RESEARCH ARTICLE

Analysis of the eastern Adriatic sea level extremes

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Aim: To examine the frequency, strength, and driving mechanisms of the eastern Adriatic sea level extremes.

Methods: In 2017, a tide-gauge station, and a meteorological station have been installed at Stari Grad (Hvar Island, eastern middle Adriatic Sea). Three years of sea level and atmospheric measurements were analysed. Ten strongest episodes of the following extreme types were extracted from sea level data: positive long-period (T >210 min) extremes; negative long-period (T >210 min) extremes; short-period (T < 210) extremes. Long-period extremes were defined as situations when sea level surpasses (is lower than) 99.7 (i.e., 2) percentile of residual long-period sea level height, and short-period extremes as situations when 2.5-h variance of short-period sea level oscillations is higher than 99.4 percentile of total variance of short-period series. Types of sea level extremes were subsequently associated to characteristic atmospheric situations.

Results: Positive long-period extremes commonly appeared during the presence of low-pressure atmospheric systems over the Adriatic – such system were accompanied with strong SE winds. Negative long-period extremes were associated with presence of high atmospheric pressure fields over the Adriatic Sea, either with strong NE winds, or calm weather. Appearance of short-period sea level extremes corresponded to either low atmospheric pressure fields and strong SE wind, or normal/high pressure fields and calm weather/no winds over the Adriatic. A strong seasonal signal was detected, with the positive long-period extremes occurring mostly during November to February, and the negative long-period extremes occurring during January to February. The short-period extremes appeared throughout the year, but strongest events appeared during May to July.

Conclusion: Results show that Stari Grad is a flood-prone location, both when it comes to positive long-period extremes and to short-period extremes. Furthermore, long-period and short-period extremes occasionally occur simultaneously in Stari Grad, pointing to a previously unknown added hazard level.

Keywords: Adriatic Sea; extremes; flood; meteotsunami; sea level, storm surge

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Introduction

One of the most threatening effects of climate change is the anticipated sea level rise which can generate significant damage to coastal regions [1]. Today, global sea level rise is mostly due to anthropogenically induced global warming resulting with the ice melting, as well as thermal expansion of seawater. The expected worldwide sea level rise by the year 2100 is 26-55 cm (RCP2.6 scenario), 32-63 cm (RCP4.5 scenario) or 45-82 cm (RCP8.5) [2]. Sea level rise is particularly dangerous at those locations at which it is likely to combine with occasional extreme sea levels, contributing to more frequent and stronger floods [3]. For example, Venice, an important Adriatic Sea port, tourist, and cultural centre, is often hit by a widely recognized phenomenon called aqua alta (Italian for "high water") - an extreme flood that lasts for hours [4]. Much like Venice, other parts of the Adriatic coast are also vulnerable to extreme sea levels [5].

The Adriatic Sea is a marginal Mediterranean Sea of a bay-like shape. It has a length of 800 km and a width of around 200 km (**Figure 1**). It is positioned between coastlines of Italy, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, and Albania [6]. The Adriatic Sea level variability is affected by numerous processes [7]: (1) sea level rise induced by climate change; (2) seasonal sea level changes and interannual variability; (3) response to planetary-scale atmospheric forcing; (4) response to synoptic atmospheric systems; (5) basin-wide seiches; (6) tides, and (7) high-frequency phenomena. Out of the mentioned processes, the ones occurring on time scales shorter than synoptic (~10 days) [5] have the strongest influence on sea level extremes. In this paper, we focus on analysis of the Adriatic Sea positive and negative long-period (T>210 min) sea level extremes, and short period sea level extremes (T < 210 min). The short period sea level extremes normally have comparable positive and negative amplitudes during any single event [5], and thus we do not separate them into a positive and a negative category.

The Adriatic positive long-period sea level extremes are mostly associated with superposition of tidal oscillations and strong storm surges [5]. The Adriatic tides can be well approximated by four semidiurnal (M2, S2, N2 and K2) and three diurnal (K1, O1, P1) harmonic constituents [8, 9]. Semidiurnal tides have an amphidromic point halfway between Šibenik and Ancona (**Figure 1**). They grow in amplitudes towards the north Adriatic and have secondary maxima along the Palagruža Sill. Diurnal tides rise in amplitudes from the southern to the northern parts of the Adriatic Sea. As a result of superposition of semidiurnal and diurnal tides, tidal range in the southern parts of the Adriatic Sea is approximately 30 cm and in the Gulf of Trieste it is approximately 120 cm [7, 8]. Storm surges are sea level rises occurring over a period of a few hours up to few days. In the Adriatic Sea, storm surges mostly occur when a low atmospheric pressure (cyclone) over the Gulf of Genoa is conjoined with strong sirocco winds (Croatian jugo) blowing along the Adriatic Sea [10]. These south-eastern winds can push water mass for hours or days towards the northern parts of the Adriatic Sea resulting in floods. Storm surges are strongest over the shallow northern Adriatic Sea [10, 11], but are known to reach hazardous heights over the middle Adriatic as well [5]. Future occurrence of storm surges will be governed by the changes of the cyclone activity over the Adriatic and by the future mean sea level rise. Even though the projections show a decrease in the frequency and intensity of cyclones over the Mediterranean, the trend in the magnitude of annual sea level maxima in the Adriatic is expected to be positive in the second half of the twenty-first century due to sea level rise [7].

Negative sea level extremes are less researched, as they present a lower hazard to coastal communities than positive extremes. Negative extremes mostly happen from January to March [5], during periods characterized by a prolonged presence of a high-pressure field (i.e., anticyclone) over the area, occasionally accompanied by a strong north-eastern bora wind which can push water mass from the eastern to the western Adriatic coast, lowering additionally sea level on the eastern coast of the Adriatic Sea [7].

High-frequency phenomena causing sea level extremes in the Adriatic Sea are local seiches, seismic and landslide tsunamis and meteorological tsunamis (meteotsunamis). Local seiches are driven by long ocean waves advancing toward bays. Studies on the local seiches for several Adriatic harbours have been conducted – it was shown, e.g., that Ploče Harbour has a fundamental period of 30 minutes, with several other significant modes (4.1 h, 2.6 h and 1.5 h), and Bakar Bay, e.g., has a wide energy peak between 19 and 27 minutes [7]. It can be noted herein that period of seiche is strongly dependant on shape, size, and depth of the bay. When long ocean waves are generated by atmospheric processes, and when they reach hazardous heights (crest-to-through height>100 cm) [12, 13], either at the open coast or within the bays, they are termed meteotsunamis. Meteotsunami is a type of tsunami – its spectral properties (periods and energy), heights, and manifestation classify it as a tsunami – generated by atmospheric processes [14]. The Adriatic Sea is a known meteotsunami hot spot, i.e., a location where meteotsunamis are particularly strong [13, 15, 16].

All the above-listed processes are relevant for Stari Grad Bay (Hvar Island, the eastern middle Adriatic; **Figure 1**), for which 1-min sea level and meteorological measurements have been available since July 2017. Stari Grad Bay has a complex bathymetry (**Figure 1**), and it experiences pronounced local seiches. Additionally, it is also a location where destructive meteotsunamis are known to happen [13, 16]. Lastly, being situated on the island in the central Adriatic, Stari Grad Bay can face sea level extremes due to storm surges as well.

Oceanographic and atmospheric data measured at Stari Grad were analysed to shed light on the eastern Adriatic Sea level extremes and their generative forces. Three types of extremes were studied: long-period (T>210 min) positive and long-period negative sea level extremes, and short-period (T < 210 min) sea level extremes. We determined frequency, strength, and dominant atmospheric forcing of each of the three types of sea level extremes.

The novelty of our research is:

1. Properties of various types of sea level extremes were assessed; and each type of extremes was associated to a characteristic atmospheric forcing.
2. Simultaneous appearance of long-period and short-period extremes was detected.

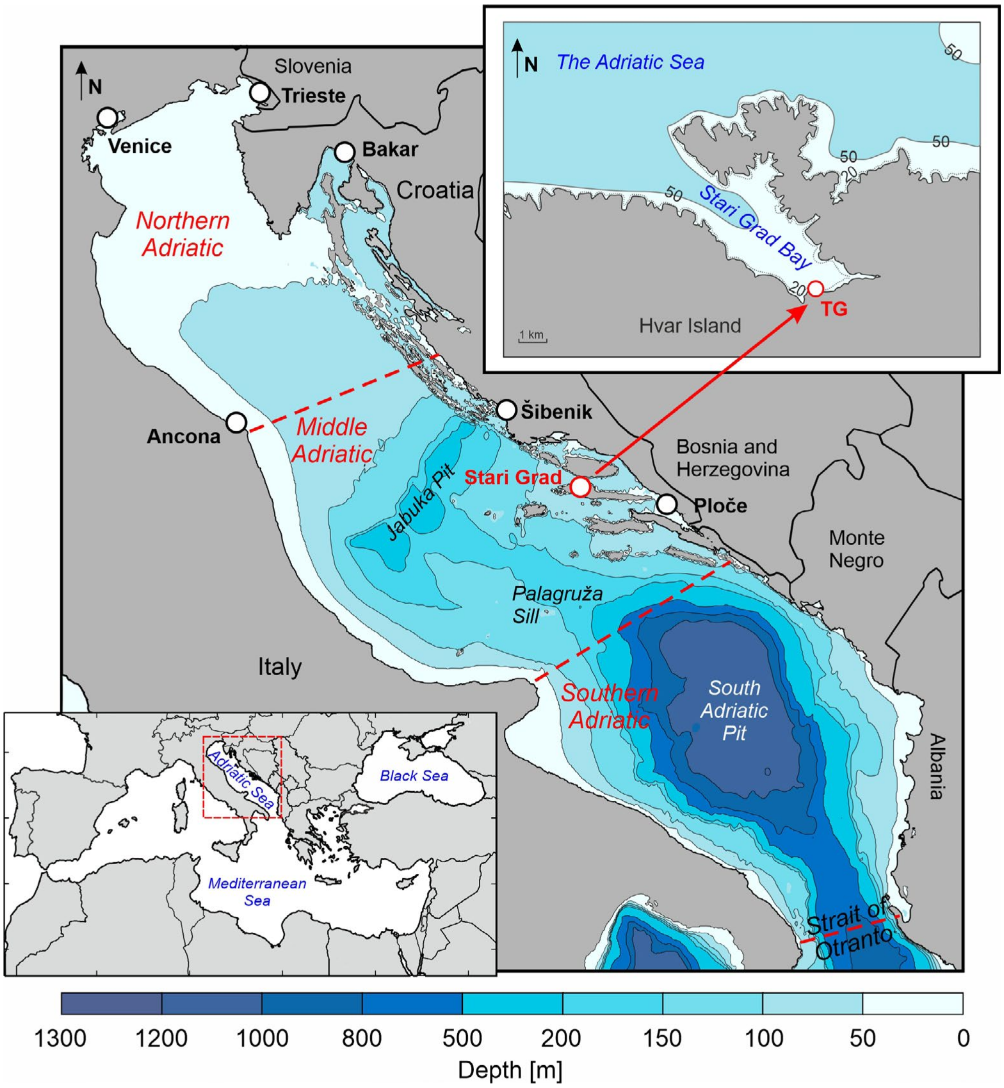

Figure 1. Bathymetry of the Adriatic Sea; Stari Grad tide gauge (TG) is marked with white circle with red edge. Traditional separation of the Adriatic Sea into the northern, middle, and southern Adriatic is depicted. Locations mentioned in the paper are marked as well. Position of the Adriatic Sea relative to the Mediterranean Sea and zoom-in to Stari Grad Bay are given in the small insets.

Materials and methods

Oceanographic and atmospheric data used in this analysis were measured at automatic measuring station located in Stari Grad Bay (Island Hvar) and operated by the Institute of Oceanography and Fisheries, Split, Croatia [17]. We analysed one minute time series of air pressure, wind speed, wind direction and sea level, measured during 28 June 2017 to 5 August 2020 (**Supplementary dataset – Figure S1**). For analysis of synoptic conditions, we used ERA5 reanalysis data. All analyses were done in MATLAB R2020a.

Data quality analysis

Data quality check revealed that data was of high quality, whereas only 0.025% of total measurements (sea level, wind direction and speed, and air pressure data points) were missing. Data gaps were filled using linear intrapolation (MATLAB interpl function).

Sea level data

To identify periods at which sea level extremes in Stari Grad occur, we applied spectral analysis to sea level time series using windows of various length. To distinguish oscillations at periods from ~10 to 26 hours (these are periods at which low-pass minima and maxima occur) it is appropriate to use a 180 days window, for oscillations at periods from 2 to 10 hours (also periods at which low-pass minima and maxima occur) to use a 30-day window and for oscillations at periods under 2 hours (short-period extremes) to use a 1-day window (**Supplementary dataset – Figure S2**).

The tidal signal in the Adriatic was removed from the original sea level series so that we could focus on exploration of extreme sea level oscillations forced by atmospheric processes. Still, tides play an important role in sea level changes. Sometimes low tides can mitigate severe high sea level events. Then again, high tides can also amplify these events: e.g., during the 13 November 2019 extreme sea level event, maximum value of total signal was 73.56 cm, and of residual (de-tided) signal 51.17 cm, implying that tide contributed to extreme with 22.39 cm.

To estimate and remove tidal oscillations we applied harmonic analysis. We did this by using the MATLAB toolbox t_tide [18]. Toolbox t_tide uses sea level time series, sampling interval, start time, latitude, and list of constituents as input parameters, and it returns tidal prediction for each of the listed constituents. Altogether, four semidiurnal (M2, S2, N2, K2) and three diurnal (K1, O1, P1) tidal components were estimated and removed. All further analyses were done on de-tided (residual) time series. As noted in the Introduction, these are seven most significant tidal constituents in the Adriatic Sea (**Supplementary dataset – Table S1**).

To separate the long-period sea level extremes from the short-period sea level extremes, residual sea level series were filtered using MATLAB kaiser function to create filtering window of 210 min (3.5 h) length and filtfilt function to filter the data. Residual and filtered sea level time series are shown in **Figure S3 in the Supplementary dataset**. Further in the text, we refer to the low-pass (period longer than 210 min) component of filtered time series as long-period time series, and to the high-pass (periods shorter than 210 min) component as short-period time series. These series are studied separately.

Extraction of sea level extremes

Positive long-period extremes were defined as those situations during which the long-period sea level series surpassed their 99.7th percentile value. Negative long-period extremes were defined as those situations during which the long-period sea level series were lower than their 2nd percentile value (**Supplementary dataset – Figure S4**). To avoid multiplication of daily events - as even residual sea level can oscillate above and below threshold lines due to the Adriatic seiche [5, 7] - all data above (or below for negative extremes) the percentile threshold lines measured within 24 hours from each other were classified as one event (**Supplementary dataset – Figures S4-6**).

Short-period extremes were defined as situations during which 2.5-h moving variance of short-period sea level oscillations was higher than the 99.4 percentile value of total variance of short-period series (**Supplementary dataset – Figure S7**). Since these oscillations fluctuate from positive to negative on a minute time scale (periods from 2 minutes to 210 minutes), identifying the extreme episodes was not straightforward as for the long-period extremes. After identifying oscillations with 2.5-h moving variance higher than the 99.4 percentile, maximum of each episode was found. Then, an algorithm was devised which moves to the left and to the right from the maximum of the episode registering as one episode all periods during which 2.5-h moving variance of series is above its 75-percentile value (**Supplementary dataset – Figure S7**).

For all extreme sea level events, maxima (minima) of sea level, duration, and intensity (sum of all sea levels measured during duration of an episode) were estimated.

Atmospheric data

After identifying extreme sea level events, the corresponding atmospheric variables were analysed: air pressure, wind speed and direction. Raw atmospheric data were interpolated and filtered as well, using the same 3.5 h cut-off period to distinguish between long-period and short-period atmospheric situations. Original and filtered air pressure time series are shown in Supplementary dataset (**Suplementary dataset – Figure S8**).

Investigation of synoptic situation before and during extreme events was necessary to understand how meteorologic factors force the extreme events. For this purpose, we downloaded and analysed the mean sea level pressure field and the 10-m wind field from the ERA5 reanalysis dataset [19], all for the dates of extreme events (at the closest available time prior the event: 00:00, 06:00, 12:00, or 18:00, as well as at additional 18 hours preceding the event).

Results

Spectral analysis of sea level time series

Spectral analysis revealed periods at which the strongest and most consistent sea level oscillations occurred. Results of spectral analysis done using 180 days window length are show in **Figure 2**. Periods of diurnal and semidiurnal tides and Adriatic seiche (20.97 h and 10.91 h) stand out. To examine higher frequency phenomena, we estimated spectra using windows of 24 hours length (**Figure 3**). Shorter-period oscillations appeared within 4 distinct groups: (1) at periods from 49.8 min to 1.26 h; (2) at periods from 23.4 to 36.0 min; (3) at 10.2 min period; and (4) at 7.8 min period. Shorter periods (10.2 min and 7.8 min) are most likely periods of the Stari Grad Bay local seiches. Estimated period of fundamental mode of Stari Grad bay is 10.6 min [20]. Periods of higher modes are 8.3 min and 6.1 min, and oscillations at longer periods possibly represent wider area seiches [20].

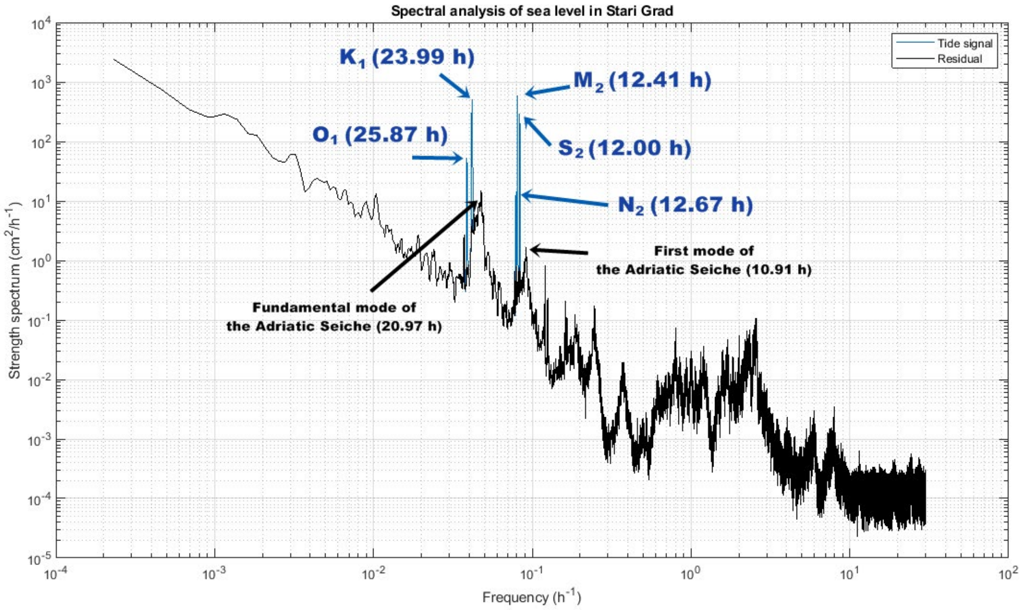

Figure 2. Spectra of Stari Grad sea level time series obtained using 180 days window length. Distinct peaks labelled blue represent tidal constituents, and distinct peaks labelled black represent the Adriatic seiche fundamental and first mode.

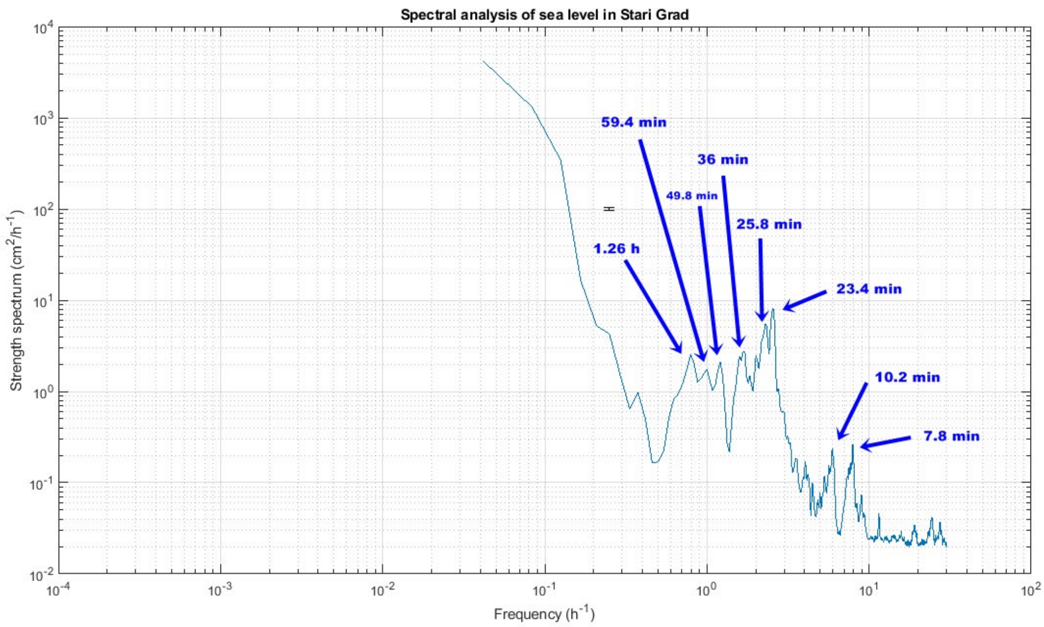

Figure 3. Spectra of Stari Grad time series obtained using 24 hours window length: periods of all significant peaks are given.

Extreme sea level events

Following the methodology described in Materials and methods, we identified 47 extreme sea level events. Out of these 47 events, 10 events represent long-period positive extremes (**Table 1**), 17 events represent long-period negative extremes (**Table 2**) and 20 events represent short-period extremes (**Table 3**).

Table 1. Chronologically sorted long-period positive sea level extremes

Episode*	Date	Max. sea level – residual (cm)	Max. sea level – low-pass filter (cm)	Duration
1	03/03/2018.	27.4038	28.9011	1h 24min
2	06/03/2018.	35.2677	36.2591	1d 5h 34min
3	18/03/2018.	31.2651	29.9174	2h
4	29/10/2018.	40.9263	29.4270	1h 12min
5	27/11/2018.	37.0830	32.7993	5h 12min
6	03/02/2019.	35.2462	32.6836	3h 57min
7	13/11/2019.	44.1509	44.6542	1d 6h 9min
8	17/11/2019.	33.2737	31.2251	2h 50min
9	13/12/2019.	53.2870	54.6993	6h 29min
10	22/12/2019.	65.3004	59.0738	1d 21h

*Episodes represent maxima of long-period time series, i.e., extremely high sea levels. Meteorologic data and synoptic situations related to all 10 episodes were further analysed.

Table 2. Chronologically sorted long-period negative sea level extremes

		Long-period minima		
Episode*	Date	Min. sea level – residual (cm)	Min. sea level – low-pass filter (cm)	Duration
1†	22/12/2017.	-35.8313	-36.4394	1d 20h 6min
2†	30/01/2018.	-40.7519	-41.9463	3d 13h 40min
3†	05/02/2018.	-34.5157	-32.0605	2h 14min
4	31/12/2018.	-32.1857	-32.0419	1h 30min
5†	14/02/2019.	-34.0898	-33.7138	15h 1min
6	21/02/2019.	-32.4851	-31.8982	2h 18min
7†	23/02/2019.	-49.2242	-48.6238	5d 7h 48min
8†	29/03/2019.	-40.7800	-42.1075	10d 22h 11min
9†	22/04/2019.	-33.5793	-33.3653	5h 15min
10†	05/01/2020.	-38.8383	-35.6288	21h 36min
11	16/01/2020.	-30.8328	-32.2692	3h
12†	21/01/2020.	-36.7362	-36.7797	2d 7h 16min
13†	22/02/2020.	-41.0570	-37.8805	2d 22h 40min
14	23/03/2020.	-30.5993	-35.0460	3d 22h 9min
15	25/03/2020.	-31.7539	-32.3786	3h 23min
16	09/04/2020.	-33.4443	-33.3331	1d 2h 36min
17	27/05/2020.	-33.0267	-33.4319	6h 13min

*Episodes represent minima of long-period time series, i.e., extremely low sea levels.
†Meteorologic data and synoptic situations related to the 10 strongest episodes were further analysed.

Table 3. Chronologically sorted short-period sea level extremes

Short-period extremes			
Episode*	Date	Max. wave height (cm)	Duration
1†	28/06/2017.	41.24	6h 12min
2	28/06/2017.	33.96	1d 5h 30min
3†	01/07/2017.	49.95	1d 21h 37min
4	12/07/2017.	27.15	1d 7h 2min
5†	24/07/2017.	43.02	1d 6h 46min
6†	11/09/2017.	46.02	2d 16h 47min
7	17/09/2017.	34.49	2d 5h 24h
8	03/01/2018.	31.84	2d 11h 48min
9	17/01/2018	38.61	1d 18h 3min
10†	03/02/2018.	40.51	1d 12h 24min
11	17/03/2018.	32.41	1d 20h 54min
12†	31/03/2018.	58.81	1d 17h 8min
13	21/07/2018.	36.81	18h 12min
14†	29/10/2018.	50.84	3d 20h 47min
15†	09/07/2019.	104.95	3d 22h 50min
16	02/08/2019.	34.86	1d 23h 13min
17	22/12/2019.	33.51	4d 6h 38min
18†	11/05/2020.	62.89	1d 14h 5min
19†	17/05/2020.	44.75	7d 5h 6min
20	24/07/2020.	25.59	23h 45min

*Episodes represent periods of strongest oscillations of short-period sea level time series.
†Meteorologic data and synoptic situations related to the 10 strongest episodes were further analysed.

Monthly distributions of episodes of long-period positive sea level extremes are given in the first column of **Figure 4**. Long-period positive extremes mostly occurred during late autumn/early winter and late winter/early spring. They lasted slightly more during late autumn/early winter, when they were also more intense, with intensity representing sum of all sea levels measured during duration of an episode.

Monthly distributions of episodes of long-period minima are given in the second column of **Figure 4**. These episodes dominantly appeared during winter and spring months with a peak occurrence in February. However, the episodes were longest and most intense during March. These episodes occasionally occurred during autumn and early spring.

Monthly distributions of short-period extremes are given in the third column of **Figure 4**. Short-period extremes occurred throughout the year. They were most frequent during July (6 episodes), and they were strongest in May and July. Additionally, the longest average duration of short-period extremes was found for episodes occurring in May.

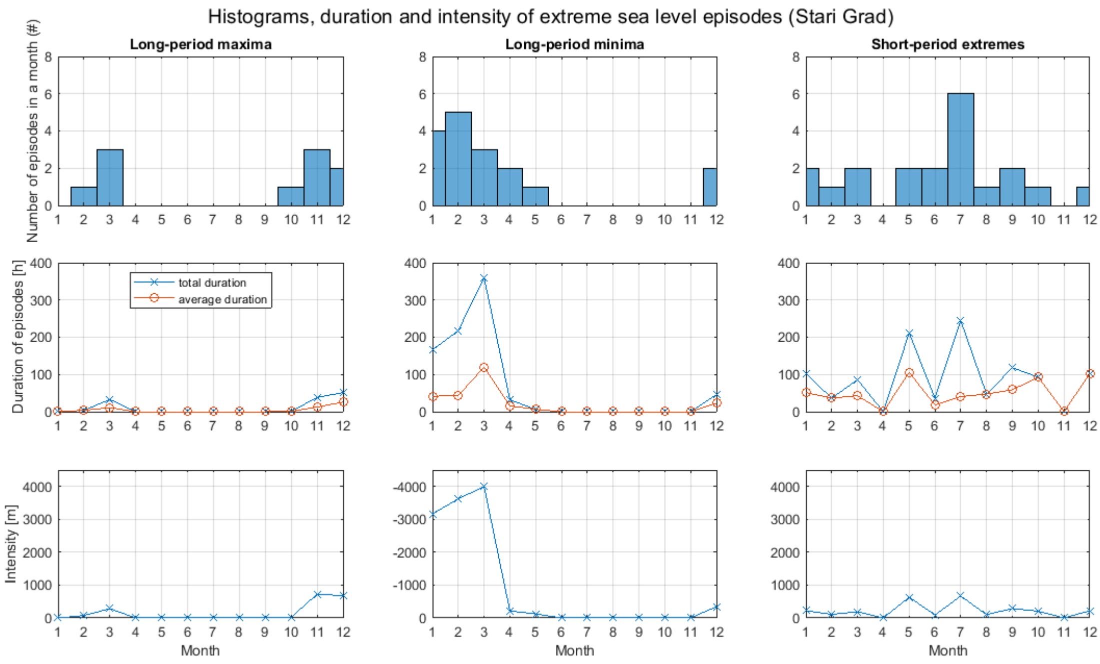

Figure 4. Number of events per month (top), duration per month – total (blue) and average (red) (middle), and intensity per month (bottom) of extreme sea level episodes in Stari Grad.

Atmospheric conditions

Air pressure and wind measured during the 10 strongest episodes of each type of sea level extremes (**Table 1** to **Table 3**) were analysed. In addition, characteristic synoptic conditions during the same episodes were assessed using the ERA5 reanalysis data. Analysis of both measured and reanalysis data pointed to existence of two types of characteristic synoptic situations for all studies type of sea level extremes.

Positive long-period extremes

When it comes to positive long-period extremes, both specific synoptic situations were characterized by a presence of a low-pressure system (midlatitude cyclone) over Europe, and a strong SE wind blowing over the Adriatic. The difference between these two situations is that during one, a low-pressure system was centred over the Gulf of Genoa, and during the other, low-pressure system spread from the Atlantic (north-western Europe) towards the Adriatic. We now present more detailed analysis of two different types of atmospheric conditions conductive for the Stari Grad positive long-period sea level extremes.

The 29 October 2018 event – details and findings

Shortly before midnight of 29 October 2018, long-period sea level surpassed its 99.7th percentile value reaching height of ~30 cm (**Table 1**; **Figure 5**, panel a). The sea level rise was accompanied by a presence of lower-than-average air pressure (< 1010 hPa) during a couple of days surrounding the event, reaching minimum value at the exact time of the event (**Figure 5**, panel b), and strong SE winds blowing before the episode (**Figure 5**, panels c, h). The wind speeds were up to ~10 m/s during the episode, but up to 20 m/s before the episode. The strongest winds were blowing from the ESE (**Figure 5**, panel h).

As for the general synoptic conditions: at 00:00 UTC of 29 October, a low mean sea level pressure field was located over the Gulf of Genoa where minimum pressure values reached 998 hPa (**Figure 5**, panel d). Over the next 18 hours, the centre of the cyclone propagated towards the north reaching the Western Alps with minimum pressure values dropping further, to 982 hPa (**Figure 5**, panel g). Northward propagation of the cyclone resulted in intensification of the pressure gradients over the Adriatic Sea and strengthening of the SE wind, creating a favourable setting for a storm surge.

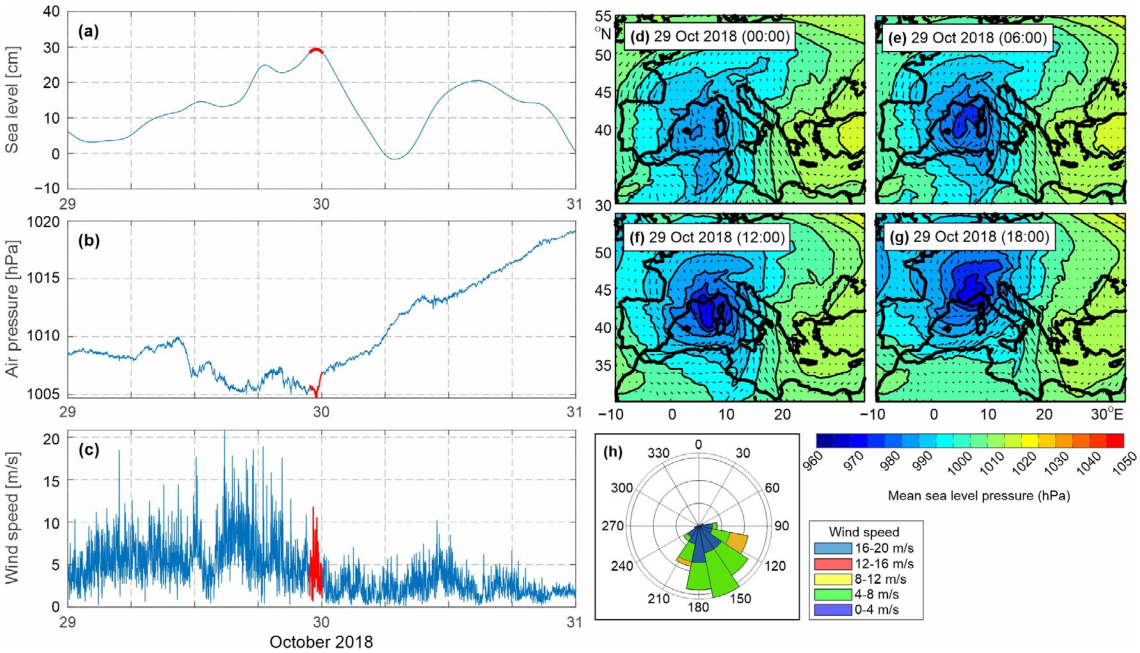

Figure 5. Positive long-period episode on 29 October 2018. Long-period residual sea level series (a), air pressure (b), wind speed (c), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (d)-(g), and wind rose (h). Episode is indicated with red (a-c).

The 13 December 2019 event – details and findings

During afternoon hours of 13 December 2019, long-period residual sea level reached 53.3 cm (**Table 1**; **Figure 6**, panel a), classifying the episode as the second strongest positive long-period extreme. Air pressure measured at Stari Grad was extremely low (< 990 hPa) for a couple of days surrounding the event (**Figure 6**, panel b), and winds of very high speeds (up to ~18 m/s) blowed over the station during the episode (**Figure 6**, panel c). The strongest winds blew from the SE, accompanied by moderate NW winds (**Figure 6**, panel h).

A wider area situation is depicted in **Figure 6**, panels d-g. At the beginning of the episode (00:00 UTC, 13 December 2019) air pressure over the Adriatic area was slightly lower than average (1002 hPa). However, a mid-latitude cyclone was detected over the north-western Europe (974 hPa). During the next 12 hours this low-pressure area propagated towards the

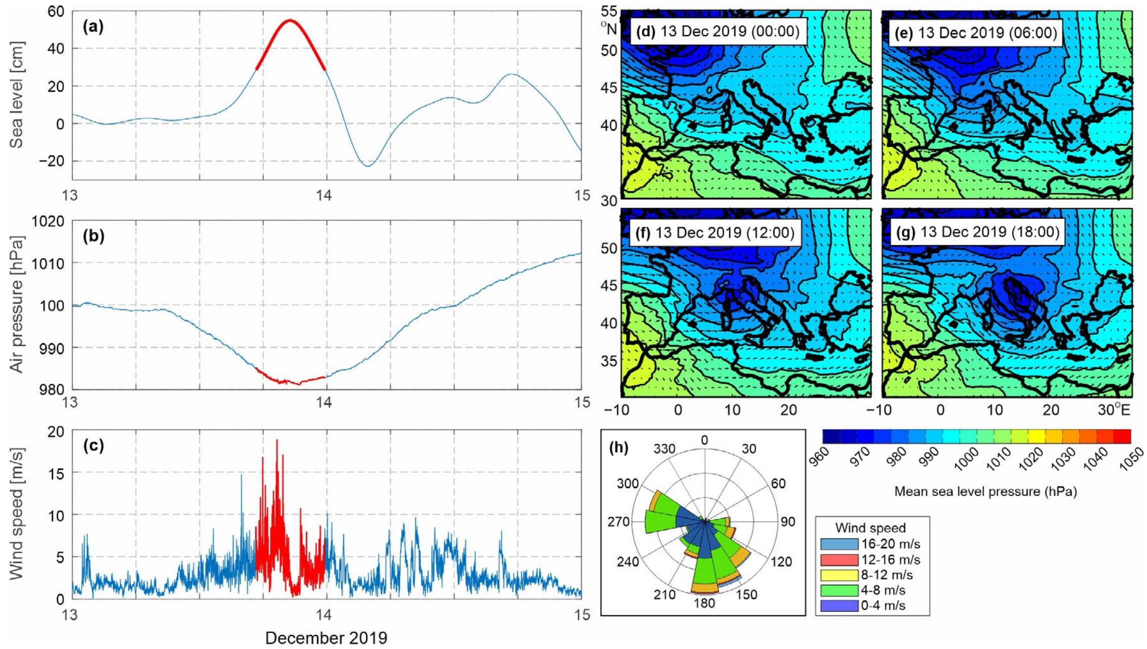

Figure 6. Positive long-period episode on 13 December 2019. Long-period residual sea level series (a), air pressure (b), wind speed (c), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (d)-(g), and wind rose (h). Episode is indicated with red (a-c).

southeast. At the outskirts of this mid-latitude cyclone, another smaller cyclone formed over the Western Alps with the minimum pressure values of 986 hPa. During the next six hours the smaller cyclone propagated towards the northern Adriatic causing strong southeast to south winds over the Adriatic.

Negative long-period extremes

Negative long-period extremes were also associated to two types of distinct atmospheric situations, both of which were characterised by very high atmospheric pressure (> 1020 hPa) fields over the Adriatic Sea. The first situation was additionally associated with strong NE (i.e., bora) winds, and the second to relatively calm weather during which light SE winds interchanged with moderate NW winds.

The 5 January 2020 event – details and findings

During 5-6 January 2020, a long-period negative extreme occurred. At its minimum, long-period residual sea level reached heights of ~-35 cm (**Table 2**; **Figure 7**, panel a). Sea level had extremely low values for ~24 hours. Air pressure was higher than average during the entire episode reaching values up to ~1030 hPa (**Figure 7**, panel b). Strong wind with speed up to 15 m/s was blowing before the episode and during its onset (**Figure 7**, panel c). During most of the episode wind was moderate with a NE direction (**Figure 7**, panel h). Right before the onset of episode, air pressure over the western Europe was extremely high (maximum value of 1038 hPa), and air pressure over the eastern Europe was average (~1014 hPa) (**Figure 7**, panel d). The pressure gradient caused NW winds over the Adriatic. Over the next 18 hours the higher air pressure area propagated towards the east, and the lower air pressure area towards the west (**Figure 7**, panels d-g). Wind direction over the Adriatic shifted accordingly – from NW to N to NE. During the

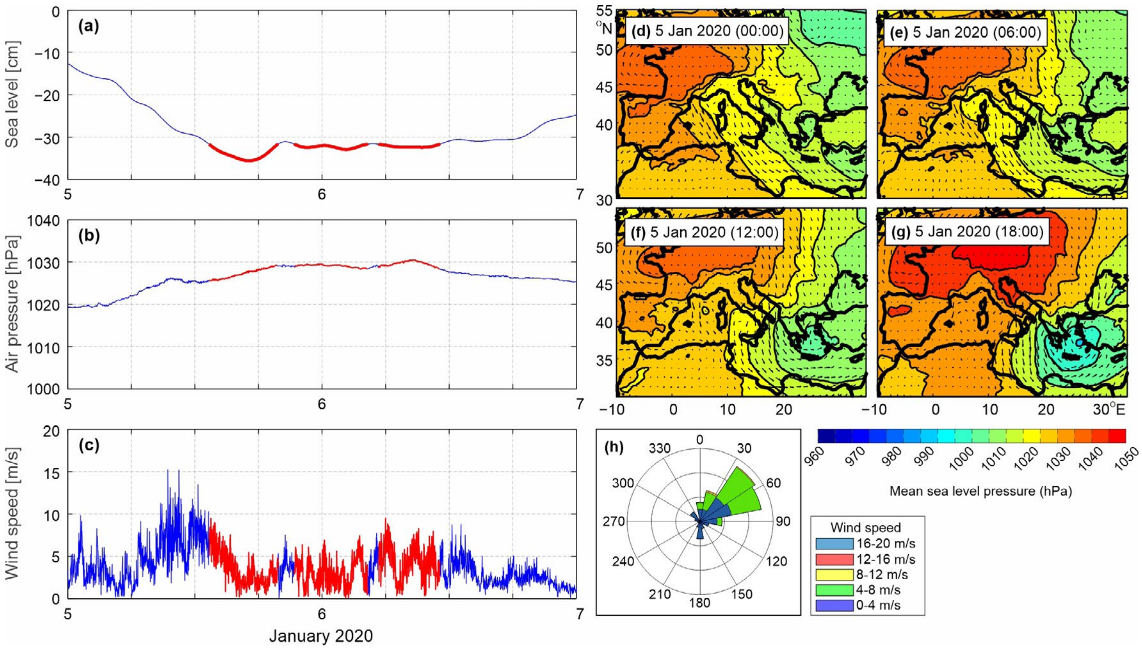

Figure 7. Negative long-period episode on 5 January 2020. Long-period residual sea level series (a), air pressure (b), wind speed (c), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (d)-(g), and wind rose (h). Episode is indicated with red (a-c).

episode there was a small cyclone over the Aegean Sea (minimum value of 1006 hPa). The observed pressure gradients over the Adriatic caused the strongest NE winds precisely during the episode.

The 23 January 2020 event – details and findings

The second characteristic situation related to negative long-period extremes is depicted in **Figure 8** for the event of 21-23 January 2020. During this episode long-period residual sea level was lower than its 2nd percentile for more than 48 hours (including a short period within the episode when it was higher than this level). At its lowest, sea level dropped to ~-37 cm (**Table 2**; **Figure 8**, panel a). Right before and at the beginning of the episode, air pressure was extremely high reaching values up to 1040 hPa (**Figure 8**, panel b). During the rest of the episode, air pressure was decreasing, but was still higher than usual. Day and a half before the episode a strong wind was blowing over the area (**Figure 8**, panel c). However, during the episode SE wind was relatively light (<4 m/s), and a NW wind was occasionally moderate (up to 10 m/s) (**Figure 8**, panel h).

Synoptic situation of the episode of 21 January 2020 can be described as stationary (**Figure 8**, panels d-g). Before and during the episode air pressure over the central Europe was extremely high (maximum value of 1046 hPa) and relatively normal over the southwest Mediterranean. Situation stayed similar for the next 18 hours. During the episode, air pressure over the Adriatic was extremely high with no strong winds.

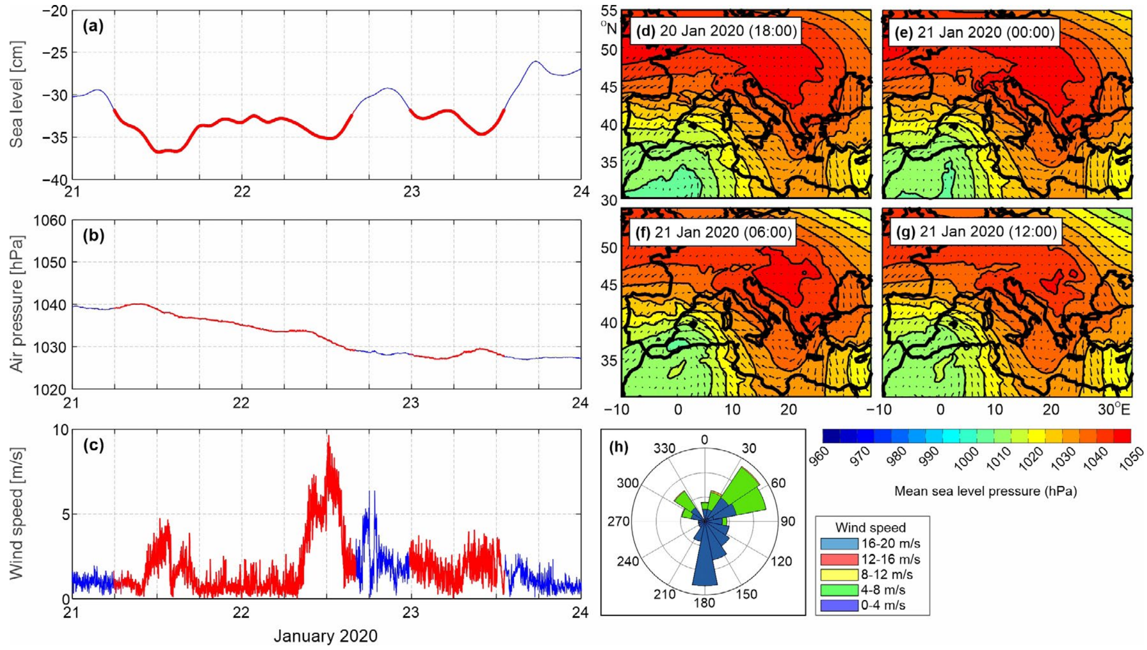

Figure 8. Negative long-period episode on 21 January 2020. Long-period residual sea level series (a), air pressure (b), wind speed (c), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (d)-(g), and wind rose (h). Episode is indicated with red (a-c).

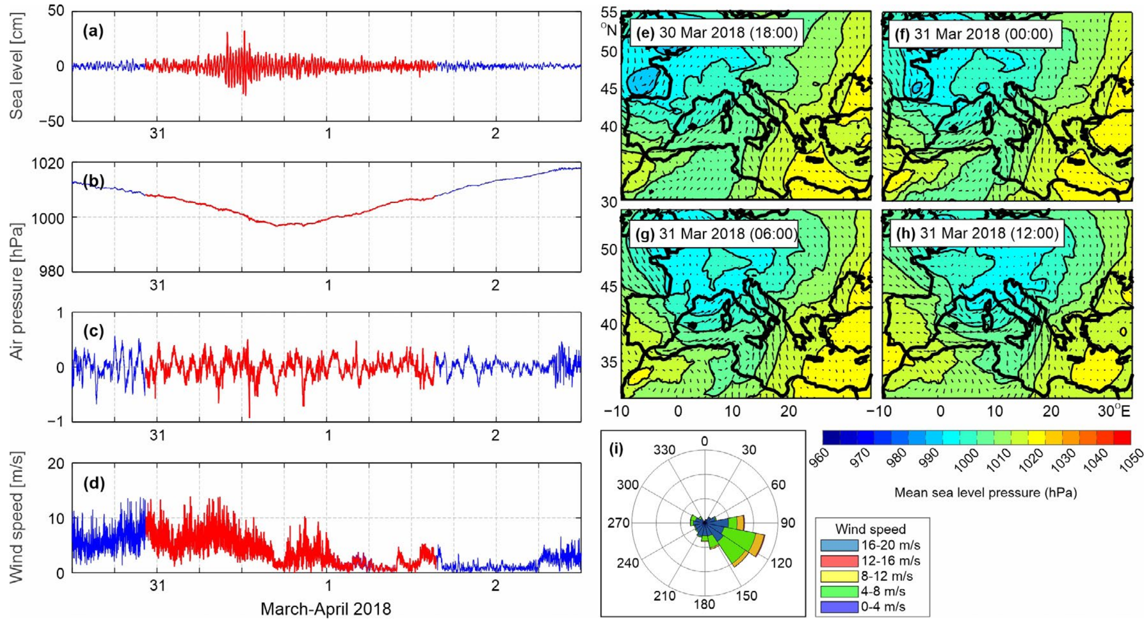

Figure 9. Short-period episode on 31 March 2018. Short-period residual sea level series (a), air pressure (b), short-period air pressure series (c), wind speed (d), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (e)-(h), and wind rose (i). Episode is indicated with red (a-d).

All episodes of short-period extremes had one common characteristic – sudden pronounced changes of short-period air pressure series. As for the unfiltered (original) air pressure, it was either lower than average or normal during all episodes. Situations characterised with lower-than-average air pressure were usually also associated with strong SE winds, and situations characterised with normal pressure were usually associated with moderate winds of no dominant direction or with weak winds only.

The 31 March 2018 event – details and findings

The first situation related to short-period extremes is depicted in **Figure 9**, for the episode of 31 March 2018. Short-period sea level oscillations reached crest-to-through heights of ~58 cm (**Table 3**; **Figure 9**, panel a). Air pressure during the episode was lower than average reaching values of ~998 hPa (**Figure 9**, panel b). Short-period component of air pressure reveals pronounced oscillations during the entire episode. The strongest air pressure oscillation with wave height of almost 1.5 hPa and of 14 minutes duration was recorded shortly after the sea level extreme (**Figure 9**, panel c). The SE and E winds were blowing before and during most of the episode (**Figure 9**, panel h). Towards the end of the episode wind speed decreased and was around 3 m/s (**Figure 9**, panel d).

Before the episode of 31 March 2018, air pressure over the western Europe was low (minimum value of 994 hPa; **Figure 9**, panel e). Over the eastern part of the Mediterranean air pressure was high (maximum value above 1016 hPa), causing strong pressure gradient over the Adriatic, where air pressure was initially ~1010 hPa. Over the next 18 hours area of low air pressure propagated to the east (during the episode air pressure above the Adriatic was ~998 hPa) (**Figure 9**, panels e-h). Strong SE and S winds were blowing over the Adriatic during the entire episode.

The 7-11 July 2019 event – details and findings

The second characteristic situation related to short-period extremes is shown in **Figure 10** for the episode of 7-11 July 2019. Stronger than usual sea level ringing lasted from midday hours of 7 July up to 11 July, with the strongest oscillations, reaching height of ~105 cm recorded around 00:00 UTC at 10 July (**Table 3**, **Figure 10**, panel a). During the entire episode, air pressure was either slightly lower than average or average (1010 hPa – average

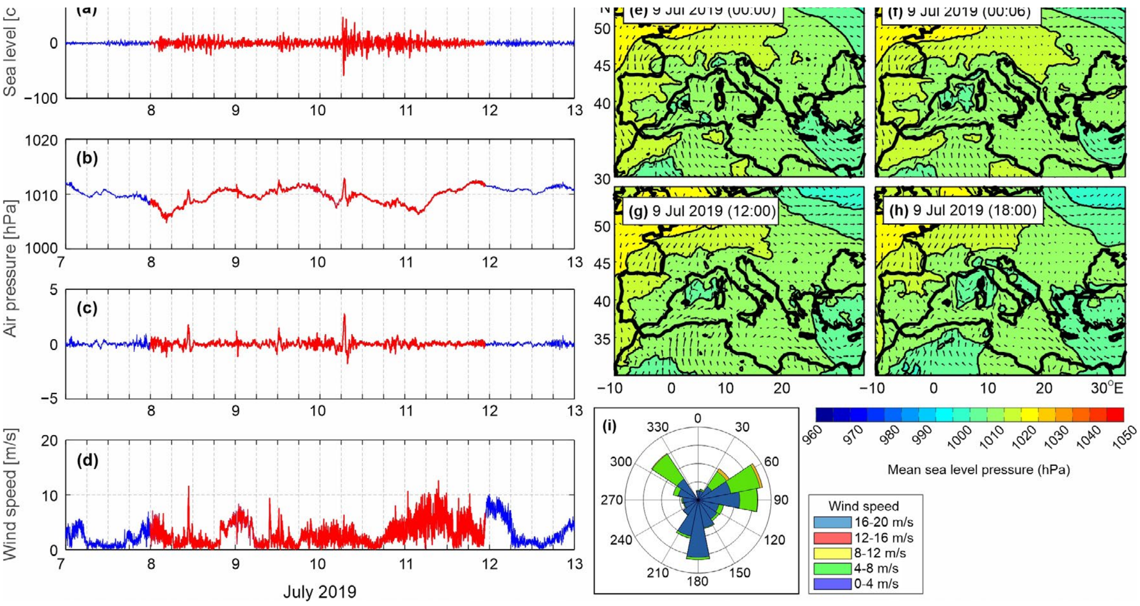

Figure 10. Short-period episode on 7-11 July 2019. Short-period residual sea level series (a), air pressure (b), short-period air pressure series (c), wind speed (d), mean sea level pressure field and 10-m wind vectors over the Mediterranean before and during the episode (e)-(h), and wind rose (i). Episode is indicated with red (a-d).

for entire period) (**Figure 10**, panel b). On the other hand, short-period component of air pressure revealed occurrence of four sudden air pressure oscillations during the episode (**Figure 10**, panel c). The strongest one, with the wave height of 4.5 hPa and an almost 1 hour period, happened at the time of the strongest short-period sea level oscillation. It can also be noticed that most of pronounced air pressure oscillations corresponded to sudden short-lasting increases of wind speed (**Figure 10**, panel d). For the rest of the episode, winds were light.

As for the synoptic situation, the episode during 7-11 July 2019 is an example for situation characterized by relatively calm synoptic conditions over the Mediterranean (**Figure 10**, panels e-h). There were no areas of extreme air pressure and no pronounced pressure gradients, meaning there were no strong winds blowing over the Adriatic Sea. Air pressure over the Adriatic was ~1012 hPa.

Discussion

We analysed sea level time series measured in Stari Grad (Hvar Island, the Adriatic Sea) during July 2017 to August 2020. From these series, we extracted long-period (T>210 min) positive and negative sea level extremes, as well as short-period (T < 210) sea level extremes and examined their statistics. Positive long-period extremes usually occurred during late autumn/early winter and late winter/early spring with sea levels reaching up to 59 cm. Negative long-period extremes dominantly appeared during winter and spring months with an occurrence peak in February, with sea level dropping to -49 cm. Short-period extremes occurred throughout the year. Still, they were most frequent during July. Maximum recorded crest-to-trough height of short-period extremes during investigated period was ~105 cm, implying that height above the mean sea level during the short-period extreme was increased for additional ~52.5 cm. Literature review reveals that even stronger short-period extremes occasionally occur in Stari Grad, reaching crest-to-trough heights up to 3.5 m [13, 20]. For the Adriatic Sea, Orlić [13] classifies all meteorologically induced short-period oscillations, with crest-to-trough height above 100 cm, as meteotsunamis.

It is of particular importance to note that, during the investigated period, short-period extremes, of which the strongest ones are meteotsunamis, were occasionally coincident with positive long-period extremes contributing with up to 50 percent to total sea level height – thus pointing to a double danger phenomenon - meteotsunami and storm surge (e.g., episode of 29 October 2018). To what extent can such superposition contribute to total sea level extremes has only recently become a topic of studies [21].

Analysis of atmospheric conditions during the events revealed that each type of extremes can be associated with two characteristic synoptic situations. Positive long-period extremes occurred during presence of a mid-latitude cyclone over (i) the Gulf of Genoa/northern Adriatic Sea, or (ii) over the eastern Atlantic (north-western Europe) – but spreading towards the Adriatic Sea. As a result, during both these situations, mean sea level pressure was lower over the Adriatic then usual – causing increase in sea level via the inverse barometer effect (a decrease of air pressure of 1 hPa corresponds to an increase of sea level of 1 cm) [22]. Additionally, mean sea level pressure gradients were such that strong S/SE wind developed over the Adriatic Sea pushing water masses towards the closed end of the basin and increasing sea levels – especially in the northern parts of the Adriatic, and somewhat less in the central Adriatic, as known to happen [11].

Oppositely, negative-long period extremes were related to high pressure centres over the area. High air pressure caused decrease in sea level (also through the inverse barometer effect; 1 cm air pressure increases results in drop of sea level of 1 cm). During one type of synoptic settings, high-pressure centre is accompanied with strong NE wind (bura) which pushes water mass away from the Croatian coast [7], and in other with calm weather/ weak winds.

Regarding short-period sea level oscillations, these happened either during a situation like the one giving rise to a positive long-period sea level extreme – thus creating a favourable setting for the above-mentioned double jeopardy phenomena, or during relatively calm weather with no pronounced mean sea level pressure gradients, and no strong winds. The most important atmospheric feature associated with the short-period sea level extremes were pronounced short-period air pressure oscillations. These are of such a small spatial and temporal extent that they are non-reproducible with global (and even regional) models, such as the ERA5 model. Thus, to explore the short-period sea level extremes, meteorological measurements at the endangered location are necessary. When such small-scale atmospheric oscillations propagate over the open sea, they can generate long ocean waves. If the speed of air pressure disturbances is the same as the speed of long ocean waves, Proudman resonance will occur [23]. Sea level oscillations can then be intensified up to 10 times when compared to the inverse barometer effect. Long ocean waves can also be amplified near the coast due to narrowing in bays or harbour resonance [14].

Even though three years of measurements provided much needed data for this research, longer measurements would give an even better insight into the sea level extremes and allow for a more detailed statistical analysis including the estimation of return periods. More extremes could be extracted and analysed, and more accurate monthly distributions could be obtained. This would be especially important for the short-period extremes since they seemingly occur throughout the year. This research revealed that Stari Grad is a flood-prone area, and it confirmed the well-known fact that the Adriatic Sea is a storm surge and a meteotsunami hotspot [7, 13]. Many other sea level phenomena leading to floods can be observed in the Adriatic Sea, making it one of the greatest natural research labs in the world.

RESEARCH ARTICLE

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Data availability statement: All atmospheric and sea level data used in the study are measured by the Institute of Oceanography and Fisheries (Split, Croatia). These data can be visualized at http://faust.izor.hr/autodatapub/postaje?jezik=eng, and downloaded via http://faust.izor.hr/autodatapub/mjesustdohvatpod?jezik=eng upon free registration. The ERA5 reanalysis data [24] can be downloaded from Copernicus Climate Change Service (C3S) Climate Data Store upon registration [19].

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