org/10.1111/j.1365-246X.1929.tb05408.x, 1929.

Pugh, D., and Woodworth, P.: Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes. Cambridge University Press, Cambridge, https://doi.org/10.1017/CBO9781139235778, 2014.

Rabinovich, A.B.: Twenty-seven years of progress in the science of meteorological tsunamis following the 1992 Daytona Beach event, Pure Appl. Geophys., 177, 1193–1230, https://doi.org/10.1007/s00024-019-02349-3, 2020.

Rabinovich, A. B., and Monserrat, S.: Meteorological tsunamis near the Balearic and Kuril Islands: descriptive and statistical analysis. Nat Hazards, 13, 55–90, https://doi.org/10.1007/BF00156506, 1996.

Raicich F: Recent evolution of sea-level extremes at Trieste (Northern Adriatic), Cont. Shelf Res., 23, 225–235, htpps://doi.org/10.1016/S0278-4343(02)00224-8, 2003.

Raicich, F.: Sea level observations at Trieste Molo Sartorio (Italy), SEANOE, https://doi.org/10.17882/62758, 2019.

Renault, L., Vizoso, G., Jansà, A., Wilkin, J., and Tintoré, J.: Toward the predictability of meteotsunamis in the Balearic Sea using regional nested atmosphere and ocean models, Geophys. Res. Lett., 38, L10601. https://doi.org/10.1029/2011GL047361, 2011.

Reimann, L., Vafeidis, A.T., Brown, S., *et al.*: Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise, Nat. Comm., 9, 4161, https://doi.org/10.1038/s41467-018-06645-9, 2018.

Romero, R., Vich, M., and Ramis, C.: A pragmatic approach for the numerical prediction of meteotsunamis in Ciutadella harbour (Balearic Islands), Ocean Model., 142, 101441, https://doi.org/10.1016/j.ocemod.2019.101441, 2019.

Rosen, D.S., and Aarup, T..: IOC/CIESM MedGLOSS Pilot Network Workshop and Coordination Meeting, Haifa, 15-17 May 2000, IOC/UNESCO Report 176, 120pp, 2002.

Samaras, A.G., Karambas, Th.V., and Archetti, R.: Simulation of tsunami generation, propagation and coastal inundation in the Eastern Mediterranean. Ocean Sci., 11, 643-655, https://doi.org/10.5194/os-11-643-2015, 2015.

Schindelé, F., Loevenbruck, A., and Hèbert, H.: Strategy to design the sea-level monitoring networks for small tsunamigenic oceanic basins: the Western Mediterranean case, Nat. Hazards Earth Syst. Sci., 8, 1019–1027, https://doi.org/10.5194/nhess-8-1019-2008, 2008.

Schindelé, F., Gailler, A., Hébert, H., *et al.*: Implementation and challenges of the tsunami warning system in the Western Mediterranean, Pure Appl. Geophys., 172, 821–833, https://doi.org/10.1007/s00024-014-0950-4, 2015.

Salat, J., Pascual, J., Flexas, M.M., Chin, T.M., and Vázquez-Cuervo, J.: Forty-five years of oceanographic and meteorological observations at a coastal station in the NW Mediterranean: a ground truth for satellite observations. Ocean Dyn., 69, 1067–1084, https://doi.org/10.1007/s10236-019-01285-z, 2019.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Ocean Science Discussions

Šepić, J., Vilibić, I., Jordà, G., and Marcos, M.: Mediterranean Sea level forced by atmospheric pressure and wind: Variability of the present climate and future projections for several period bands, Global Planet. Change, 86–87, 20-30, https://doi.org/10.1016/j.gloplacha.2012.01.008, 2012.

Šepić, J., and Vilibić, I.: The development and implementation of a real-time meteotsunami warning network for the Adriatic Sea, Nat. Hazards Earth Syst. Sci., 11, 83–91, https://doi.org/10.5194/nhess-11-83-2011, 2011.

Šepić, J., Vilibić, I., and Monserrat, S.: Teleconnections between the Adriatic and the Balearic meteotsunamis, Phys. Chem. Earth, 34, 928–937, https://doi.org/10.1016/j.pce.2009.08.007, 2009.

Šepić, J., Međugorac, I., Janeković, I., Dunić, N., and Vilibić, I.: Multi-meteotsunami event in the Adriatic Sea generated by atmospheric disturbances of 25–26 June 2014, Pure Appl. Geophys., 173, 4117–4138, https://doi.org/10.1007/s00024-016-1249-4, 2016a.

Šepić, J., Vilibić, I., and Monserrat, S.: Quantifying the probability of meteotsunami occurrence from synoptic atmospheric patterns, Geophys. Res. Lett., 43,10377-10384, https://doi.org/10.1002/2016GL070754, 2016b.

Šepić, J., Vilibić, I., Rabinovich, A. B., and Tinti, S.: Meteotsunami (“Marrobbio”) of 25-26 June 2014 on the southwestern coast of Sicily, Italy, Pure Appl. Geophys., 175, 1573-1593, https://doi.org/10.1007/s00024-018-1827-8, 2018.

Spada, G., and Galassi, G.: New estimates of secular sea level rise from tide gauge data and GIA modelling, Geophys. J. Int., 191, 1067-1094, https://doi.org/10.1111/j.1365-246X.2012.05663.x, 2012.

Sotillo, M. G., Cailleau, S., Lorente, P., Levier, B., Aznar, R., Reffray, G., *et al.*: The MyOcean IBI ocean forecast and reanalysis systems: operational products and roadmap to the future Copernicus Service, J. Operat. Oceanogr., 8, 1–18. https://doi.org/10.1080/1755876X.2015.1014663, 2015.

Sørensen, M.B., Spada, M., Babeyko, A., Wiemer, S., and Grünthal, G.: Probabilistic tsunami hazard in the Mediterranean Sea. J. Geophys. Res., 117, B01305, https://doi.org/10.1029/2010JB008169, 2012.

Taibi, H., and Haddad, M.: Estimating trends of the Mediterranean Sea level changes from tide gauge and satellite altimetry data (1993–2015), J. Oceanol. Limnol., 37, 1176–1185, https://doi.org/10.1007/s00343-019-8164-3, 2019.

Tinti, S., and Maramai, A.: Catalogue of tsunamis generated in Italy and in Cote d´Azur, France: a step towards a unified catalogue of tsunamis in Europe. Ann. Geophys., 39, 1253-1299, 1996.

Tinti, S., Maramai, A., and Grazziani, L.: A new version of the European tsunami catalogue: Updating and revision, Nat. Hazards Earth Syst. Sci., 1, 255–262, https://doi.org/10.5194/nhess-1-255-2001, 2001.

Tinti, S., Manucci, A., Pagnoni, G., Armigliato, A., and Zaniboni, F.: The 30th December 2002 tsunami in Stromboli: sequence of the events reconstructed from the eyewitness accounts, Nat. Hazards Earth Syst. Sci., 5, 763-775, https://doi.org/10.5194/nhess-5-763-2005, 2005.

Tintoré, J. , Vizoso, G., Casas, B., Heslop, E., Pascual, A., Orfila, A., Ruiz, S., Martínez-Ledesma, M., Torner, M., Cusí, S., Diedrich, A., Balaguer, P., Gómez-Pujol, Ll., Álvarez-Ellacuria, A., Gómara, S., Sebastian, K., Lora, S., Renault, L., Juzà, M., Álvarez, D., March, D., Garau, B., Cañellas, T., Roque, D., Lizarán, I., Pitarch, S., Carrasco, M.A., Lana, A., Mason, E., Escudier, R., Conti, D.S., Barceló, B., Alemany, F., Reglero, P., Massuti, E., Vélez-Belchí, P., Ruiz, J., Oguz, T., Gómez, M., Álvarez Fanjul, E., Ansorena, L. and Manriquez, M.: The Balearic Islands Coastal Ocean Observing and Forecasting System Responding to Science, Technology and Society Needs, Mar. Technol. Soc. J., 47 (1), 101-117, doi: 10.4031/MTSJ.47.1.10, 2013.

Tintoré J., Pinardi N., Álvarez-Fanjul E., Aguiar E., Álvarez-Berastegui D., Bajo M., Balbin R., Bozzano R., Nardelli B.B., Cardin V., Casas B., Charcos-Llorens M., Chiggiato J., Clementi E., Coppini G., Coppola L., Cossarini G., Deidun A., Deudero S., D'Ortenzio F., Drago A., Drudi M., El Serafy G., Escudier R., Farcy P., Federico I., Fernández J.G., Ferrarin C., Fossi C., Frangoulis C., Galgani F., Gana S., García Lafuente J., Sotillo M.G., Garreau P., Gertman I., Gómez-Pujol L., Grandi A., Hayes D., Hernández-Lasheras J., Herut B., Heslop E., Hilmi K., Juza M., Kallos G., Korres G., Lecci R., Lazzari P., Lorente P., Liubartseva S., Louanchi F., Malacic V., Mannarini G., March D., Marullo S., Mauri E., Meszaros L., Mourre B., Mortier L., Muñoz-Mas C., Novellino A., Obaton D., Orfila A., Pascual A., Pensieri S., Pérez Gómez B., Pérez Rubio S., Perivoliotis L., Petihakis G., de la Villéon L.P., Pistoia J., Poulain P.M., Pouliquen S., Prieto L., Raimbault P., Reglero P., Reyes E., Rotllan P., Ruiz S., Ruiz J., Ruiz I., Ruiz-Orejón L.F., Salihoglu B., Salon S., Sammartino S., Sánchez Arcilla A., Sánchez-Román A., Sannino G., Santoleri R., Sardá R., Schroeder K., Simoncelli S., Sofianos S., Sylaios G., Tanhua T., Teruzzi A., Testor P., Tezcan D., Torner M., Trotta F., Umgiesser G., von Schuckmann K., Verri G., Vilibic I., Yucel M., Zavatarelli M. and Zodiatis G.: Challenges for Sustained Observing and Forecasting Systems in the Mediterranean Sea. Front. Mar. Sci. 6:568. doi: 10.3389/fmars.2019.00568, 2019.

Tsimplis, M.N.: Tidal oscillations in the Aegean and the Ionian Seas. Estuar. Coastal Shelf Sci., 39, 201-208, https://doi.org/10.1006/ecss.1994.1058, 1994.

Tsimplis, M.N., Proctor, R., and Flather, R.A.: A 2-dimensional tidal model for the Mediterranean Sea, J. Geophys. Res., 100, 16223-16239, https://doi.org/ 10.1029/95JC01671, 1995.

Tsimplis, M.N., and Spencer, N.E.: Collection and analysis of monthly mean sea level data in the Mediterranean and the Black Sea, J. Coastal Res., 13, 534-544, 1997.

Tsimplis, M.N., Álvarez-Fanjul, E., Gomis, D., Fenoglio-Marc, L., and Pérez Gómez, B.: Mediterranean sea level trends: atmospheric pressure and wind contribution, Geophys. Res. Lett., 32, L20602, https://doi.org/10.1029/2005GL023867, 2005.

Umgiesser, G., Bajo, M., Ferrarin, C., Cucco, A., Lionello, P., Zanchettin, D., Papa, A., Tosoni, A., Ferla, M., Coraci, E., Morucci, S., Crosato, F., Bonometto, A., Valentini, A., Orlić, M., Haigh, I., Nielsen, J.W., Bertin, X., Fortunato, A.B., Pérez Gómez, B., *et al.*: The prediction of floods in Venice: methods, models and uncertainty. Nat. Hazards Earth Syst. Sci., https://doi.org/10.5194/nhess-2020-361, 2021.

UNESCO/IOC: Quality Control of in situ sea level observations: a review and progress towards automated quality control, Vol. 1, UNESCO IOC Manuals and Guides No. 83 (IOC/2020/MG/83 Vol. 1), 2020.

UNESCO/IOC: Interim operational users guide for the tsunami early warning and mitigation system in the Northeastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS). Version 2.00. (http://ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=12077), 2012a.

UNESCO/IOC: Global Sea Level Observing System (GLOSS) Implementation Plan, 2012b.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Ocean Science Discussions

UNESCO IOC: North-East Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System, NEAMTWS, Implementation Plan (Third Session of the Intergovernmental Coordination Group for the North-East Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System, NEAMTWS), IOC Technical Series No. 73, 2007.

Vela, J., Pérez Gómez, B., González, M., Otero, L., Olabarrieta, M., Canals, M., and Casamor, J. L.: Tsunami resonance in Palma Bay and harbor, Majorca Island, as induced by the 2003 Western Mediterranean earthquake, J. Geol., 122, 165–182, https://doi.org/10.1086/675256, 2014.

Vignudelli, S., Birol, F., Benveniste, J., Fu, L.L., Picot, N., Raynal, M., and Roinard, H.: Satellite altimetry measurements of sea level in the coastal zone, Surv. Geophys., 40, 1319-1349, https://doi.org/10.1007/s10712-019-09569-1, 2019.

Vilibić, I., Orlić, M., Čupić, S., Domijan, N., Leder, N., Mihanović, H., Pasarić, M., Pasarić, Z., Srdelić, M., and Strinić, G.: A new approach to sea level observations in Croatia, Geofizika, 22, 21-57, 2005.

Vilibić, I., Monserrat, S., Rabinovich, A.B., and Mihanović, H.: Numerical modelling of the destructive meteotsunami of 15 June 2006 on the coast of the Balearic Islands, Pure Appl. Geophys., 165, 2169–2195, https://doi.org/10.1007/s00024-008-0426-5, 2008.

Vilibić, I., Šepić, J., Ranguelov, B., Strelec Mahović, N., and Tinti, S.: Possible atmospheric origin of the 7 May 2007 western Black Sea shelf tsunami event, J. Geophys. Res., 115, C07006, https://doi.org/10.1029/2009JC005904, 2010.

Vilibić, I., Šepić, J., Rabinovich, A. B., and Monserrat, S.: Modern approaches in meteotsunami research and early warning, Front. Mar. Sci., 3, 57, https://doi.org/10.3389/fmars.2016.00057, 2016.

Vilibić, I., Denamiel, C., Zemunik, P., and Monserrat, S.: The Mediterranean and the Black Sea meteotsunamis: an overview, Nat. Hazards, 106, 1223-1267, https://doi.org/10.1007/s11069-020-04306-z, 2021.

Wahl, T., and Chambers, D. P.: Evidence for multidecadal variability in US extreme sea level records, J. Geophys. Res. Oceans, 120, 1527–1544, https://doi.org/10.1002/2014JC010443, 2015.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.:: The FAIR Guiding Principles for scientific data management and stewardship, Sci. Data, 3, 160018. https://doi.org/10.1038/sdata.2016.18, 2016.

Woodworth, P.L., and Player, R.: The Permanent Service for Mean Sea Level: An update to the 21st century, J. Coastal Res., 19, 287-295, 2003.

Woodworth, P. L., Rickards, L. J., and Pérez Gómez, B.: A survey of European sea level infrastructure, Nat. Hazards Earth Syst. Sci., 9, 927–934, https://doi.org/10.5194/nhess-9-927-2009, 2009.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Woodworth, P. L., Hunter, J. R., Marcos Moreno, M., Caldwell, P. C., Menendez, M., and Haigh, I. D.: GESLA (Global Extreme Sea Level Analysis) high frequency sea level dataset – Version 2, British Oceanographic Data Centre – Natural Environment Research Council, UK, https://doi.org/10.5285/3b602f74-8374-1e90-e053-6c86abc08d39, 2016.

Woodworth, P. L., Hunter, J. R., Marcos, M., Caldwell, P., Menéndez, M., and Haigh, I.: Towards a global higher-frequency sea level dataset, Geosci. Data J., 3, 50–59, https://doi.org/10.1002/gdj3.42, 2017.

Woodworth, P. L., Wöppelmann, G., Marcos, M., Gravelle, M., and Bingley, R. M.: Why we must tie satellite positioning to tide gauge data, Eos, 98, https://doi.org/10.1029/2017EO064037, 2017.

Woodworth, P.L., Melet, A., Marcos, M., et al.: Forcing factors affecting sea level changes at the coast, Surv. Geophys., 40, 1351–1397, https://doi.org/10.1007/s10712-019-09531-1, 2019.

Wöppelmann, G., Marcos, M., Coulomb, A., Martín Míguez, B., Bonnetain, P., Boucher, C., Gravelle, M., Simon, B., and Tiphaneau, P.: Rescue of the historical sea level record of Marseille (France) from 1885 to 1988 and its extension back to 1849-1851, J. Geodesy, 88, 869-885, https://doi.org/10.1007/s00190-014-0728-6, 2014.

Yang, Y., Jin, T., Gao, X., Wen, H., Schöne, T., Xiao, M., and Huang, H.: Sea level fusion of satellite altimetry and tide gauge data by deep learning in the Mediterranean Sea, Remote Sens., 13, 908, https://doi.org/10.3390/rs13050908, 2021.

Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., Antonioli, F., Artale, V., Carminati, E., Ferrarin, C., Fofonova, V., Nicholls, R. J., Rubinetti, S., Rubino, A., Sannino, G., Spada, G., Thiéblemont, R., Tsimplis, M., Umgiesser, G., Vignudelli, S., Wöppelmann, G., and Zerbini, S.: Sea-level rise in Venice: historic and future trends (review article), Nat. Hazards Earth Syst. Sci., 21, 2643–2678, https://doi.org/10.5194/nhess-21-2643-2021, 2021.

Zemunik, P., Bonanno, A., Mazzola, S., Giacalone, G., Fontana, I., Genovese, S., Basilone, G., Candela, J., Šepić, J., Vilibić, I., and Aronica, S.: Observing meteotsunamis („Marrobbio") in the southwestern coast of Sicily, Nat Hazards, 106, 1337-1363, https://doi.org/10.1007/s11069-020-04303-2, 2021a.

Zemunik, P., Šepić, J., Pellikka, H., Ćatipović, L., and Vilibić, I.: MISELA: 1-minute sea-level analysis global dataset, Earth Syst. Sci. Data, 13, 4121–4132, https://doi.org/10.5194/essd-13-4121-2021, 2021b.

Zerbini S., Plag, H.-P., Baker, T., Becker, M., Billiris, H., Bürki, B., Kahle, H.-G., Marson, I., Pezzoli, L., Richter, B., Romagnoli, C., Sztobryn, M., Tomasi, P., Tsimplis, M., Veis, G., and Verrone, G.: Sea level: in the Mediterranean: a first step towards separating crustal movements and absolute sea-level variations, Global Planet. Change, 14, 1–48, https://doi.org/10.1016/0921-8181(96)00003-3, 1996.

Zerbini, S., Raicich, F., Prati, C.M., Bruni, S., Del Conte, S., Errico, M., and Santi, E.: Sea-level change in the Northern Mediterranean Sea from long-period tide gauge time series, Earth-Sci. Rev., 167, 72-87, https://doi.org/10.1016/j.earscirev.2017.02.009, 2017.

Zhuk, E., Zodiatis, G., and Sylaios, G.: The Web GIS monitoring and forecasting platforms in the Mediterranean and Black seas. seas, Proc. SPIE 11524, Eighth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2020), 359-365, 26 August 2020, https://doi.org/10.1117/12.2570969, 2020.

https://doi.org/10.5194/os-2021-125
Preprint. Discussion started: 20 January 2022

Žust, L., Fettich, A., Kristan, M., and Ličer, M.: HIDRA 1.0: deep-learning-based ensemble sea level forecasting in the northern Adriatic, Geosci. Model Dev., 14, 2057–2074, https://doi.org/10.5194/gmd-14-2057-2021, 2021.