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Article

Comprehensive Wind and Wave Statistics and Extreme Values for Design and Analysis of Marine Structures in the Adriatic Sea

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Abstract: Wind and waves present the main causes of environmental loading on seagoing ships and offshore structures. Thus, its detailed understanding can improve the design and maintenance of these structures. Wind and wave statistical models are developed based on the WorldWaves database for the Adriatic Sea: for the entire Adriatic Sea as a whole, divided into three regions and for 39 uniformly spaced locations across the offshore Adriatic. Model parameters are fitted and presented for each case, following the conditional modelling approach, i.e., the marginal distribution of significant wave height and conditional distribution of peak period and wind speed. Extreme significant wave heights were evaluated for 20-, 50- and 100-year return periods. The presented data provide a consistent and comprehensive description of metocean (wind and wave) climate in the Adriatic Sea that can serve as input for almost all kind of analyses of ships and offshore structures.

Keywords: offshore Adriatic Sea; significant wave height; peak period; wind speed; extreme value; conditional modelling; joint distributions

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1. Introduction

Wave (re-analysis) databases, comprising numerical wave model hindcasts and assimilated altimetry satellite data, present a comprehensive state-of-the-art source for analysis of metocean data that serve as input for the design and assessment of oceangoing vessels and offshore structures [1]. The WorldWaves database was used in this study to derive wind and wave statistics for the Adriatic Sea, which is a semi-enclosed sea basin with specific wind–wave climate. The basin is analyzed as a whole, divided into three regions and at 39 evenly spaced locations. Procedures and concepts applied in the study resulted with environmental wind and wave models that provide a detailed and structured insight into the wind–wave climate of this basin. Joint probability distributions of significant wave height and peak periods and distribution of wind speed to significant wave height are developed together with extreme wave height estimation for 20, 50 and 100 year return periods.

The obtained results are useful for the design, operation planning, maintenance and life-time extension of marine-related engineering objects in the Adriatic. Specific calculations such as: extreme sea states analysis for the design of marine structures [2], coupled aero- and hydro-dynamic analysis of floating offshore wind turbines [3], long-term fatigue calculations [4], structural reliability [5] and mooring analyses [6], can benefit from the input of the developed data. Wave statistics in the Adriatic is also used for exploring wave energy potential [7,8] and for planning and evaluating the performance of high-requirement service vessels such as the coastal patrol boat developed for the Adriatic [9]. Safety analysis of a fishing vessel due to roll in a seaway [10] and organization of special marine operations [11] are other examples where accurate wave statistics for the Adriatic is indispensable.

In the second half of 20th century, wave statistics in the Adriatic was based on visual observations collected from merchant and meteorological vessels and published in the wave climatology atlas [12]. Wave statistics was rather roughly graphically presented in the form of wave roses that were later digitalized and studied in terms of extreme values [13]. These data, however, suffer from known inaccuracies of visual wave observations and lack of extreme events due to heavy weather avoidance by ships [14]. Later, measurements have been performed from four floating buoys installed along the west coast of the Adriatic [15]. However, these data were recorded and are available only for limited time of 5 years, with some interruptions due to failure and maintenance. One of the most comprehensive wave-data sources in general are the measurements from the Aqua Alta oceanographic tower, located near Venice in the north part of the Adriatic [16]. Although 38 years of continues uninterrupted measurements are available, they refer only to one specific location and cannot be used for the whole Adriatic Sea.

The present study represents the first complete wave and wind statistics for the whole Adriatic Sea, representing progress compared to previous studies [17]. The way the data are presented enables its application to almost all purposes related to marine structural design and analysis, as reviewed in the preceding paragraphs. Site specific design (e.g., for offshore structures) might require spatial interpolation of presented data; however, it can be directly applicable for the analysis of ships, as they are not confined to a specific location. Particular attention is paid to the accuracy of calculated extreme values, to avoid too conservative results that could lead to non-economical and over-dimensioned structures [18].

The paper is organized as follows. Initially, the WorldWaves database, used as the underlying material for the study, is described in Section 2 along with preliminary data structuring such as the development of sea-state and wind contingency tables, wave roses visualizations and example validations against existing buoy data. In Section 3 the theoretical background of applied methods is presented for the development of the joint probability distribution models. In Section 4, all model parameters and extreme values are presented graphically, both regionally and per individual location analyzed. Section 5 gives a discussion on the results and Section 6 presents the conclusion. At the end of the paper, Appendix A provides basic data, such as location coordinates and regional subdivision and Appendix B gives detailed tabulated results that are graphically presented in Section 4.

2. Data

The underlying data used for the analysis of wave and wind climate analysis in the Adriatic Sea were extracted from the WorldWaves (WW) database. The database represents numerical wave model hindcasts with assimilated available satellite altimetry measurements [19,20]. It includes 39 locations, evenly distributed across the Adriatic Sea with $0.5^\circ \times 0.5^\circ$ (lat.-long.) spacing, in the period from September 1992 to January 2016. The underlying numerical wave model WAM (Wave Modelling) is run at the ECMWF (European Centre for Medium-Range Weather Forecasts) which acts as a European meteorological institute providing numerical atmospheric and ocean forecasts, archiving data and improving forecasting models. WAM is extensively validated in the literature [21,22]. Satellite altimetry measurements are, in general, validated by in-situ measurements made with wave buoys and are considered an empirical source of data for larger domains but lack in continuity as they are confined by individual satellite tracks and overflight times. WW includes satellite altimetry data from satellite missions taking measurements over the Mediterranean (i.e., the Adriatic): European Remote Sensing Satellites (ERS-1 and ERS-2), Ocean Topography Experiment (TOPEX), Geosat Follow-On, Jason and Environmental Satellite (Envisat).

WW Data Subdivision, Preparation and Preliminary Considerations

A total of 39 locations were available within the WW database for the Adriatic Sea. The locations were analyzed: individually, grouped into regions (southern, central and northern Adriatic, according to DHMZ–Croatian Meteorological and Hydrological Service official subdivision) and joint together for the basin as a whole. Location, their numbering and regional subdivision are presented in Figure 1, and exact geographic coordinates are given in Appendix A Table A1.

Figure 1. Studied locations in the Adriatic Sea as available from the WW database.

At each location, 12 physical wave and wind parameters are available at 6-h intervals (four per day) as presented in Appendix A Table A2 and for each location there are total of 34,460 lines of records.

Maximum recorded significant wave heights, along with accompanying parameters, were extracted and are presented in Appendix A Table A3. The single highest significant wave height in the database is recorded at location 9 (E14.5°–N44.0°) 16.11.2002, reading H_s = 6.72 m during southeast wind (local names *jugo/scirocco*). For comparison, the single highest wave measured until now along the east coast reads H_{max} = 10.87 m off the city of Dubrovnik on 12.11.2019, associated with the significant wave height of H_s = 4.75 m. The highest significant wave height so far is measured from the gas platform in the north Adriatic and reads 7.5 m [23].

Visualization of H_s time series for a one-year period, presented in Figure 2, confirms expected higher variability during winter months.

An example validation of WW data against available in-situ wave buoy measurement data from the Italian RON project [15] is shown for H_s and T_p on locations nearby for one winter month period, in Figures 3 and 4.

The WW and RON locations compared in Figures 3 and 4 are about 26 km apart. The time series shows a good match, especially for significant wave heights. General H_s trends match well and peaks coincide. Variations between extremes in Figure 3 can be accounted to distance between the compared locations (with influence of the coastline and surrounding orography), to physical and numerical limitations and settings of the numerical model and measurement buoy properties. Deviations between wave period Tp records are slightly larger than for H_s. Buoy data for wave periods show local "jumps" which could suggest that the buoy data possibly need additional filtering.

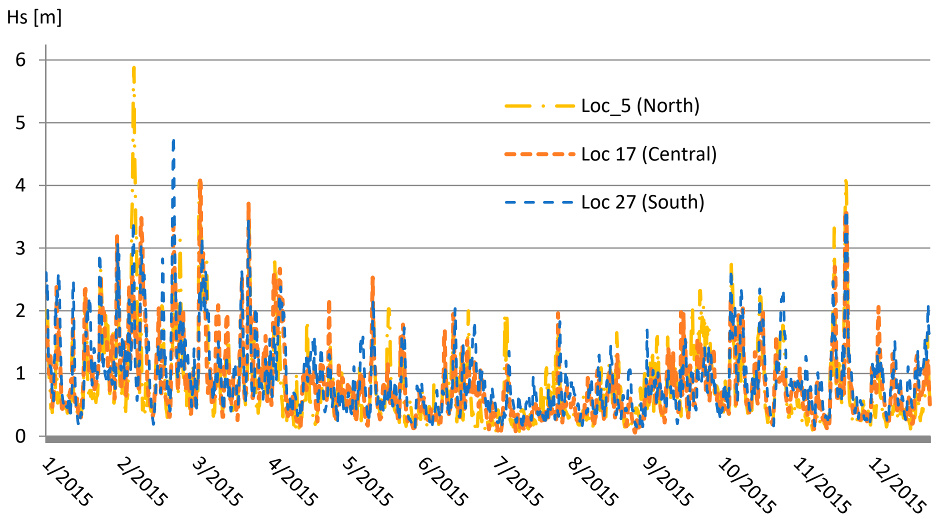


Figure 2. H_s time series during 2015 at three locations, in North, Central and South Adriatic.

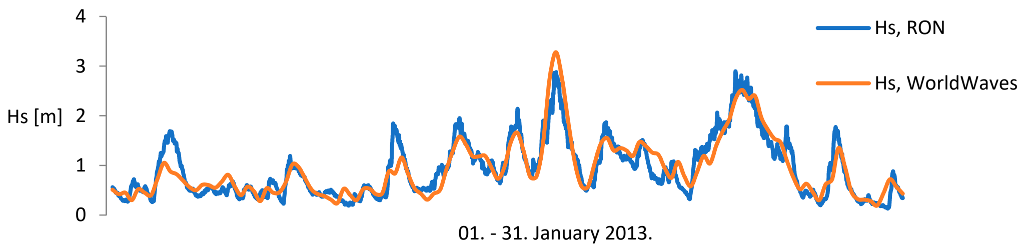


Figure 3. H_s time series from WW database (location 4) and RON buoy "Ancona" (13°43′10″ E–43°49′26″ N).

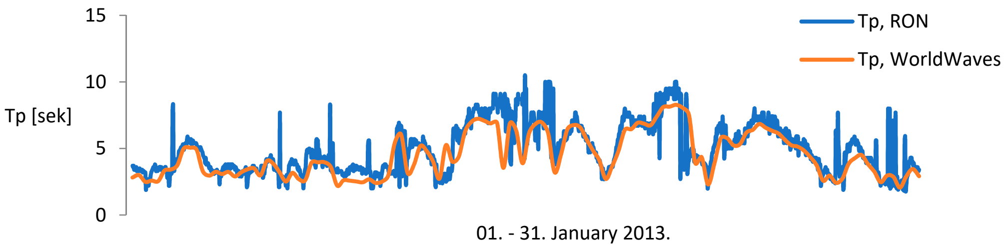


Figure 4. Tp time series from WW database (location 4) and RON buoy "Ancona" (13°43′10″ E–43°49′26″ N).

To prepare the data for analysis, the following frequency of occurrence tables were extracted from the WW database:

1. Sea state tables (H_s–Tp), for the following:
    - The Adriatic Sea with all location merged as presented in Table 1;
    - Adriatic regions as presented in Appendix A (North, Table A4; Central, Table A5; and South, Table A6);
    - Each of the 39 locations individually.
2. Wind speed to significant wave height (u_w–H_s), for the following:
    - The Adriatic Sea with all location merged as presented in Table 2;
    - Adriatic regions (North, Central and South) as presented in Appendix A (North, Table A7; Central, Table A8; and South, Table A9);
    - Each of the 39 locations individually.

Table 1. Sea state table–entire Adriatic Sea basin, period September 1992–January 2016.

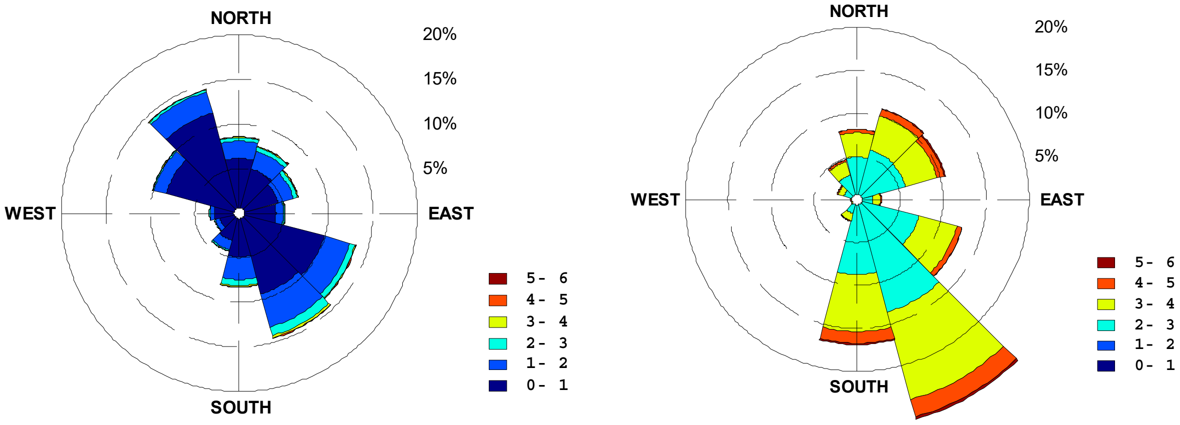
T_p/H_s	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	Sum
0–1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2–3	221,186	65,034	754	7	0	0	0	0	0	0	0	0	0	286,981
3–4	149,331	225,790	32,459	1233	39	1	1	0	0	0	0	0	0	408,854
4–5	36,859	130,876	80,830	19,669	1732	109	7	1	0	0	0	0	0	270,083
5–6	17,747	52,597	54,473	38,089	15,605	3194	469	54	3	0	0	0	0	182,231
6–7	10,379	24,193	20,917	17,297	14,389	8836	3255	731	183	32	5	2	1	100,220
7–8	3704	8591	8993	6373	4838	3810	3141	1879	701	215	54	18	10	42,327
8–9	1863	3459	3515	2727	1930	1361	956	677	470	197	78	13	8	17,254
9–10	1174	1055	1115	819	654	495	336	231	156	92	48	26	3	6204
10–11	376	434	420	294	217	120	98	64	40	22	6	2	1	2094
11–12	363	105	107	81	91	31	26	16	10	9	5	2	1	847
12–13	434	39	23	10	8	10	7	7	2	2	1	1	0	544
13–14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	443,416	512,173	203,606	86,599	39,503	17,967	8296	3660	1565	569	197	64	24	1,317,639

Note. Total of 73% of sea states are less than 1 m.

Table 2. Wind speed—significant wave height occurrence—entire Adriatic, Sept 1992–Jan 2016.

u_w/H_s	0–0.25	0.25–0.5	0.5–0.75	0.75–1	1–1.25	1.25–1.5	1.5–1.75	1.75–2	2–2.25	2.25–2.5	2.5–2.75	2.75–3	3–3.25	3.25–3.5	Sum
0–1	20,070	33,291	10,955	3152	1198	462	187	81	29	26	4	3	1	0	69,459
1–2	32,250	68,242	25,570	7861	2803	1134	453	200	83	23	9	7	2	2	138,639
2–3	27,155	84,153	38,583	12,391	4471	1707	703	313	131	61	23	17	5	3	169,716
3–4	14,064	81,193	52,240	18,013	6548	2608	1067	437	209	86	47	24	7	9	176,552
4–5	5139	54,153	66,294	24,730	9238	3666	1504	614	306	104	70	23	26	8	165,875
5–6	1666	16,761	68,671	35,231	12,912	5099	2161	990	425	209	90	48	16	6	144,285
6–7	393	3321	37,421	45,709	18,845	7541	3211	1419	628	295	132	63	38	17	119,033
7–8	103	964	8754	37,098	26,470	11,372	4919	2082	954	452	232	97	39	26	93,562
8–9	33	310	1519	13,596	25,426	16,301	7712	3415	1534	731	317	160	57	30	71,141
9–10	11	77	416	2830	12,104	16,639	10,722	5572	2490	1196	502	235	96	75	52,965
10–11	6	23	129	625	3206	8879	10,611	7563	3966	1962	815	426	175	112	38,498
11–12	4	16	44	168	770	2781	5704	6793	5306	3051	1556	700	328	155	27,376
12–13	0	10	33	51	161	779	1995	3477	4147	3606	2245	1206	585	249	18,544
13–14	0	6	9	31	66	207	585	1191	2063	2588	2283	1684	975	545	12,233
14–15	0	2	8	15	28	88	192	397	709	1194	1425	1365	1087	698	7208
15–16	0	0	4	9	11	32	69	141	243	398	604	724	823	709	3767
Sum	100,894	342,522	310,650	201,510	124,257	79,295	51,795	34,685	23,223	15,982	10,354	6782	4260	2644	13,088

Additionally, the well-known directionality of higher wave height associated with S-SE winds (*jugo/scirocco*) and NE winds (*bura/bora*), as the Adriatic basin specificities due to the surrounding orography, is confirmed by wave roses. Wave roses for the Adriatic as a whole are presented in Figure 5.



(**a**) (**b**)

Figure 5. Wave roses for the entire Adriatic basin: (**a**) all sea states and (**b**) sea states with $H_s > 2.5$ m.

There is a noticeable amount of smaller N–NW waves accounted to the same direction (*maestral/maestrale)* wind—a typical daily coastal circulation, caused by temperature oscillation between land and sea during summer months, which is important to the leisure nautical sector due to its predictability and mild character. Regional wave roses are available in Appendix A Figures A1 and A2 and suggest higher dominance of S–SE waves in South and Central Adriatic and NE high wave dominance in the North Adriatic region.

3. Methods

The WW data were analyzed in accordance with Det Norske Veritas (DNV) classification society recommendations for determining environmental conditions and loads on marine structures [2]. A joint distribution is applied, consisting of a marginal three-parameter Weibull distribution of significant wave heights and a conditional log-normal distribution for peak periods. For wind speeds, a conditional distribution is given as function of significant wave height and described by a two-parameter Weibull distribution.

3.1. Joint Distribution of Significant Wave Height and Peak Periods

Based on sea state tables, both regional and per individual location, a joint probability distribution model was derived with the aim to optimize the parameters that will later be used to determine extreme sea states for return periods longer than the database span and to provide a consistent approach for determination of loads for fatigue and strength analyses of ships and offshore structures.

CMA approach (Conditional Modelling Approach) is applied for modelling the joint distribution of significant wave height and peak (spectral) period. In general, this method defines the probability density function (PDF) by a marginal distribution and a set of conditional probability densities, each of which is modelled by a parametric function whose parameters are optimized by mathematical fitting techniques to represent data from the WW database in the best possible way. The CMA approach of fitting joint distribution to the wave data was first proposed by Bitner-Gregersen and Haver [24] and discussed in detail in Reference [25]. It is currently an integral part of standardized engineering procedures (e.g., Reference [2]) and scientific practice (e.g., Reference [26]).

3.1.1. Marginal Distribution of Significant Wave Height

The proposed CMA model uses the three-parameter Weibull distribution to describe a PDF of significant wave height H_s as first proposed in Reference [27].

$$f_{H_S}(\hat{H}_s) = \frac{\beta_{H_s}}{\alpha_{H_s}}\left(\frac{\hat{H}_s-\gamma_{H_s}}{\alpha_{H_s}}\right)^{\beta_{H_s}-1} exp\left\{-\left(\frac{\hat{H}_s-\gamma_{H_s}}{\alpha_{H_s}}\right)^{\beta_{H_s}}\right\} \quad (1)$$

where α_{Hs} is the scaling parameter, β_{Hs} is the shape parameter and γ_{Hs} is the location parameter. The parameters are optimized on linearized scale with the least square method (LSM).

The cumulative 3-parameter Weibull probability density function (CDF) then follows:

$$F(H_S) = P(\hat{H}_s < H_S) = 1 - exp\left[-\frac{(\hat{H}_s-\gamma_{H_s})}{\alpha_{H_s}}\right]^{\beta_{H_s}}, \qquad H_S,\ \hat{H}_s \geq \gamma_{H_s} \quad (2)$$

where $P(\hat{H}_s < H_S)$ represents the probability that a certain random significant wave height $\hat{H}_s$ will take on a value less than H_S. Probability of exceedance is than given as

$$Q(\hat{H}_s) = 1 - P(\hat{H}_s) \quad (3)$$

When a large number of observations are available, as in the WW database, a common approach is to sort the data into $H_{s,i}$ bins, as presented in the sea-state tables, e.g., Table 1. The empirical probability of exceeding of each bin is then determined by the usual expression [13]:

$$Q(H_{s,i}) = \frac{\sum_{j=1}^{i} f_j}{N+1} \quad (4)$$

where $\sum\limits_{\mathrm{j=1}}^{\mathrm{i}} f_j$ represents the cumulative frequency of all values equal to or greater than $H_{s,i}$, while N is the total number of observations (the sum of all observations as shown in the sea state tables).

The theoretical probability $P(\hat{H}_{s,i})$ that $H_{s,i}$ will not be exceeded can be determined according to Equation (2). To fit the theoretical distribution to the empirical points, calculated from the database, the distribution parameters α_{Hs} and β_{Hs} were optimized using the least squares method on a linearized double-log scale.

$$ln(-ln\left(F\left((\hat{H}_s\right)\right) = \beta_{H_s} * ln\left((\hat{H}_s - \gamma_{H_s}\right) - \alpha_{H_s} * ln(\beta_{H_s}) \quad (5)$$

Shape and scale parameters are determined from the linearized model coefficients (y_1–slope and y_0–ordinate intersection) according to the following:

$$\alpha_{H_s} = y_1 \quad (6)$$

$$\beta_{H_s} = e^{-\frac{y_0}{y_1}} \quad (7)$$

The choice of the third parameter—the proper threshold parameter γ_{Hs}—whilst permitting some data points to lay below is an anomaly that is sometimes dealt with by discarding (censoring) smallest empirical CDF data points prior to fitting the theoretical CDF. For example, suggestions given in Reference [5], in order to formalize such an approach, recommended discarding the data points corresponding to the probability level F = 0.2 and below, but simultaneously argued that such criterion does not work equally well on all datasets.

The threshold parameter γ_{Hs} in this paper is chosen without discarding any data and in accordance with the procedure given in Reference [28]. The procedure concept is to test different values of γ_{Hs} which then obviously affects the quality of the fit. Since the expected relationship in Equation (5) is expected to be linear the assumption is that the optimal threshold parameter γ_{Hs} will provide the best possible approximation to a linear model. This argument is formalized by applying an optimization algorithm to maximize the coefficient of determination R^2, as a statistical measure of accuracy, of a linear regression on the transformed variables $ln\left(\left(\hat{H}_s - \gamma_{H_s}\right)\right.$ and $ln\left(-ln\left(\mathrm{F}\left(\left(\hat{H}_s\right)\right)\right.\right.$ across all possible threshold values.

It was also noticed that the choice of the bin size used to calculate the empirical probability of exceedance in Equation (4) has a significant influence on the theoretical model because it determines the resolution of the empirical CDF data points on which the theoretical model is fitted. A too-coarse resolution loses precision and increases error, while too fine resolution results in sporadic empty bins in the upper Hs range thus creating false points of the empirical cumulative density function that would influence the results and respective evaluated extremes. After initial testing of model behavior on the analyzed dataset, the bin size was determined by defining 30 equally spaced bins between the minimum and the maximum recorded value on each location separately.

3.1.2. Conditional Distribution of Peak Periods Depending on Significant Wave Height

The conditional distribution of peak period T_p based on H_s is modelled by the log-normal PDF, as first proposed by Bitner-Gregersen and Haver in Reference [24] (see also Reference [29]):

$$f_{T_P|H_S}\left(\hat{T}_p|\hat{H}_s\right) = \frac{1}{\sigma\,\hat{T}_p\,\sqrt{2\,\pi}} exp\left\{-\frac{\left(ln\hat{T}_p - \mu\right)^2}{2\sigma^2}\right\} \tag{8}$$

where the distribution parameters μ is the mean logarithmic value of the variable $\mu = E\left[lnT_p\right]$, and σ is the standard deviation of the variable logarithmic value $\sigma = \mathrm{std}\left[lnT_p\right]$ [16]. Both parameters are, easy to calculate statistical quantities, dependent on H_s. Since H_s is divided into bins, according to Table 1, the change of σ and μ calculated for each bin is modelled as follows:

$$\mu = a_0 lnH_s + a_1 \tag{9}$$

$$\sigma = a_2 * lnH_s + a_3 \tag{10}$$

Coefficients a_0, a_1, a_2 and a_3 are calculated for each location individually, regionally and for the entire Adriatic Sea.

3.2. Joint Distribution of Significant Wave Height and Wind Speed

Like joint distribution of significant wave height and peak period, a statistical model for joint distribution of significant wave height and wind speed is developed. The wind speed u_w is defined as a variable dependent on the significant wave height, H_s. Although physically inversing the cause and consequence, such description, together with results from Section 3.1, presents a complete metocean description dependent on a single variable, i.e., H_s. Wind speed and direction data are an integral part of the underlying WW database and refer to the data used by ECMWF to force WAM model. Wind speeds are given at 10 m above sea level with an assumed duration of 6 h (as for the corresponding sea state).

The conditional distribution of the wind speed as a function of the significant wave height can be described by the two-parameter Weibull distribution as proposed by Bitner-Gregersen and Haver [24] and included in DNV RP C-205 [2]:

$$f_{U|H_S}(u_w|H_s) = k\frac{{u_w}^{k-1}}{U_c^k} exp\left[-\left(\frac{u_w}{U_c}\right)^k\right] \tag{11}$$

where the scale parameter U_c and the shape parameter k are estimated from the available data, using the following model:

$$k = c_1 + c_2 H_s^{c3} \;\; U_c = c_4 + c_5 H_s^{c6} \tag{12}$$

3.3. Extremes Values of Significant Wave Height for Long Return Periods

Extreme H_s values, for return periods (RP) longer than the scope of the WW database, can been evaluated based on using the three-parameter Weibull distribution fit described in Section 3.1.1. The fitted distribution upper tail is extrapolated to theoretical probability of exceedance $Q(H_s{}^{RP})$ of a certain H_s value and return period RP. Probability of exceedance $Q(H_s{}^{RP})$ is generally determined as follows:

$$Q\left(H_s^{RP}\right) = \frac{T_{REG}}{N} * \frac{1}{RP} \tag{13}$$

where T_{REG} is the duration of uninterrupted observations within the database (23.5 year), and N is the total number of data records. Once the 3-parameter Weibull CDF (as given in Equation (2)) is fitted to data, the significant wave height that will be exceeded once for certain return period can be determined as its inverse:

$$H_s^{RP} = \alpha_{Hs} * \left(-ln\left(Q\left(H_s^{RP}\right)\right)\right)^{1/\beta_{Hs}} + \gamma_{Hs} \tag{14}$$

4. Results

Within this section, models parameters, as described in Section 3, fitted to data are presented graphically for brevity and the same tabulated data are presented in Appendix B.

4.1. Parameters of the Joint Distribution of Significant Wave Height and Peak Wave Periods

The three-parameter Weibull distribution parameters were fitted for each of the 39 location, for data merged according to the regional subdivision and for the all location merged, i.e., the entire Adriatic Sea. An example fitting on a linearized scale, as per Equation (5), is presented in Figure 6 for location 9, where the maximum H_s was recorded within the database.

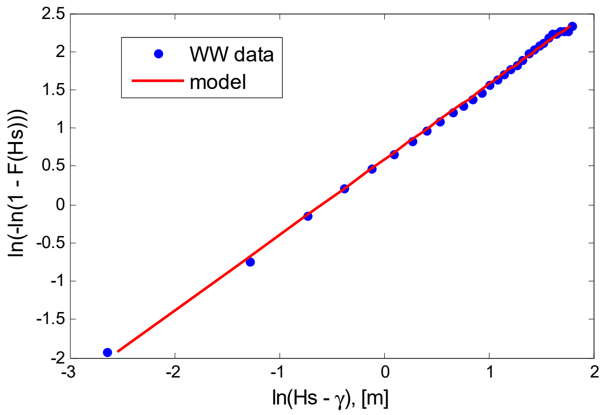


Figure 6. Parameter Weibull parameter fit for marginal distribution of *Hs.* (E 14.5–N 44.0).

The fit presented in Figure 6 shows an example validation of the model. All 39 location fits were visually inspected, and the calculated coefficient of determination, R^2, ranging between $R^2{}_{min}$ = 0.9971 and $R^2{}_{max}$ = 0.9996, confirms that the model is appropriate. Likewise, an example fit is presented in Figure 7 of the log-normal distribution fit for a conditional distribution of peak periods dependent on significant wave height.

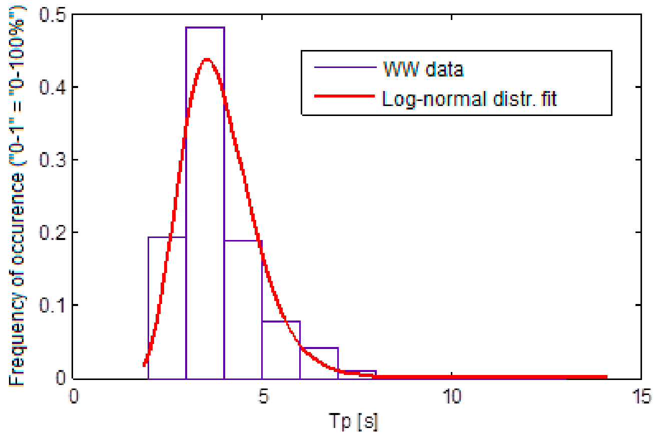


Figure 7. Log-normal conditional distribution fit of *Tp* on *Hs*, e.g., H_s = 0.5–1.0 m; E 14.5–N 44.0.

The sea state, H_s and T_p description are completed by determining the mean and the standard deviation values that define the log-normal distribution for the entire bin range of H_s, as presented in Figure 8.

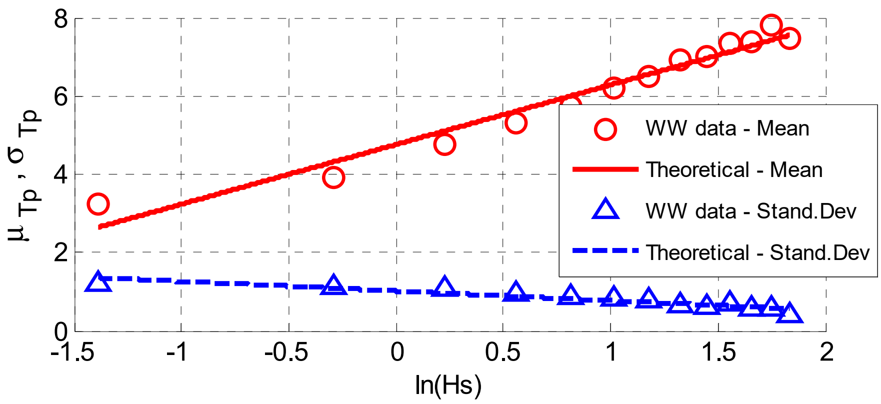


Figure 8. Mean and standard deviation for calculation of *Tp* distribution across *Hs* bin range; E 14.5–N 44.0.

The model parameters for the joint distribution of significant wave height and peak period are finally presented in Table 3 for regions, and Figures 9 and 10 for individual locations.

Table 3. Model parameters for joint distribution of *Hs* and *Tp*. Adriatic regional subdivision.

Region	α_{Hs}	β_{Hs}	γ_{Hs}	a_0	a_1	a_2	a_3
Adriatic Sea	0.553	0.987	0.071	1.7862	5.1201	−0.2003	1.0634
North Adriatic	0.527	0.955	0.076	1.6161	4.8126	−0.2876	1.0508
Central Adriatic	0.659	1.091	0.068	1.8676	5.0563	−0.1995	0.9285
South Adriatic	0.762	1.166	0.091	1.9353	5.2776	−0.1492	1.0775

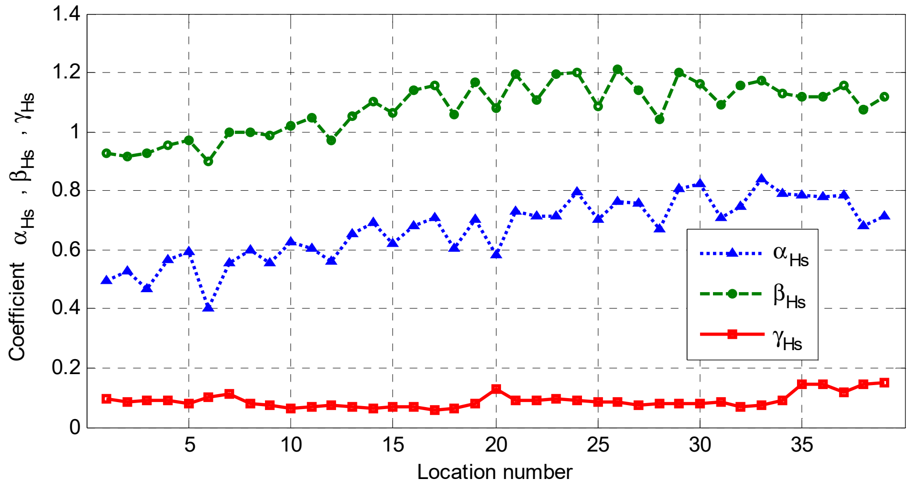


Figure 9. Model parameters for marginal distribution of significant wave height per location.

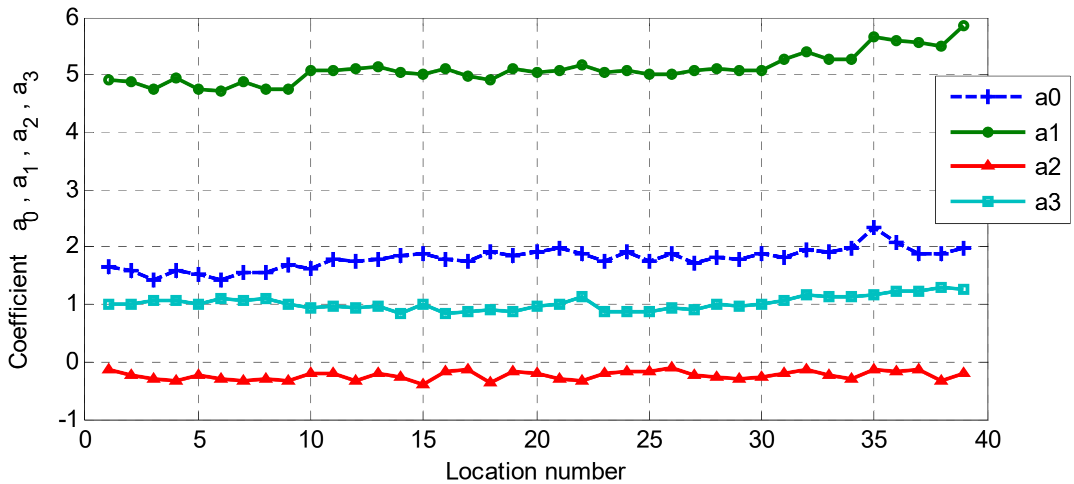


Figure 10. Model parameters for mean and standard deviation across *Hs* bin range to model log-normal distribution of peak period *Tp*-per location.

For precision, and to enable repeatability and practical usage, numerical parameters for individual locations are given in Appendix B Table A10.

4.2. Parameters of the Joint Distribution of Wind Speed and Significant Wave Height

For H_s bins, the theoretical distribution of wind speeds proposed by the model in Equation (11) is derived. The model parameters k and U_c are optimized using the nonlinear least squares method. An example fit of the two-parameter Weibull distribution of wind speed for bin H_s = 2.25–2.5 m for the entire Adriatic is shown in Figure 11.

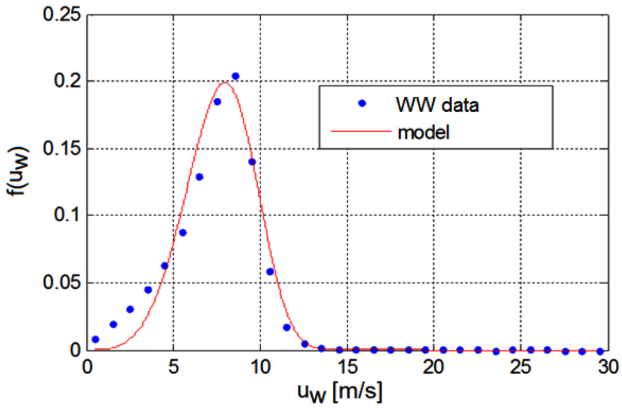


Figure 11. Fitting the model to WW data; entire Adriatic; *Hs,i* = 2.25–2.5 m.

By repeating the same procedure for each $H_{s,i}$ bin, a model of fit parameters k and U_c is obtained. Their results for the entire Adriatic are presented in Figure 12 as a function of H_s.

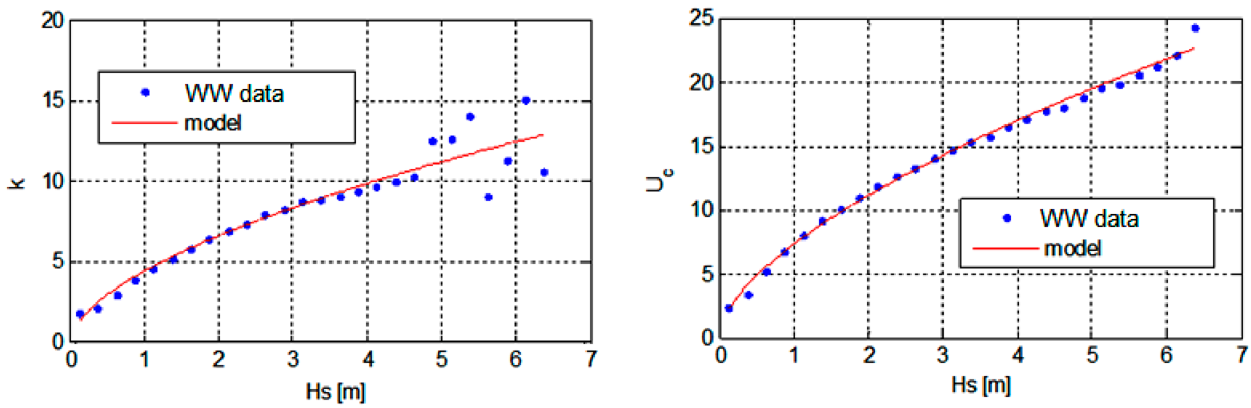


Figure 12. Distribution of *k* and *Uc* for Adriatic as a whole.

A data scattering of WW data points for the shape parameter *k* can be seen for higher *Hs* values. This feature is even more pronounced having a more detailed look for certain locations and is due to small amount of data at high *Hs*. Poor agreement of the statistical model at higher values also has a negative effect on poorer agreement of the model with data at lower values. It was found that more than 99.5% of the recorded data are usually below significant wave height of 3.25–3.75 m. In order to achieve a better agreement data corresponding to the highest 0.5% *Hs* were discarded, both for individual locations analysis and grouped data, having in mind that such filtering makes the model acceptable for fatigue or seakeeping considerations of offshore structures but not for the extreme value analysis.

The model parameters for the joint distribution of wind speed and significant wave height are finally presented in Table 4 for regions, and Figures 13 and 14 for individual locations.

Table 4. Model parameters for joint distribution of *Hs* and *u_w*. Adriatic regional subdivision.

Region	c_1	c_2	c_3	c_4	c_5	c_6
Adriatic Sea	1.6533	2.2548	1.1557	−0.3633	7.7434	0.5817
North Adriatic	1.6910	1.8402	1.2730	−0.0925	7.4936	0.6245
Central Adriatic	1.4848	2.5383	1.0783	−0.2775	7.7063	0.5978
South Adriatic	1.5796	2.5238	1.0601	−0.2048	7.5145	0.5886

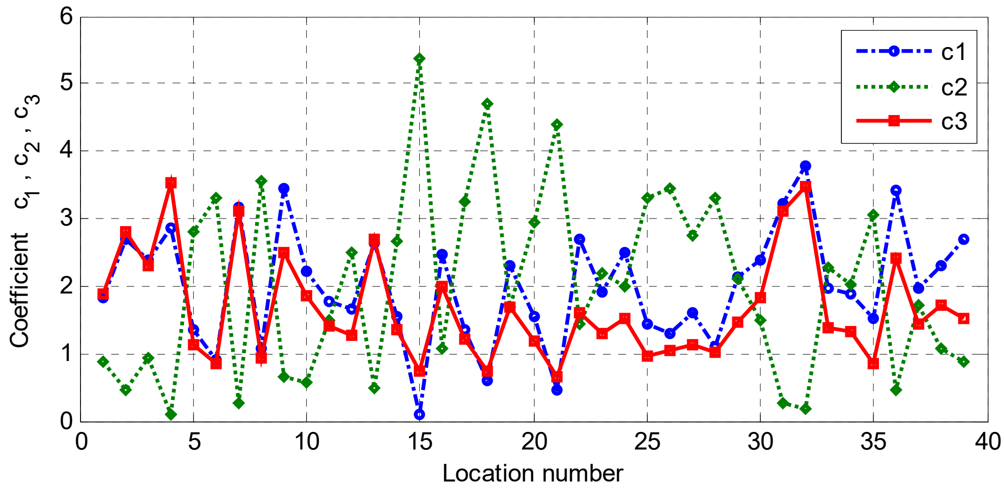


Figure 13. Model parameters c_1–c_3 for description of the joint distribution of u_w and Hs per location.

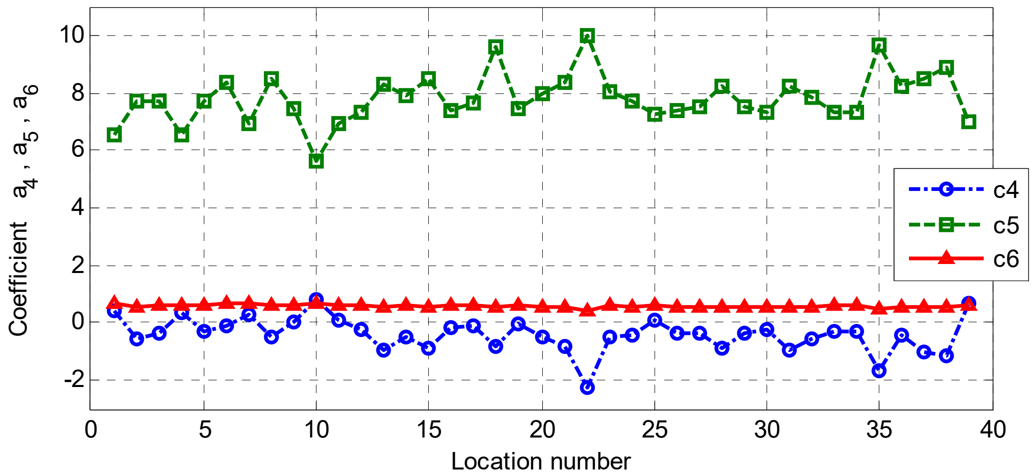


Figure 14. Model parameters c_4–c_6 for description of the joint distribution of u_w and Hs per location.

For precision, and to enable repeatability and practical use, parameters for individual locations are given in Appendix B-Table A11.

4.3. Extreme Wave Heights for Different Return Periods

Once the three-parameter Weibull distribution parameters were evaluated (Table 3), determining a theoretical significant wave height probability of occurrence, an extreme Hs value prediction was possible for return periods longer than the initial database by extrapolating the distribution "upper tail" to an appropriate probability of occurrence (Equations (13) and (14)). Most probable extreme significant wave heights for 20-, 50- and 100-year return periods, according to regional subdivision, are presented in Table 5.

Table 5. Most probable extreme significant wave height for 20-, 50- and 100-year return periods.

Region	RP = 20 Year	RP = 50 Year	RP = 100 Year
Adriatic Sea	5.94	6.47	6.87
North Adriatic	6.12	6.69	7.12
Central Adriatic	5.64	6.10	6.44
South Adriatic	5.72	6.14	6.46

The difference between *Hs,max_recorded*, the recorded maximum within the WW database and *Hs,max_calculated*, the most probable theoretical extreme for the exact same return period as the database, per location, is presented in Figure 15.

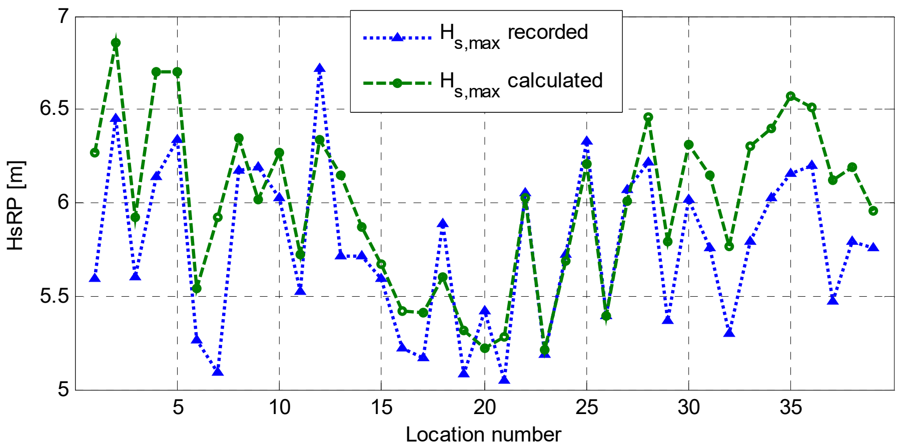


Figure 15. *Hs* comparison, per location, of most probable theoretical extreme and recorded maximum within WW database (duration 23.5 year).

The average difference between *Hs,max_recorded* and *Hs,max_calculated* is 4.1% in average across all locations with a standard deviation of 4.7%, i.e., *Hs,max_calculated* overestimates *Hs,max_recorded* by 0.23 m in average with a standard deviation of 0.27 m.

For precision, and to enable repeatability and practical use, parameters for individual locations are given in Appendix B-Table A12.

5. Discussion

The results presented in Section 4 provide parameters for a systematic theoretical model of wind and wave statistics for the Adriatic Sea. The distributions are fitted to the data from the WorldWaves database for the period 1992–2016. As such, the results are limited with precision and accuracy of the underlying database. Each data-acquisition technique or modelling approach has limitations but the used dataset currently represent the state-of-the-art by combining a third-generation numerical model hindcast, that provides the systematic character in space and time, with the available satellite altimetry measurements. If a specific random location would be of interest between the analyzed location, four-point interpolation can be used. As for the near-shore region, winds and consequent waves in the Adriatic are highly locally influenced by surrounding land topography, i.e., mountains and islands; thus, results should be extrapolated in those regions with care or used only as boundary conditions for site specific studies.

The applied three-parameter Weibull and log-normal distributions, used for the CMA approach for joint distribution of significant wave height and peak period, showed excellent agreement with the data (e.g., Figures 6 and 7). The upper tail of the fit, essential for extremes evaluation, is always sensitive to fewer data records of high sea states. It thus caries a greater uncertainty also subject to distribution model choice/data preparation and parameter-fitting technique [17,30]. The applied method however remains a common choice and recommendation by classification societies guidelines [2]. The shape and scale parameters in Figure 9 of the three-parameter Weibull distribution show a slight increasing linear trend going towards higher location numbers, i.e., towards the south of the Adriatic. The coefficients for T_p distribution modelling across the H_s range, shown in Figure 10, show almost constant values and could be used as such. On the other hand, the adequacy of the chosen linear model for the mean value parameters across the H_s range, as given in Equations (9) and (10) and presented in Figure 8, exhibits a slight non-linear trend and considering a higher order model could be beneficial.

As for the wind speed to significant wave height fit it should be noted that the highest 0.5% of data were filtered out due to high scatter (Figure 12) to improve fit quality but this makes the model less appropriate for possible upper tail extremes extrapolation. The shape scale parameter U_c shows greater fit confidence than the shape parameter k across the H_s range (Figure 12).

In general, the best accuracy is always expected by applying location or region-specific parameters without generalization as their fit parameters were optimized simultaneously.

Extremes evaluation as presented in Figure 16, noting the location regional subdivision (North, 1–9; Central, 10–22; South, 23–39), show that highest extremes can be expected in North and South Adriatic and smaller in the Central Adriatic with several locations (20, 21, 22) in its southeast that are closest to South Adriatic and exposed to SE wind (*jugo/scirocco*) show high extremes as well. The highest recorded significant wave height within the WW database reads 6.72 m (location 9) and the comparable, theoretical, most probable 20-year calculated on merged data for the entire Adriatic reads 5.94 m, thus being un-conservative and highlighting issues of generalization.

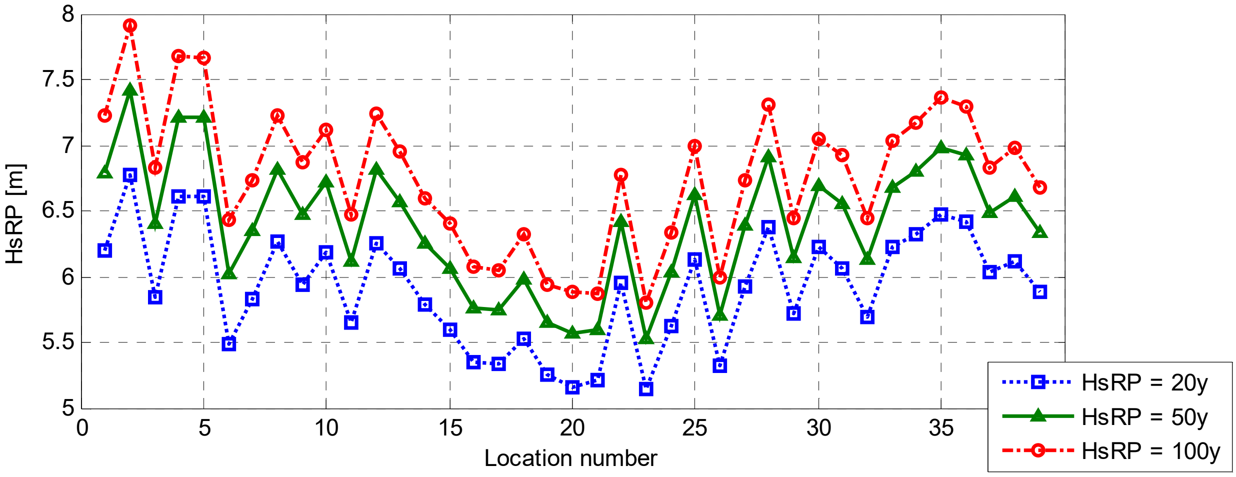


Figure 16. Most probable extreme significant wave height for RP = 20, 50 and 100 y per location.

6. Conclusions

The paper analyzed the wind and wave WorldWaves database (1992–2016), which is an assimilation of numerical hindcast and satellite altimetry wave measurements for a specific wind–wave climate region in the Adriatic Sea. The Adriatic Sea is seeing increasing commercial activity and is a fragile ecological system due to its relatively small area and being a semi-enclosed basin deserving thus an in-detail look. Based on the WW database the models were developed: joint distribution of significant wave height and peak period; extreme significant wave height for long return periods; joint distribution of wind speed and wave height. The model parameters and the extremes are presented for each of the 39 uniformly spaced locations (0.5° × 0.5° lat./long.) across the offshore Adriatic, divided in three regions (North, Central and South Adriatic) and for the entire Adriatic Sea as a whole (all location data merged together). The model parameters, as well as the extremes, can be found presented in paper main body, for the three regions and the Adriatic as a whole, either as tabulated numerical values or graphically. Locations specific results are, for brevity, only graphically presented in paper main body and the numerical tabulated data are provided in the Appendix.

The presented models (Section 3) and optimized model parameters (Section 4/Appendix) provide a complete description of main wind and wave value statistics. Such data can be useful for the design, risk-based operation planning, lifetime extension and maintenance of new and existing seagoing vessels and offshore installations in the Adriatic Sea.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available within the article, mainly in Appendix A & Appendix B. Restrictions apply to the availability of the underlying WorldWaves database that is the property of Fugro OCEANOR [www.fugro.com; www.oceanor.info, accessed on 5 May 2021].

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Location numbering and coordinates with regional subdivision.

North Adriatic			Central Adriatic			South Adriatic		
Nb.	**Latitude**	**Longitude**	**Nb.**	**Latitude**	**Longitude**	**Nb.**	**Latitude**	**Longitude**
1	44.5° N	12.5° E	10	43.5° N	14.0° E	23	41.5° N	16.5° E
2	44.5° N	13.0° E	11	43.0° N	14.5° E	24	42.0° N	16.5° E
3	45.0° N	13.0° E	12	43.5° N	14.5° E	25	41.5° N	17.0° E
4	44.0° N	13.5° E	13	42.5° N	15.0° E	26	42.0° N	17.0° E
5	44.5° N	13.5° E	14	43.0° N	15.0° E	27	41.5° N	17.5° E
6	45.0° N	13.5° E	15	43.5° N	15.0° E	28	42.0° N	17.5° E
7	44.0° N	14.0° E	16	42.5° N	15.5° E	29	41.0° N	18.0° E
8	44.5° N	14.0° E	17	43.0° N	15.5° E	30	41.5° N	18.0° E
9	44.0° N	14.5° E	18	43.5° N	15.5° E	31	42.0° N	18.0° E
-	-	-	19	42.5° N	16.0° E	32	40.5° N	18.5° E
-	-	-	20	42.5° N	16.5° E	33	41.0° N	18.5° E
-	-	-	21	42.5° N	17.0° E	34	41.5° N	18.5° E
-	-	-	22	42.5° N	17.5° E	35	40.0° N	19.0° E
-	-	-	-	-	-	36	40.5° N	19.0° E
-	-	-	-	-	-	37	41.0° N	19.0° E
-	-	-	-	-	-	38	41.5° N	19.0° E
-	-	-	-	-	-	39	40.0° N	19.5° E

Table A2. Wind and wave parameters available for each location in in the WW database.

Symbol	Name	Unit
H_s	Significant wave height	m
θ_{mean}	Mean wave direction	°
T_p	Peak period of the 1D spectrum	s
T_m	Mean wave period [1]	s
$H_{s,ww}$	Significant wind–wave height	m
θ_{ww}	Mean wind direction. waves	°
$T_{m,ww}$	Mean period wind–waves	s
$H_{s,sw}$	Significant wave height of swell	m
θ_{sw}	Mean wave direction of sea	°
$T_{m,sw}$	Mean period of swell	s
u_w	Wind speed at 10 m	m/s
θ_w	Wind direction at 10 m	°

[1] T_m represents the energy period defined by spectral moments, $T_m = m_1/m_0$.

Table A3. Maximum recoded wave heights, *Hs*, per location with accompanying parameters. Maximum marked in red.

Latitude/Longitude	Year	mm	dd	hh	H_s (m)	θ_{mean} (°)	T_p (s)	T_m (s)	U_w (m/s)	θ_w (°)
E12.5_N44.5	2015	2	6	6	5.59	75	9.22	8.35	24.07	55
E13.0_N44.5	1993	1	2	18	6.45	58	8.48	7.40	19.96	55
E13.0_N45.0	1993	1	2	18	5.60	59	7.71	6.64	20.26	54
E13.5_N44.0	1992	12	28	12	6.14	48	7.71	6.85	24.80	53
E13.5_N44.5	1993	1	2	18	6.34	56	7.71	6.97	22.77	55
E13.5_N45.0	1993	1	2	18	5.26	58	7.01	5.97	23.66	54
E14.0_N43.5	2002	11	16	12	5.09	132	8.39	7.07	14.21	141
E14.0_N44.0	2002	11	16	12	6.17	138	8.39	7.16	20.15	144
E14.0_N44.5	2002	11	16	12	6.19	145	7.63	7.00	20.69	148
E14.5_N43.0	2015	3	5	12	6.03	30	8.86	7.92	19.56	34
E14.5_N43.5	2004	11	14	12	5.52	39	8.39	7.98	19.73	40
E14.5_N44.0	2002	11	16	12	6.72	142	8.39	7.15	22.22	146
E15.0_N42.5	2003	12	23	12	5.71	22	8.12	7.40	20.94	22
E15.0_N43.0	2004	11	14	12	5.71	39	9.13	8.19	20.34	50
E15.0_N43.5	2008	12	11	18	5.59	138	9.23	8.35	18.85	150
E15.5_N42.5	2015	3	5	18	5.22	68	8.57	7.65	18.36	68
E15.5_N43.0	2008	12	11	18	5.17	138	9.20	8.12	20.15	148
E15.5_N43.5	2008	12	11	18	5.89	142	9.27	8.17	23.42	138
E16.0_N42.5	1992	12	8	18	5.08	131	8.48	7.55	17.87	149
E16.5_N41.5	1994	1	29	18	5.42	0	8.48	7.56	19.18	3
E16.5_N42.0	2008	12	11	12	5.05	130	9.02	8.00	17.82	143
E16.5_N42.5	1992	12	8	18	6.05	136	8.48	7.67	21.89	145
E17.0_N41.5	1994	1	29	18	5.19	355	8.48	7.66	18.24	6
E17.0_N42.0	1992	12	8	18	5.72	139	7.71	7.39	20.69	149
E17.0_N42.5	1992	12	8	18	6.33	142	8.48	7.65	22.75	143
E17.5_N41.5	1992	10	4	6	5.39	144	7.71	7.27	20.44	148
E17.5_N42.0	1992	12	8	18	6.07	147	7.71	7.39	22.38	146
E17.5_N42.5	1992	12	8	18	6.22	149	8.48	7.49	22.90	143
E18.0_N41.0	2012	1	6	18	5.37	344	8.45	7.58	19.21	354
E18.0_N41.5	2009	3	5	6	6.02	149	9.08	8.05	20.03	152
E18.0_N42.0	1992	10	4	6	5.76	150	7.71	7.41	23.16	138
E18.5_N40.5	2004	3	8	6	5.30	157	9.23	8.03	15.06	154
E18.5_N41.0	2008	12	17	18	5.79	159	9.23	8.19	20.47	158
E18.5_N41.5	2008	11	29	0	6.03	162	9.15	8.04	22.97	153
E19.0_N40.0	2009	1	14	6	6.16	162	11.92	10.15	17.71	138
E19.0_N40.5	2008	12	4	12	6.20	171	10.07	8.79	19.97	167
E19.0_N41.0	2015	1	30	18	5.47	193	9.04	7.73	20.15	196
E19.0_N41.5	2000	12	27	18	5.79	184	9.09	7.90	22.14	179
E19.5_N40.0	2015	1	30	18	5.76	217	9.29	7.93	19.58	201

Sea state tables:

Table A4. Sea table for North Adriatic region (locations 1–9).

T_p/H_s	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	Sum
0–1	0	0	0	0	0	0	0	0	0	0	0	0	0	
1–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2–3	75,917	20,382	471	7	0	0	0	0	0	0	0	0	0	96,777
3–4	32,032	47,456	9372	776	32	1	1	0	0	0	0	0	0	89,670
4–5	9729	21,114	13,783	4780	992	88	7	1	0	0	0	0	0	50,494
5–6	6070	9268	7909	5909	3208	1203	353	46	3	0	0	0	0	33,969
6–7	3669	5239	3408	2151	1763	1265	716	304	124	22	4	2	1	18,668
7–8	1329	1363	1374	945	576	389	296	234	160	68	31	12	9	6786
8–9	744	523	313	199	127	106	79	43	31	17	8	6	2	2198
9–10	658	117	72	32	18	20	11	4	3	3	0	1	1	940
10–11	81	29	6	2	2	0	0	0	0	0	0	0	0	120
11–12	72	11	6	1	0	0	0	0	0	0	0	0	0	90
12–13	37	7	1	1	0	0	0	0	0	0	0	0	0	46
13–14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	130,338	105,509	36,715	14,803	6718	3072	1463	632	321	110	43	21	13	299,758

Note: 79% of waves are less than 1 m; H_{max} = 6.72 m on 16.11.2002, location 14.5° E–44.0° N, wind SE.

Table A5. Sea table for Central Adriatic region (locations 10–22).

T_p/H_s	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	Sum
0–1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2–3	79,272	19,536	133	0	0	0	0	0	0	0	0	0	0	98,941
3–4	55,629	79,120	9121	218	4	0	0	0	0	0	0	0	0	144,092
4 -5	10,939	45,343	27,579	6231	307	12	0	0	0	0	0	0	0	90,411
5–6	4666	16,530	18,555	13,290	5146	897	54	3	0	0	0	0	0	59,141
6–7	2417	6113	6372	5555	4628	2937	1014	170	21	6	1	0	0	29,234
7–8	1015	1705	2128	1767	1442	1228	1024	655	236	71	11	2	0	11,284
8–9	590	690	673	554	492	313	245	173	124	49	21	4	6	3934
9–10	305	219	187	120	105	81	52	40	27	24	10	9	0	1179
10–11	147	92	66	26	13	6	2	1	0	0	0	0	0	353
11–12	197	35	17	12	1	0	1	0	0	0	0	0	0	263
12–13	350	15	7	2	1	0	0	0	0	0	0	0	0	375
13–14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	155,527	169,398	64,838	27,775	12,139	5474	2392	1042	408	150	43	15	6	439,207

Note: 74% of waves are less than 1 m; H_{max} = 6.33 m on 08.12.1992, location 17.0° E–42.5° N, wind SE.

Table A6. Sea table for South Adriatic region (locations 22–39).

T_p/H_s	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–2.5	2.5–3.0	3.0–3.5	3.5–4.0	4.0–4.5	4.5–5.0	5.0–5.5	5.5–6.0	6.0–6.5	Sum
0–1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1–2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2–3	65,997	25,116	150	0	0	0	0	0	0	0	0	0	0	91,263
3–4	61,670	99,214	13,966	239	3	0	0	0	0	0	0	0	0	175,092
4 -5	16,191	64,419	39,468	8658	433	9	0	0	0	0	0	0	0	129,178
5–6	7011	26,799	28,009	18,890	7251	1094	62	5	0	0	0	0	0	89,121
6–7	4293	12,841	11,137	9591	7998	4634	1525	257	38	4	0	0	0	52,318
7–8	1360	5523	5491	3661	2820	2193	1821	990	305	76	12	4	1	24,257
8–9	529	2246	2529	1974	1311	942	632	461	315	131	49	3	0	11,122
9–10	211	719	856	667	531	394	273	187	126	65	38	16	2	4085
10–11	148	313	348	266	202	114	96	63	40	22	6	2	1	1621
11–12	94	59	84	68	90	31	25	16	10	9	5	2	1	494
12–13	47	17	15	7	7	10	7	7	2	2	1	1	0	123
13–14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	157,551	237,266	102,053	44,021	20,646	9421	4441	1986	836	309	111	28	5	578,674

Note: 68% of waves are less than 1 m; H_{max} = 6.20 m on 04.12.2008, location 19.0° E–40.5° N, wind SE.

Wave roses:

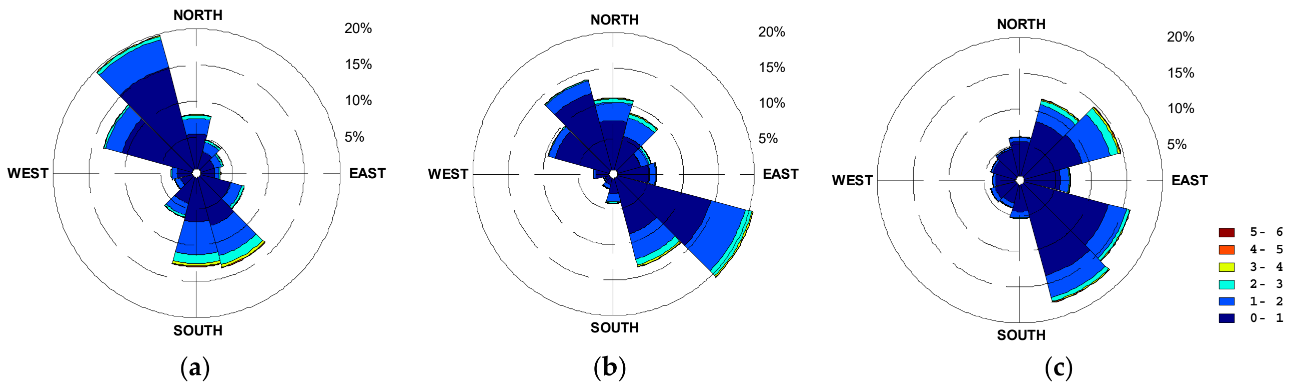

Figure A1. Wave roses for all sea states: (**a**) South Adriatic, (**b**) Central Adriatic and (**c**) North Adriatic.

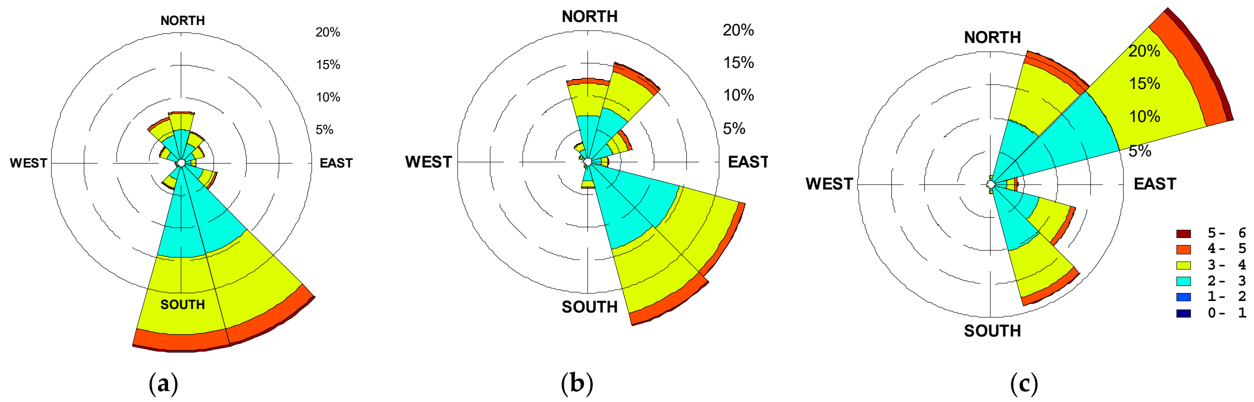

Figure A2. Wave roses with Hs > 2.5 m: (**a**) South Adriatic, (**b**) Central Adriatic and (**c**) North Adriatic

Wind speed to significant wave height simultaneous occurrence tables:

Table A7. Wind speed with significant wave height for North Adriatic region (locations 1–9).

u_w/H_s	0–0.25	0.25–0.5	0.5–0.75	0.75–1	1–1.25	1.25–1.5	1.5–1.75	1.75–2	2–2.25	2.25–2.5	2.5–2.75	2.75–3	3–3.25	Sum
0–1	8078	10,626	2985	805	250	105	46	19	9	5	1	1	0	22,930
1–2	11,964	19,039	5997	1675	575	209	88	44	14	5	0	1	1	39,612
2–3	10,067	22,010	8436	2556	873	342	129	60	35	13	7	5	3	44,536
3–4	5436	20,689	10,830	3536	1267	502	181	73	43	12	9	7	0	42,585
4 -5	2118	13,747	13,453	4941	1789	688	305	109	54	17	11	5	3	37,240
5–6	719	4251	14,188	6562	2358	910	339	183	72	31	20	11	4	29,648
6–7	169	894	7866	8210	3348	1377	520	227	97	49	26	14	9	22,806
7–8	51	281	2091	6700	4318	1943	791	333	150	75	28	14	3	16,778
8–9	21	106	399	2981	4323	2574	1223	510	237	126	38	29	10	12,577
9–10	6	27	102	805	2410	2649	1613	889	358	194	75	34	14	9176
10–11	3	13	48	221	806	1723	1656	1188	552	310	125	63	21	6729
11–12	4	9	9	56	247	695	1100	1150	795	438	262	117	50	4932
12–13	0	5	5	18	52	215	472	715	653	581	325	172	85	3298
13–14	0	3	3	10	20	65	166	370	480	456	349	258	158	2338
14–15	0	2	3	5	9	36	66	115	224	306	293	207	162	1428
15–16	0	0	2	3	2	18	28	42	80	134	158	150	177	794
Sum	38,636	91,702	66,417	39,084	22,647	14,051	8723	6027	3853	2752	1727	1088	700	297,407

Table A8. Wind speed with significant wave height for Central Adriatic region (locations 10–22).

u_w/H_s	0–0.25	0.25–0.5	0.5–0.75	0.75–1	1–1.25	1.25–1.5	1.5–1.75	1.75–2	2–2.25	2.25–2.5	2.5–2.75	2.75–3	3–3.25	Sum
0–1	7543	11,777	3808	1203	482	168	76	34	12	13	3	2	1	25,122
1–2	12,153	23,747	8439	2653	969	387	170	82	30	6	6	3	1	48,646
2–3	10,042	29,030	12,412	3968	1478	561	256	115	30	20	7	7	1	57,927
3–4	4932	27,955	16,813	5537	2050	843	366	155	67	26	12	10	3	58,769
4–5	1778	18,793	22,073	7547	2766	1113	476	170	93	30	28	2	10	54,879
5–6	551	5680	23,811	10,869	3830	1592	670	268	138	65	19	10	7	47,510
6–7	131	968	13,407	14,649	5586	2281	997	428	197	97	39	22	12	38,814
7–8	30	284	3085	12,290	8009	3387	1463	603	267	127	60	28	12	29,645
8–9	8	88	534	4712	8283	5092	2262	1022	427	200	108	41	15	22,792
9–10	3	17	141	1053	4216	5523	3403	1588	683	323	140	59	25	17,174
10–11	1	4	40	216	1263	3054	3619	2328	1157	588	229	118	54	12,671
11–12	0	5	13	53	313	1013	1929	2267	1696	842	443	190	77	8841
12–13	0	4	16	18	56	322	716	1211	1426	1084	679	322	143	5997
13–14	0	3	4	12	28	90	283	411	668	869	742	473	266	3849
14–15	0	0	4	6	14	30	86	180	223	397	484	444	321	2189
15–16	0	0	2	5	4	9	23	70	97	125	224	218	253	1030
Sum	37,172	118,355	104,602	64,791	39,347	25,465	16,795	10,932	7211	4812	3223	1949	1201	435,855

Table A9. Wind speed with significant wave height for South Adriatic region (locations 22–39).

u_w/H_s	0–0.25	0.25–0.5	0.5–0.75	0.75–1	1–1.25	1.25–1.5	1.5–1.75	1.75–2	2–2.25	2.25–2.5	2.5–2.75	2.75–3	3–3.25	3.25–3.5	Sum
0–1	4449	10,888	4162	1144	466	189	65	28	8	8	0	0	0	0	21,407
1–2	8133	25,456	11,134	3533	1259	538	195	74	39	12	3	3	0	1	50,380
2–3	7046	33,113	17,735	5867	2120	804	318	138	66	28	9	5	1	2	67,252
3–4	3696	32,549	24,597	8940	3231	1263	520	209	99	48	26	7	4	1	75,190
4–5	1243	21,613	30,768	12,242	4683	1865	723	335	159	57	31	16	13	4	73,752
5–6	396	6830	30,672	17,800	6724	2597	1152	539	215	113	51	27	5	2	67,123
6–7	93	1459	16,148	22,850	9911	3883	1694	764	334	149	67	27	17	8	57,404
7–8	22	399	3578	18,108	14,143	6042	2665	1146	537	250	144	55	24	13	47,126
8–9	4	116	586	5903	12,820	8635	4227	1883	870	405	171	90	32	17	35,759
9–10	2	33	173	972	5478	8467	5706	3095	1449	679	287	142	57	44	26,584
10–11	2	6	41	188	1137	4102	5336	4047	2257	1064	461	245	100	69	19,055
11–12	0	2	22	59	210	1073	2675	3376	2815	1771	851	393	201	89	13,537
12–13	0	1	12	15	53	242	807	1551	2068	1941	1241	712	357	151	9151
13–14	0	0	2	9	18	52	136	410	915	1263	1192	953	551	341	5842
14–15	0	0	1	4	5	22	40	102	262	491	648	714	604	413	3306
15–16	0	0	0	1	5	5	18	29	66	139	222	356	393	363	1597
Sum	25,086	132,465	139,631	97,635	62,263	39,779	26,277	17,726	12,159	8418	5404	3745	2359	1518	574,465

Appendix B

Table A10. Model parameters for joint distribution of Hs and Tp per location.

Location	Latitude	Longitude	α_{H_s}	β_{H_s}	γ_{H_s}	a_0	a_1	a_2	a_3
1	44.5° N	12.5° E	0.4946	0.9278	0.0960	1.6508	4.9038	−0.1349	0.9996
2	44.5° N	13.0° E	0.5270	0.9174	0.0840	1.5989	4.8663	−0.2394	1.0083
3	45.0° N	13.0° E	0.4669	0.9277	0.0889	1.4343	4.7483	−0.3082	1.0595
4	44.0° N	13.5° E	0.5676	0.9551	0.0905	1.5737	4.9547	−0.3390	1.0692
5	44.5° N	13.5° E	0.5918	0.9709	0.0797	1.5241	4.7550	−0.2468	1.0163
6	45.0° N	13.5° E	0.4027	0.8991	0.1022	1.4205	4.7214	−0.3020	1.0980
7	44.0° N	14.0° E	0.5559	0.9996	0.1110	1.5487	4.8686	−0.3226	1.0741
8	44.5° N	14.0° E	0.6014	1.0001	0.0797	1.5590	4.7616	−0.2930	1.0929
9	44.0° N	14.5° E	0.5527	0.9864	0.0713	1.6962	4.7527	−0.3482	1.0131
10	43.5° N	14.0° E	0.6256	1.0219	0.0653	1.6257	5.0742	−0.1880	0.9436
11	43.0° N	14.5° E	0.6058	1.0498	0.0686	1.7686	5.0812	−0.2032	0.9557
12	43.5° N	14.5° E	0.5626	0.9730	0.0757	1.7560	5.0967	−0.3474	0.9452
13	42.5° N	15.0° E	0.6516	1.0504	0.0705	1.7682	5.1241	−0.2000	0.9650
14	43.0° N	15.0° E	0.6895	1.1006	0.0624	1.8519	5.0259	−0.2664	0.8547
15	43.5° N	15.0° E	0.6208	1.0658	0.0663	1.8665	5.0121	−0.3965	1.0147
16	42.5° N	15.5° E	0.6809	1.1377	0.0687	1.7760	5.1141	−0.1846	0.8368
17	43.0° N	15.5° E	0.7078	1.1593	0.0579	1.7639	4.9854	−0.1436	0.8805
18	43.5° N	15.5° E	0.6042	1.0587	0.0639	1.9243	4.9109	−0.3730	0.9135
19	42.5° N	16.0° E	0.7021	1.1666	0.0775	1.8357	5.1016	−0.1805	0.8747
20	42.5° N	16.5° E	0.5821	1.0806	0.1259	1.9280	5.0423	−0.2165	0.9552
21	42.5° N	17.0° E	0.7308	1.1965	0.0889	1.9765	5.0861	−0.2935	1.0112
22	42.5° N	17.5° E	0.7160	1.1083	0.0899	1.8923	5.1747	−0.3226	1.1380
23	41.5° N	16.5° E	0.7160	1.1924	0.0951	1.7637	5.0261	−0.1872	0.8867
24	42.0° N	16.5° E	0.7952	1.2018	0.0916	1.9159	5.0582	−0.1821	0.8742
25	41.5° N	17.0° E	0.7053	1.0845	0.0840	1.7589	5.0221	−0.1577	0.8663
26	42.0° N	17.0° E	0.7651	1.2108	0.0839	1.8765	5.0093	−0.1148	0.9245
27	41.5° N	17.5° E	0.7587	1.1403	0.0737	1.7333	5.0756	−0.2276	0.9040
28	42.0° N	17.5° E	0.6711	1.0414	0.0805	1.8172	5.0981	−0.2826	0.9866
29	41.0° N	18.0° E	0.8070	1.1981	0.0774	7/1992	5.0700	−0.2865	0.9567
30	41.5° N	18.0° E	0.8241	1.1597	0.0805	1.8929	5.0848	−0.2553	0.9996
31	42.0° N	18.0° E	0.7105	1.0937	0.0847	1.8282	5.2537	−0.1942	1.0828
32	40.5° N	18.5° E	0.7463	1.1540	0.0706	1.9343	5.4101	−0.1318	1.1505
33	41.0° N	18.5° E	0.8391	1.1704	0.0746	1.9085	5.2676	−0.2317	1.1422
34	41.5° N	18.5° E	0.7881	1.1276	0.0909	1.9653	5.2621	−0.2896	1.1458
35	40.0° N	19.0° E	0.7842	1.1158	0.1470	2.3429	5.6666	−0.1459	1.1775
36	40.5° N	19.0° E	0.7773	1.1160	0.1459	2.0690	5.6052	−0.1609	1.2272
37	41.0° N	19.0° E	0.7857	1.1541	0.1177	1.8779	5.5497	−0.1404	1.2359
38	41.5° N	19.0° E	0.6826	1.0750	0.1445	1.8826	5.5057	−0.3257	1.2906
39	40.0° N	19.5° E	0.7110	1.1167	0.1523	1.9860	5.8377	−0.1993	1.2479

Table A11. Model parameters for joint distribution of u_w and Hs per location.

Location	Latitude	Longitude	c_1	c_2	c_3	c_4	c_5	c_6
1	44.5° N	12.5° E	1.8287	0.8839	1.8706	0.4008	6.5230	0.6874
2	44.5° N	13.0° E	2.6996	0.4646	2.7946	−0.5785	7.6803	0.5720
3	45.0° N	13.0° E	2.3739	0.9366	2.3135	−0.3538	7.6986	0.6120
4	44.0° N	13.5° E	2.8672	0.1021	3.5395	0.3758	6.5210	0.6351
5	44.5° N	13.5° E	1.3584	2.7997	1.1344	−0.2716	7.7026	0.6375
6	45.0° N	13.5° E	0.9027	3.3056	0.8464	−0.1105	8.3417	0.6495
7	44.0° N	14.0° E	3.1583	0.2676	3.0993	0.2633	6.9271	0.6503
8	44.5° N	14.0° E	1.0656	3.5599	0.9325	−0.4680	8.4683	0.6078

Table A11. *Cont.*

Location	Latitude	Longitude	c_1	c_2	c_3	c_4	c_5	c_6
9	44.0° N	14.5° E	3.4349	0.6648	2.4882	0.0210	7.4633	0.6163
10	43.5° N	14.0° E	2.2139	0.5802	1.8626	0.7982	5.6484	0.6907
11	43.0° N	14.5° E	1.7806	1.4912	1.4212	0.1227	6.8980	0.6447
12	43.5° N	14.5° E	1.6694	2.4990	1.2746	−0.2594	7.3387	0.6164
13	42.5° N	15.0° E	2.6457	0.4845	2.6885	−0.9321	8.3174	0.5338
14	43.0° N	15.0° E	1.5558	2.6546	1.3560	−0.4822	7.9338	0.5880
15	43.5° N	15.0° E	0.0975	5.3749	0.7278	−0.8914	8.5053	0.5586
16	42.5° N	15.5° E	2.4763	1.0616	2.0036	−0.1806	7.3984	0.6108
17	43.0° N	15.5° E	1.3398	3.2645	1.2099	−0.1325	7.6290	0.6445
18	43.5° N	15.5° E	0.6012	4.7120	0.7377	−0.8361	9.6300	0.5546
19	42.5° N	16.0° E	2.3045	1.6842	1.6936	−0.0628	7.4353	0.6090
20	42.5° N	16.5° E	1.5565	2.9451	1.1911	−0.4995	7.9883	0.5610
21	42.5° N	17.0° E	0.4484	4.3941	0.6586	−0.8094	8.3739	0.5384
22	42.5° N	17.5° E	2.7019	1.4317	1.6042	−2.2645	10.0111	0.4218
23	41.5° N	16.5° E	1.9212	2.1902	1.3027	−0.4685	8.0142	0.5814
24	42.0° N	16.5° E	2.5028	1.9846	1.5132	−0.4024	7.7330	0.5345
25	41.5° N	17.0° E	1.4263	3.3137	0.9603	0.1137	7.2428	0.6201
26	42.0° N	17.0° E	1.3069	3.4433	1.0381	−0.3364	7.3625	0.5786
27	41.5° N	17.5° E	1.6107	2.7539	1.1409	−0.3586	7.5308	0.5811
28	42.0° N	17.5° E	1.1066	3.3096	1.0187	−0.9027	8.2040	0.5321
29	41.0° N	18.0° E	2.1302	2.0997	1.4768	−0.3466	7.5308	0.5733
30	41.5° N	18.0° E	2.3992	1.4794	1.8260	−0.2249	7.2957	0.5767
31	42.0° N	18.0° E	3.2241	0.2731	3.1053	−0.9730	8.2339	0.5187
32	40.5° N	18.5° E	3.7825	0.1902	3.4631	−0.5351	7.8737	0.5565
33	41.0° N	18.5° E	1.9557	2.2628	1.3792	−0.2943	7.2896	0.5987
34	41.5° N	18.5° E	1.8915	2.0273	1.3252	−0.2834	7.3117	0.6024
35	40.0° N	19.0° E	1.5075	3.0655	0.8516	−1.6956	9.6439	0.4664
36	40.5° N	19.0° E	3.4256	0.4636	2.4093	−0.4509	8.2005	0.5608
37	41.0° N	19.0° E	1.9585	1.7032	1.4485	−1.0247	8.4629	0.5470
38	41.5° N	19.0° E	2.2952	1.0621	1.7132	−1.1432	8.9021	0.5206
39	40.0° N	19.5° E	2.6826	0.8658	1.5144	0.6763	7.0036	0.6234

Table A12. Most probable extreme significant wave heights, Hs^{RP} (m), for various return periods.

Location	Lat.	Long.	~23 y Recorded	5 y	10 y	20 y	50 y	100 y
1	44.5° N	12.5° E	5.59	5.31	5.75	6.19	6.78	7.23
2	44.5° N	13.0° E	6.45	5.79	6.28	6.77	7.42	7.92
3	45.0° N	13.0° E	5.60	5.01	5.43	5.85	6.40	6.82
4	44.0° N	13.5° E	6.14	5.69	6.14	6.60	7.21	7.67
5	44.5° N	13.5° E	6.34	5.70	6.15	6.61	7.21	7.66
6	45.0° N	13.5° E	5.26	4.68	5.08	5.48	6.02	6.42
7	44.0° N	14.0° E	5.09	5.06	5.45	5.83	6.34	6.73
8	44.5° N	14.0° E	6.17	5.43	5.85	6.26	6.81	7.23
9	44.0° N	14.5° E	6.19	5.14	5.54	5.94	6.47	6.87
10	43.5° N	14.0° E	6.03	5.38	5.78	6.18	6.72	7.12
11	43.0° N	14.5° E	5.52	4.93	5.29	5.65	6.12	6.47
12	43.5° N	14.5° E	6.72	5.39	5.82	6.25	6.81	7.24
13	42.5° N	15.0° E	5.71	5.29	5.68	6.06	6.57	6.95
14	43.0° N	15.0° E	5.71	5.09	5.44	5.79	6.25	6.60
15	43.5° N	15.0° E	5.59	4.89	5.24	5.59	6.06	6.40
16	42.5° N	15.5° E	5.22	4.72	5.04	5.35	5.76	6.07

Table A12. *Cont.*

Location	Lat.	Long.	~23 y Recorded	5 y	10 y	20 y	50 y	100 y
17	43.0° N	15.5° E	5.17	4.72	5.03	5.34	5.75	6.05
18	43.5° N	15.5° E	5.89	4.83	5.18	5.52	5.98	6.33
19	42.5° N	16.0° E	5.08	4.65	4.95	5.25	5.65	5.94
20	42.5° N	16.5° E	5.42	4.53	4.84	5.16	5.57	5.88
21	42.5° N	17.0° E	5.05	4.63	4.92	5.21	5.59	5.88
22	42.5° N	17.5° E	6.05	5.23	5.59	5.95	6.42	6.77
23	41.5° N	16.5° E	5.19	4.57	4.86	5.15	5.53	5.81
24	42.0° N	16.5° E	5.72	4.99	5.31	5.62	6.03	6.33
25	41.5° N	17.0° E	6.33	5.38	5.75	6.13	6.63	7.00
26	42.0° N	17.0° E	5.39	4.74	5.03	5.33	5.71	6.00
27	41.5° N	17.5° E	6.07	5.23	5.58	5.93	6.38	6.73
28	42.0° N	17.5° E	6.22	5.55	5.96	6.37	6.91	7.31
29	41.0° N	18.0° E	5.37	5.08	5.40	5.72	6.14	6.45
30	41.5° N	18.0° E	6.02	5.51	5.87	6.23	6.70	7.05
31	42.0° N	18.0° E	5.76	5.33	5.70	6.07	6.55	6.92
32	40.5° N	18.5° E	5.30	5.03	5.36	5.69	6.12	6.45
33	41.0° N	18.5° E	5.79	5.50	5.86	6.22	6.68	7.03
34	41.5° N	18.5° E	6.03	5.57	5.94	6.32	6.81	7.17
35	40.0° N	19.0° E	6.16	5.71	6.09	6.48	6.98	7.36
36	40.5° N	19.0° E	6.20	5.66	6.04	6.42	6.92	7.29
37	41.0° N	19.0° E	5.47	5.34	5.69	6.04	6.49	6.83
38	41.5° N	19.0° E	5.79	5.36	5.74	6.11	6.60	6.97
39	40.0° N	19.5° E	5.76	5.19	5.54	5.88	6.34	6.68

References

1. Bitner-Gregersen, E.M.; Dong, S.; Fu, T.; Ma, N.; Maisondieu, C.; Miyake, R.; Rychlik, I. Sea state conditions for marine structures' analysis and model tests. *Ocean Eng.* **2016**, *119*, 309–322. [CrossRef]
2. Det Norske Veritas. Recommended Practice DNV-Rp-C-205, Environmental Conditions and Environmental Loads. 2019. Available online: www.dnv.com (accessed on 5 May 2021).
3. Liščić, B.; Senjanović, I.; Čorić, V.; Kozmar, H.; Tomić, M.; Hadžić, N. Offshore Wind Power Plant in the Adriatic Sea: An Opportunity for the Croatian Economy. *Trans. Marit. Sci.* **2014**, *3*, 103–110. [CrossRef]
4. Det Norske Veritas. Classification Notes No. 30.7: Fatigue Assessment of Ship Structures. 2014. Available online: www.dnv.com (accessed on 5 May 2021).
5. Parunov, J.; Rudan, S.; Ćorak, M. Ultimate hull-girder-strength-based reliability of a double-hull oil tanker after collision in the Adriatic Sea. *Ships Offshore Struct.* **2017**, *12* (Suppl. S1), S55–S67. [CrossRef]
6. Senjanović, I.; Fan, Y. Nonlinear oscillations of quadratic nonlinear systems and its application to mooring analysis. *Int. Shipbuild. Prog.* **1994**, *41*, 149–177.
7. Barbariol, F.; Benetazzo, A.; Carniel, S.; Sclavo, M. Improving the assessment of wave energy resources by means of coupled wave-ocean numerical modelling. *Renew. Energy* **2013**, *60*, 462–471. [CrossRef]
8. Liberti, L.; Carillo, A.; Sannino, G. Wave energy resource assessment in the Mediterranean, the Italian perspective. *Renew. Energy* **2013**, *50*, 938–949. [CrossRef]
9. Ljulj, A.; Slapničar, V. Seakeeping Performance of a New Coastal Patrol Ship for the Croatian Navy. *J. Mar. Sci. Eng.* **2020**, *8*, 518. [CrossRef]
10. Senjanović, I.; Parunov, J.; Ciprić, G. Safety analysis of ship rolling in rough sea. *Chaos Solitons Fractals* **1997**, *8*, 659–680. [CrossRef]
11. Čorić, V.; Ćatipović, I.; Slapničar, V. Floating crane response in sea waves. *Brodogradnja* **2014**, *65*, 111–202.
12. Hydrographic Institute of Republic of Croatia. In *Atlas of the Climatology of the Adriatic Sea*; HHI: Split, Croatia, 1979. (In Croatian)
13. Parunov, J.; Ćorak, M.; Pensa, M. Wave height statistics for seakeeping assessment of ships in the Adriatic Sea. *Ocean. Eng.* **2011**, *38*, 1323–1330. [CrossRef]
14. Soares, C.G. Assessment of the uncertainty in visual observations of wave height. *Ocean Eng.* **1986**, *13*, 37–56. [CrossRef]
15. Bencivenga, M.; Nardone, G.; Ruggiero, F.; Calore, D. The Italian data buoy network (RON). *Adv. Fluid Mech. Ix* **2012**, *74*, 305.
16. Pomaro, A.; Cavaleri, L.; Papa, A.; Lionello, P. 39 years of directional wave recorded data and relative problems, climatological implications and use. *Sci. Data* **2018**, *5*, 180139. [CrossRef] [PubMed]
17. Katalinić, M.; Parunov, J. Wave statistics in the Adriatic Sea based on 24 years of satellite measurements. *Ocean Eng.* **2018**, *158*, 378–388. [CrossRef]
18. Katalinić, M.; Parunov, J. Uncertainties of Estimating Extreme Significant Wave Height for Engineering Applications Depending on the Approach and Fitting Technique—Adriatic Sea Case Study. *J. Mar. Sci. Eng.* **2020**, *8*, 259. [CrossRef]

19. Barstow, S.; Mørk, G.; Lønseth, L.; Mathisen, J.P. WorldWaves wave energy resource assessments from the deep ocean to the coast. *J. Energy Power Eng.* **2011**, *5*, 730–742.
20. Barstow, S.F.; Mork, G.; Lonseth, L.; Schjolberg, P.; Machado, U.; Athanassoulis, G.; Belibassakis, K.; Gerostathis, T.; Stefanakos, C.; Spaan, G. WORLDWAVES: High quality coastal and offshore wave data within minutes for any global site. In Proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering, Cancun, Mexico, 8–13 June 2003; Volume 3, pp. 633–642.
21. Romeiser, R. Global validation of the wave model WAM over a one-year period using Geosat wave height data. *J. Geophys. Res. Space Phys.* **1993**, *98*, 4713–4726. [CrossRef]
22. Heimbach, P.; Hasselmann, S. Statistical analysis and intercomparison of WAM model data with global ERS-1 SAR wave mode spectral retrievals over 3 years. *J. Geophys. Res. Space Phys.* **1998**, *103*, 7931–7977. [CrossRef]
23. Tabain, T. Standard wind wave spectrum for the Adriatic Sea revisited (1977-1997). *Brodogradnja* **1997**, *45*, 303–313.
24. Bitner-Gregersen, E.M.; Haver, S. Joint long term description of environmental parameters for structural response calculation. In Proceedings of the 2nd International Workshop on Wave Hindcasting and Forecasting, Vancouver, BC, Canada, 25 April 1989; pp. 25–28.
25. Bitner-Gregersen, E.M. Joint long term models of met-ocean parameters. In *CENTEC Anniversary Book*; Soares, C.G., Garbatov, Y., Fonseca, N., Texeira, A.P., Blakema, A.A., Eds.; Taylor and Francis: London, UK, 2012.
26. Parunov, J.; Senjanovic, I. Methods for long-term prediction of extreme sea states. *Brodogradnja* **2000**, *48*, 131–138. (In Croatian)
27. Nordenström, N. A method to predict long-term distributions of waves and wave-induced motions and loads on ships and other floating structures. In *Classification and Registry of Shipping, Report 81*; Det Norske Veritas: Oslo, Norway, 1973.
28. MATLAB. Fitting a Univariate Distribution Using Cumulative Probabilities—A Threshold Parameter Example. Available online: https://www.mathworks.com/help/stats/fitting-a-univariate-distribution-using-cumulative-probabilities.html (accessed on 5 May 2021).
29. Mathisen, J.; Bitner-Gregersen, E. Joint distributions for significant wave height and wave zero-up-crossing period. *Appl. Ocean Res.* **1990**, *12*, 93–103. [CrossRef]
30. Mauro, F.; Braidotti, L.; La Monaca, U.; Nabergoj, R. Extreme loads determination on complex slender structures. *Int. Shipbuild. Prog.* **2019**, *66*, 57–76. [CrossRef]