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A Wave Directionality and a Within-Year Wave Climate Variability Effects on the Long-Term Extreme Significant Wave Heights Prediction in the Adriatic Sea

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Abstract: The extreme significant wave height predictions often neglect within-year wave climate variability and wave directionality. Depending on a geographical region, local wind patterns and year climate variability could have an influence on the long-term prediction of waves. The Adriatic Sea having two dominant wind patterns of different characteristics, *Bura* and *Jugo*, is a great example for the case study. The 23-year hindcast wave data used in the presented study is extracted from the WorldWaves database. Based on wind and wave data, annual extreme significant wave heights generated by different wind patterns and for different months are fitted by Gumbel distribution using maximum likelihood estimation. Combined long-term extremes are then predicted by calculating system probability. It was found that considering the wave directionality, and especially the seasonality of wave climate, leads to a larger prediction of extreme significant wave heights. The extreme value prediction considering wave directionality on average yields 4% larger significant wave heights, while considering within-year climate variability leads to, on average, 8% larger extremes compared to the predictions when both effects are neglected.

Keywords: significant wave height; long-term probability; wind direction; wave directionality effects; seasonal variability effects; monthly maxima; directional maxima; annual maxima; Adriatic Sea

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1. Introduction

Throughout the years, significant wave height (SWH) has become the most important variable in engineering practices for the wave environment description. Prediction accuracy is important for performance and design optimization within many marine-related industries, such as shipbuilding, offshore, renewable energy, aquaculture, etc.

For the analysis of extreme wave loads, two methods are recommended by [1]. The design sea state method (DSSM) performs wave loads analysis on a selected short-term sea state condition called design sea state, while the all sea state method (ASSM) calculates the most probable extreme value considering the probability of occurrence of all sea states. The former method is usually used in the design of offshore structures, while the latter is recommended for the analysis of ship structures by the International Association of Classification Societies (IACS) [2].

A return period, also known as a recurrence interval, is often used to determine extreme sea states. In the case of marine structures, it is an average time or estimated average time between the occurrences of the extreme sea states. The theoretical return period between occurrences is the inverse of the average frequency of occurrence. Ships are designed considering a 25-year return period, which grows to 100 for offshore structures, while for some coastal defense systems like dams, it starts from 1000 years and above.

The main aim of the present study is to define extreme SWHs that may be used in the context of DSSM. Traditionally, these extreme values are determined by using annual extreme values without considering within-year variability or wave directionality.

Therefore, the research investigates using maxima for each month or each wave prevailing direction to estimate long-term extreme SWHs instead of using only annual maxima (AM). As the creation of surface waves in the Adriatic is predominantly influenced by two winds of completely different characteristics [3], it is useful to investigate the seasonality and directionality effect on long-term predictions.

A within-year wave climate variability was first questioned in [4], demonstrating theoretical proof that long-term extreme values estimated, neglecting seasonality of the wave climate, introduce unconservative bias. Using the approach proposed by Carter and Challenor (C–C) in [4] to account for monthly variability, extreme SWHs in the northern Adriatic is examined in [5]. The study shows that neglecting seasonality effects leads to smaller extreme SWH values for a given return period. The main drawback of these analyses is that they were performed based on the dataset where many of the monthly extremes were missing. Complete datasets containing many years of uninterrupted wave measurements are required to obtain a reliable prediction of long-term extremes.

The effect of within-year wave climate variability on the design of ship structures is examined in [6]. Consequences of the extreme vertical wave bending moment (VWBM) are explored along frequent shipping routes in the Atlantic and Pacific Oceans and compared to IACS rules. Neglecting within-year wave climate variability could lead to the underestimation of long-term extreme SWHs and VWBMs by up to 10%.

The pioneering research of wave statistics in the Adriatic region was performed by Tabain in [7] and later revised and updated in [8], developing the most commonly used Tabain's wave spectrum. Tabain's spectrum is a single-parameter modification of the JONSWAP spectrum based on the limited number of wave measurements and observations from merchant and meteorological ships.

A collection of wave data from visual observation across the Adriatic is collected inside the *Atlas of Climatology of the Adriatic Sea* [9] published by the Republic of Croatia Hydrographic Institute. The data obtained by observations from the merchant and meteorological ships from 1949–1970 is presented in the form of wave roses. Around 15 years of wave observations from [9] are fitted using the three-parameter Weibull distribution in [10] to develop extreme wave statistics. However, the data from [9] suffers from uncertainties due to the lack of extremes caused by heavy weather avoidance and visual wave observation inaccuracies. The term visual wave observation refers to observations taken by trained officers from voluntary observing ships (VOS) and should not be confused with highly accurate optical measurements, like stereo cameras from fixed offshore installations [11]. There is a general concern that VOS wave data are less reliable than in-situ and remotely sensed wave measurements because of their low accuracy and insufficient sampling [12] (Gulev, 2003).

Except for visual observations, wave data are obtained by measurements from fixed wave buoys, radars, lasers, stereo cameras, etc. [13]. Wave buoys and oceanographic towers are considered reference measurement sources regarding accuracy. For application on ship structures, however, they have drawbacks as they are located outside main shipping routes and quite often appear to be out of service for an extended period. A rare example of uninterrupted long-term wave measurements from a fixed oceanographic tower is Acqua Alta in the North Adriatic Sea [14]. Within the RON project (The Italian Data Buoy Network), four wave buoys along the western Adriatic coast off the cities of Monopoli, Ortona, Ancona, and Venezia, were operational during the period between 2009 and 2014, with occasional breaks due to failure or service intervals [15].

The extreme SWHs are usually evaluated using wave statistical data accumulated on an annual basis incorporating all directions, thus neglecting within-year (also called intra-annual) wave climate variability and directionality effects. Until long-term, high-quality hindcast wave databases became available, the number of observations had been insufficient to confidently fit the theoretical probability distribution to monthly or directional maxima, namely for the ship design, since the visual observations were the main data source suffering from a lack of quality and consistency. Currently, several long-term hindcast wave databases are available for the Adriatic, such as ERA5, the fifth generation ECMWF (The European Centre for Medium-Range Weather Forecasts) reanalysis, or the WorldWaves atlas (WWA) developed by Fugro Oceanor.

Comparative analysis of wave data from different formerly described sources (Acqua Alta, RON, ERA5, and WWA) is performed in [16] for the location in the North Adriatic, close to Venice, where long-term databases are available. Different data sources provide similar time series trends of SWHs and storm predictions, but the extreme values have larger discrepancies. Rather large uncertainties of wave data sources have the greatest consequences on fatigue life prediction. Since the WWA database is found to be conservative, it is recommended for practical engineering applications in deep water compared to ERA5, while for the near-shore region, it is recommended to use models accounting for wave–current interaction and shallow water effects.

Wave statistics based on WWA are developed by [17] for one location in the middle of the Adriatic Sea. The model includes three-parametric Weibull distribution as the marginal distribution of SWH and the log-normal distribution as the conditional distribution of peak wave periods, while the relation between wind speed and wave height is established by regression analysis. The analysis is further extended in [18] to all 39 grid points in the Adriatic basin while replacing the regression analysis with a conditional distribution of wind speed. The same WWA database was also used for the operability analysis of a passenger ship sailing through the Adriatic [19] and for the assessment of wind and wave energy potential in the Adriatic [20].

There are many works discussing the evolution of wave motion in the Adriatic Sea with deterministic models. Benetazzo et al. [21] studied expected changes in wind and wave severity for the period 2070–2099. The wind field computed by a high-resolution regional climate model (RCM) is used to force the SWAN spectral wave model. The performed statistical analysis is compared to the simulation results for 1965–1994. Although increases in the wave severity were found locally, a milder future wave climate in the Adriatic was predicted compared to the present climate. A similar conclusion was drawn by [22], running the high-resolution RCM over the Adriatic Sea. Future projections generally confirmed the tendency to a decreasing energy trend, with more extreme events in the northern part of the Adriatic. The important practical aspect was the identification of potential storms, allowing researchers to focus on extreme events and avoiding the need to run entire climatological wave simulations. Deterministic wave simulations, based on climate models, could represent the future trend in the design and analysis of marine structures. However, these models are still not recognized and included in the procedures for the computation of extreme wave and wind loads on marine structures by relevant institutions and classification societies. Probabilistic predictions based on past measurements are still the recommended procedure [1]. Therefore, the focus of the present study is on a probabilistic rather than a deterministic model.

The motivation for the study was born because almost all previous analyses for the Adriatic considered the AM method, thus neglecting directional and seasonal effects. Only the study by Leder et al. [5] quantified the seasonality effect on long-term SWHs prediction. However, the analysis was performed based on the fragmented dataset where more than a third of the monthly extremes were missing and had to be estimated from the wind data using quadratic regression. The surface wave creation in the Adriatic, however, is predominantly influenced by two winds of completely different characteristics [3]. Therefore, it would be very useful to question the directionality effect on long-term predictions.

The aim of the presented research is to develop and compare statistics of the extreme significant wave height in the Adriatic region obtained by considering wind patterns, within-year climate variability and neglecting both. Yearly maxima are extracted for each direction and month, and extreme value distributions are fitted. System probability, i.e., the C–C method, is applied to determine combined extreme significant wave heights. Obtained extreme values are then compared to the ones calculated by neglecting both effects. The calculations are done for the whole Adriatic Sea.

The research is described and presented through five sections and an Appendices A and B. After the Introduction, Section 2 first describes the case study, available dataset, landscape, and climate of the Adriatic region. The second subsection of Section 2 describes the methodology used for the computation of extreme values. The underlined results are presented in Section 3, while the remainder is provided in the Appendices A and B. The fourth section is reserved for a discussion, followed by conclusions and future steps.

2. The Case Study and Methodology

2.1. The Adriatic Sea

2.1.1. Characteristics of Wind and Wave Climate

With an average width of around 200 km, winds in the Adriatic are limited by fetch. The creation of surface waves in the Adriatic is dominated by two winds of completely different characteristics. The north-eastern wind *Bura* and south-eastern *Jugo*, thus, also creating consequently different waves. Although the strongest winds blow from the north-east, having shorter fetch results in the wave spectrums is typical for partially developed sea states. The longest fetch is obviously along the basin, corresponding with southeast winds yielding the highest recorded wave heights of 10.87 m. More than 1000 islands along the east coast shelter the wave influence in that near-shore region, while relatively small sea depths are present in the northern part of the basin and could influence the wave characteristics. The bathymetric map of the Adriatic Sea is shown in Figure 1.

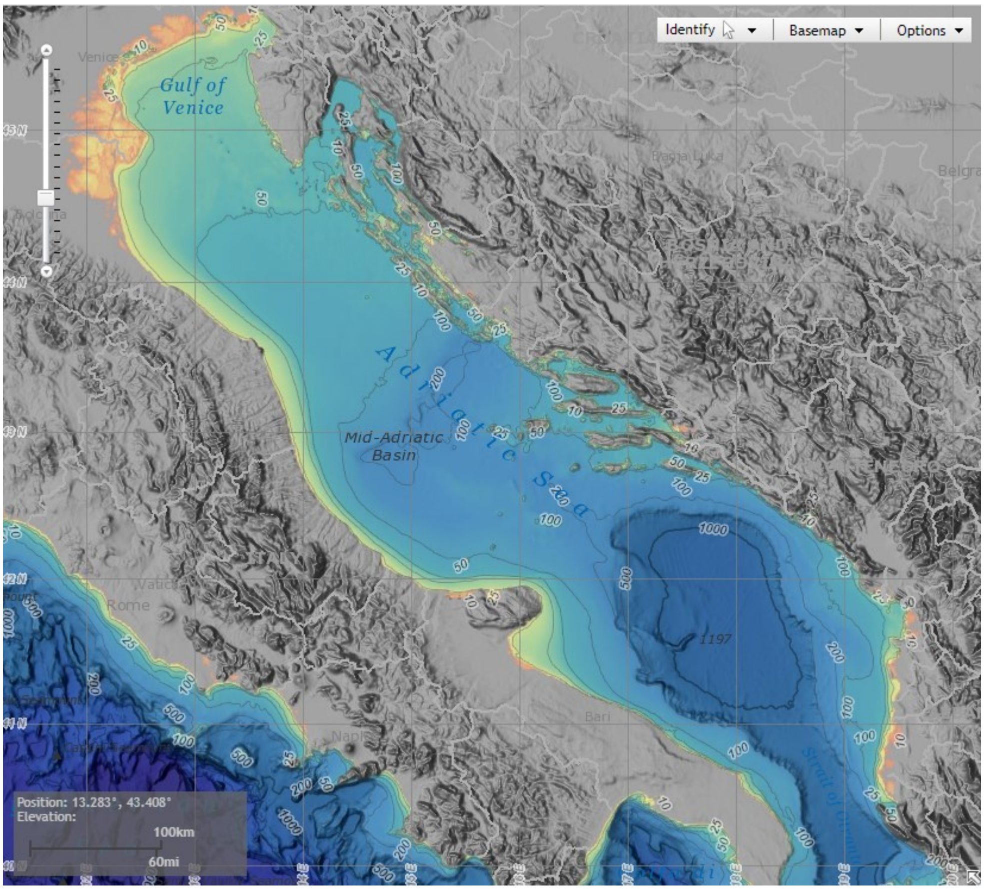


Figure 1. The Adriatic Sea is located in the central-north part of the Mediterranean Sea. Surrounded by the mountain ranges Apennine in the west and Dinaric in the east, the basin stretches for more than 800 km from the shallower northwest to the deeper southeast, where the Strait of Otranto connects with the rest of the Mediterranean Sea. Depth contours or isobaths outline basin bathymetry offering an insight into seafloor terrain—source: https://maps.ngdc.noaa.gov/viewers/bathymetry/ (accessed on 30 November 2022).

Jugo (E–SE to SS–E, Italian sirocco) is a strong and warm southeast wind that comes with a lot of rain. Blowing through the whole year, it is more common in the south of the Adriatic, which is characterized by strong winds and rough seas. *Jugo* reaches its peak strength after two to three days of persistent blowing and usually lasts days. Sometimes, however, especially during the winter season, it can last up to a week.

A very cold, dry wind *Bura* (N–NE to E–NE, Italian bora) blows from the northeast over the coastal Dinaric Mountains slopes. Characterized by violent gusts, it brings accelerating cold air that meets the seawater with great force, spreading it in the shape of a fan. With powerful blows and rapid changes of direction, *Bura* generates short but very high waves with a lot of foam and spray [3].

Lebić is a south-western wind blowing mostly during the winter and usually announced by above-average tides. Although short in duration, it can generate rough waves while also carrying abundant rainfall. *Maestral* is a constant, humid, and mostly thermal summer wind blowing from the northwest. As a regular wind of moderate strength, it is very convenient for sailing. The main wind patterns in the Adriatic Sea are presented on the lower left part of the map in Figure 2.

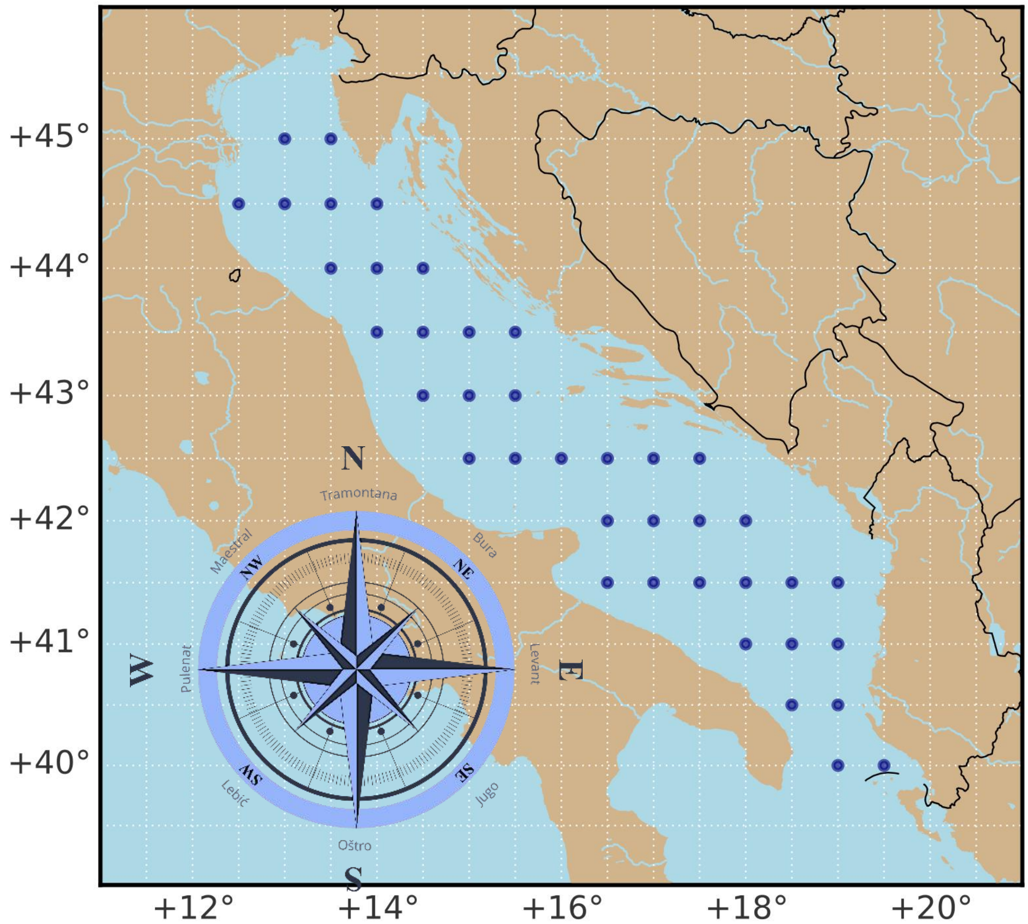


Figure 2. The Adriatic Sea map. The offshore grid of 39 blue dots denotes available locations for wave data extraction from the WWA database. Lat-lon grid resolution is 0.5 degrees. Almost all defined points are at the same time calibration points close to the satellite tracks. The wind rose is presented in the lower-left corner of the map.

The surface wave creation in the Adriatic is dominated by *Bura* and *Jugo*, having entirely distinct characteristics and creating different waves. Wave statistics in Adriatic are thus far mostly developed regardless of the wind pattern. Hence, the paper attempts to provide more detailed insights in that regard.

2.1.2. Wave Data

The study is conducted based on data extracted from the World Wave atlas (WWA). The WWA is the collective name for a series of comprehensive high-resolution atlases developed by Fugro Oceanor, providing wind and wave climate statistics/data for any region worldwide. The data derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) wave models are calibrated by Fugro Oceanor against satellite altimetry measurements gathered from eight different satellite missions: Geosat (1986–1989), Topex (1992–2002), Topex/Poseidon (2002–2005), Jason (2002–2008), Geosat Follow-On (2000–2008), EnviSat (2002–2010), Jason-1s (2009–2012), and Jason-2 (2008–on-going). The WWA database for the Adriatic covers a period of 23 years from 1997 until 2020 in 6 h intervals giving a total of 33,600 records per parameter at each location. Data are available at a lat-lon grid resolution of 0.5 degrees creating the offshore grid of 39 points across the Adriatic, as shown in Figure 2. Available data include wind speed and direction, integral spectral wave parameters (e.g., significant wave height, peak spectral period, mean wave period), and wave direction for wind waves and swell, considered separately and combined, offering, in total, 12 wind and wave parameters.

The WWA model data are calibrated against the long-term satellite data in order to provide bias-free homogeneous long-term model data of the highest quality. Thus, representing a state-of-the-art comprehensive and systematic source of wave data as input to coastal models and studies for the Adriatic region.

2.2. Methodology

For each location where data is available, the procedure runs as presented in the flow chart in Figure 3. The procedure is performed separately for wave directionality and intra-annual variability. The basic steps of the analysis are:

1. Extracting empirical extreme values from the database;
2. Fitting theoretical extreme value distribution to the empirical data;
3. Combining individual distributions in the system probability distribution;
4. Calculating a long-term extreme value from the system probability distribution.

Each step is described in more detail below.

A time series of SWH data and mean wave direction (MWD) is extracted from the WWA database serving as model input. Through filtering and sorting, two separate subsets of SWH maxima are extracted from 23 years of data. The seasonality is studied through 12 months, while for directionality, 4 main directions are chosen as follows:

1. *Bura*—mean direction 45°, N–E;
2. *Jugo*—mean direction 135°, S–E;
3. *Lebić*—mean direction 225°, S–W;
4. *Maestral*—mean direction 315°, N–W.

For the seasonality study, monthly maxima (MM) are extracted for every year available, resulting in a subset of 12 records of MM easily visualized as a matrix containing 23 rows (years) and 12 columns (months), named MM23 × 12. Similarly, directional maxima (DM) are extracted, resulting in a subset of size 23 × 4 (4 directions) named DM23 × 4. The AM are easily obtained using any of these 2 datasets and extracting a maximum value for a given year, i.e., getting a maximum value of a row. The year is defined as the period from summer to summer, starting 1st July, not the calendar year, as recommended in [1].

The maximum SWHs are described using type-I generalized extreme value distribution, also known as Gumbel distribution. The probability density function (PDF) (1) and cumulative distribution (2) are defined as (DNV, 2017):

$$f_{H_s}(x) = \frac{1}{B} e^{-\left(\left(\frac{x-A}{B}\right) + e^{-\left(\frac{x-A}{B}\right)}\right)} \quad (1)$$

$$F_{H_s}(x) = e^{-e^{-\left(\frac{x-A}{B}\right)}} \quad (2)$$

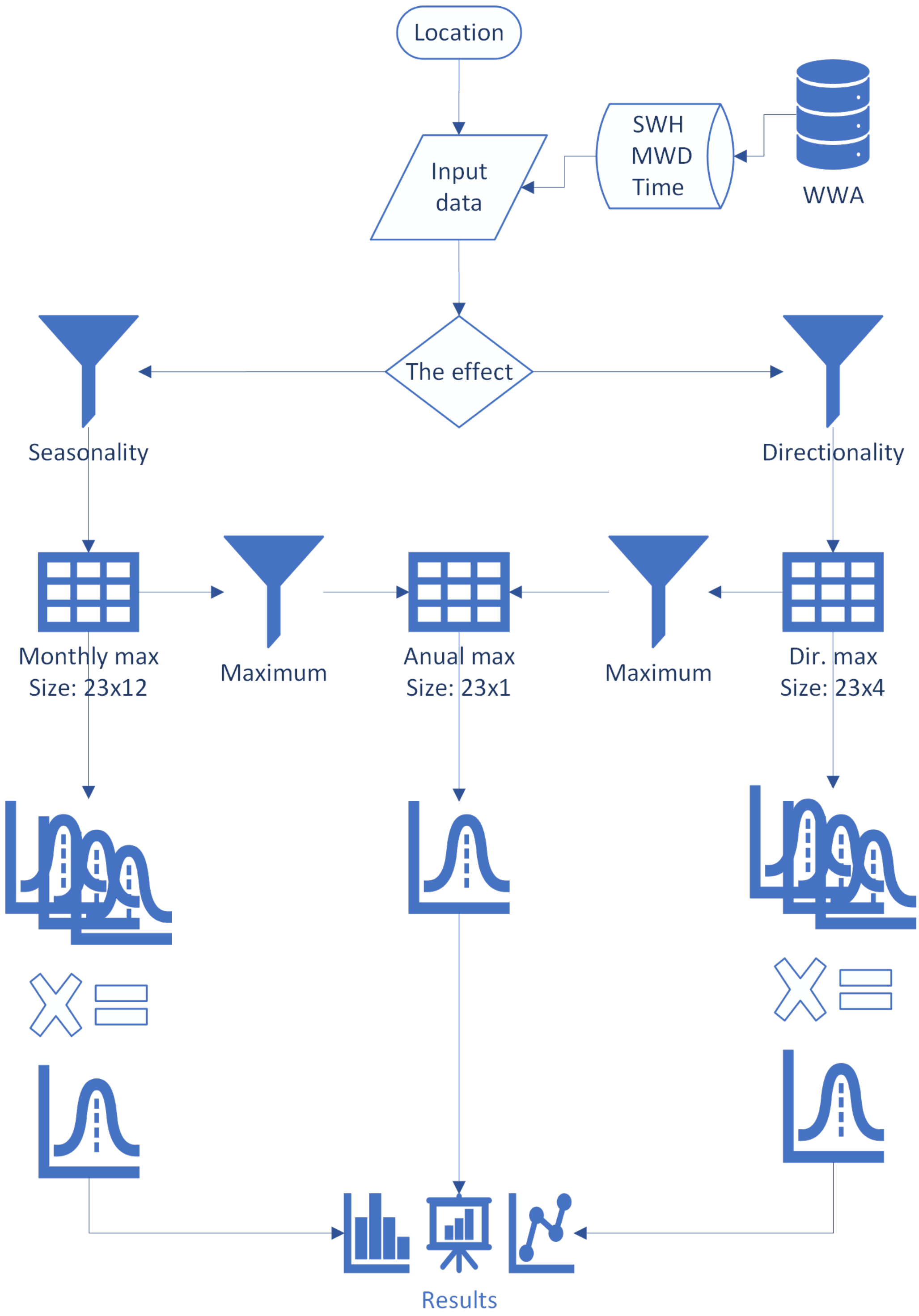


Figure 3. The flow chart of the presented approach.

Parameter A, although called the location parameter, in this context represents the most probable extreme SWH, and B is the scale parameter. Gumbel PDF is fitted to 12 records of MM, 4 records of DM, and AM. Fitting of Gumbel distribution is performed by the maximum likelihood method (MLE), utilizing the scipy.stats package in Python [23]. From individual distributions of directional or monthly maxima, combined 'annual maxima' is calculated by the C–C method, using Equation (3) [4].

$$P_{H_s}(X < x) = \prod_{i=1}^{N} F_i(x) \quad (3)$$

The C–C method assumes cumulative distributions $F_i(x)$ to be independent, while N represents the total number of months or directions. For the prediction of long-term extremes, the return period $T(x)$ is defined as the mean period (in years) between the occurrence of two values equal to or higher than x. For different return periods $T(x)$, the probability is calculated, and corresponding return SWHs are easily obtained from the CDFs defined in Equations (2) and (3). Unless distributions of directional or monthly extremes are identical, the resulting distribution from Equation (3) is not Gumbel distribution. Thus, results must be calculated numerically. Obtained values are then compared, and the results are presented in the next section.

3. Results

The extreme SWHs summarized in Figures 4 and 5 are calculated for the return periods of 25 and 100 years, respectively, at 39 locations across the Adriatic. The dashed lines on the upper graph represent the extreme value resulting from the system probability approach (C–C method, Equation (3)). The blue dashed line accounts for different directions combining probability distributions of DM, while the orange dashed line combines probability distributions of MM. The red line displays results from the conventional method using AM, neglecting both effects. Lower graphs on both figures highlight deviations of C–C using DM and MM from the AM. Locations on the left side of the graphs in Figures 4 and 5 correspond to the southern part of the Adriatic Sea, moving to the locations in the northern Adriatic as we move to the right side of the graphs. The exact position of locations could be easily identified using the map presented in Figure 2.

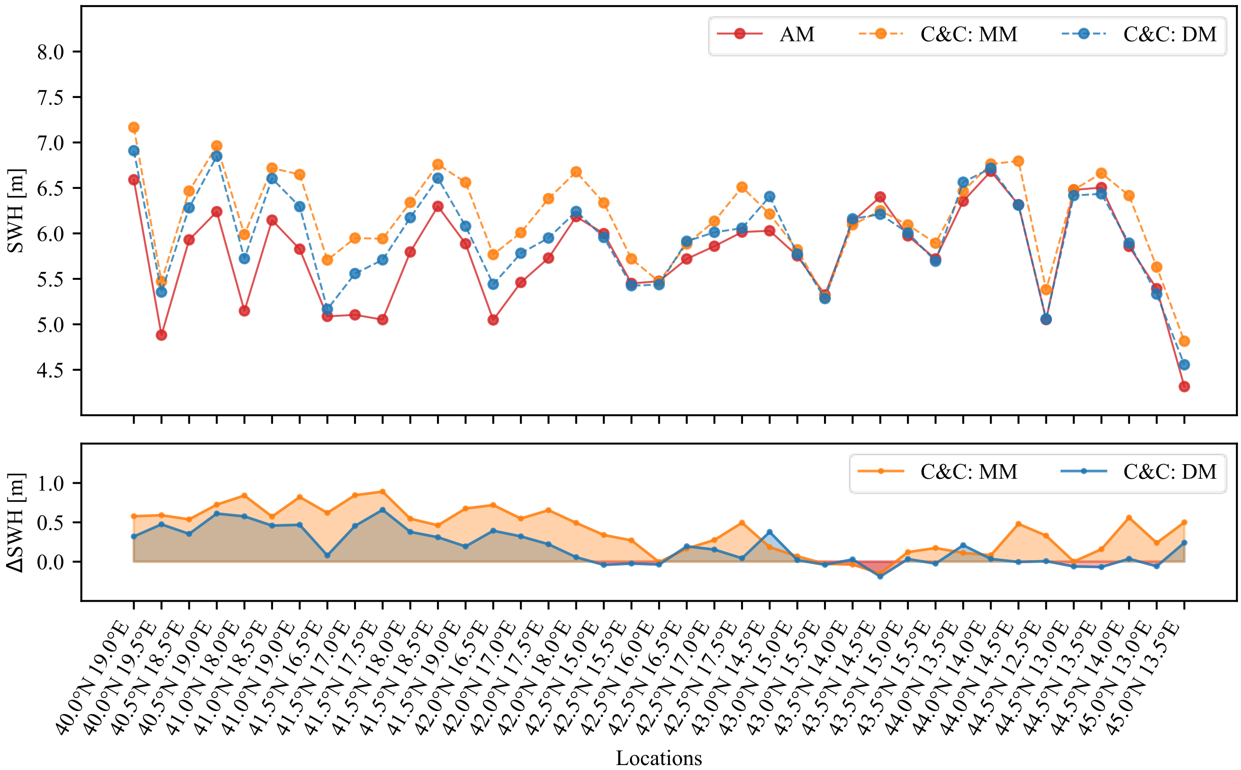


Figure 4. The extreme SWHs for the return period of 25 years. The blue dashed line represents long-term predictions calculated using system probability distribution obtained by the C–C method combining probability distributions of DM. The orange dashed line combines distributions of MM. The red line represents the conventional method using AM, neglecting both effects. Moving from left to right on the horizontal axis corresponds to moving across locations from southeast to northwest. The lower graph displays the differences between the given C–C and the AM approach.

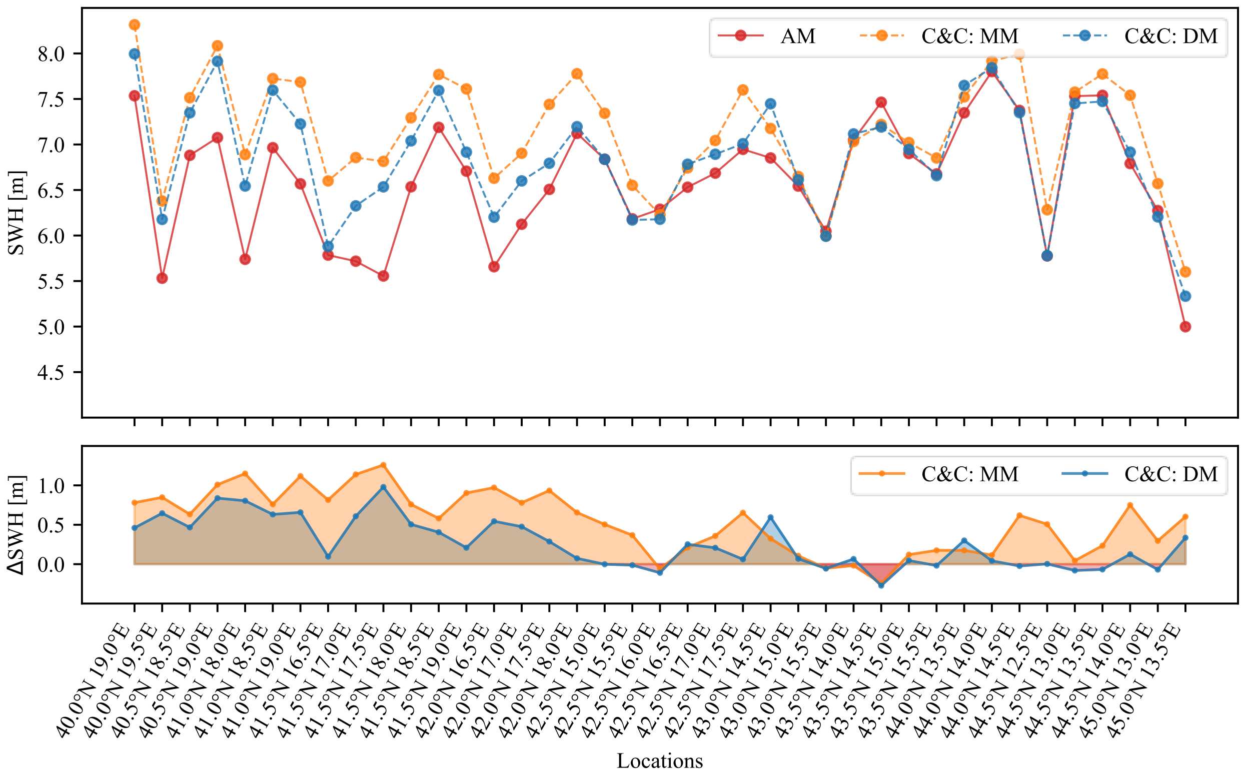


Figure 5. The extreme SWHs for the return period of 100 years. The blue dashed line represents long-term predictions calculated using system probability distribution obtained by the C–C method combining probability distributions of DM. The orange dashed line combines distributions of MM. The red line represents the conventional method using AM, neglecting both effects. Moving from left to right on the horizontal axis corresponds to moving across locations from southeast to northwest. The lower graph displays the differences between the given C–C and the AM approach.

Relations between extreme values from C–C and AM are qualitatively similar for both months and directions. Throughout locations, C–C MM produces the most conservative results for almost all locations, with few exceptions where it is equal to or slightly exceeded by the other two. These exceptions occur in the middle part of the Adriatic, where the wave climate is the mildest. The C–C DM produces evidently smaller differences, offering predictions close to AM for almost half of the studied locations. Extending the return period from 25 to 100 years only amplifies differences while trends remain unchanged. For both return periods, southern locations observe higher differences, yielding the highest values for 41.5° N 17.5° E. The lowest deviations are displayed for locations in the middle Adriatic (43.0° N 15.5° E), whereas for some locations, C–C MM and DM predict SWHs even lower than the standard AM approach. Several locations are found in the northern Adriatic where *Bura* has the highest influence yielding results equal to or higher than the AM, from which location 44.0° N 13.5° E is further analyzed.

Detailed results of the three locations mentioned in the previous paragraph are displayed in Figures 6 and 7. Directional effects are exhibited in Figure 6a, plotting the extreme SWHs at different return periods for each direction, C–C, and AM approach. Dispersion of the DM is described in Figure 6b using box plots, where white circles represent the AM that occurred in each direction. Similarly, the within-year climate variability effects are examined in Figure 7. The predicted extreme SWHs at different return periods are compared between individual months, C–C, and the AM approach. Box plots are based on MM, and the white circles herein represent the AM that occurred each month.

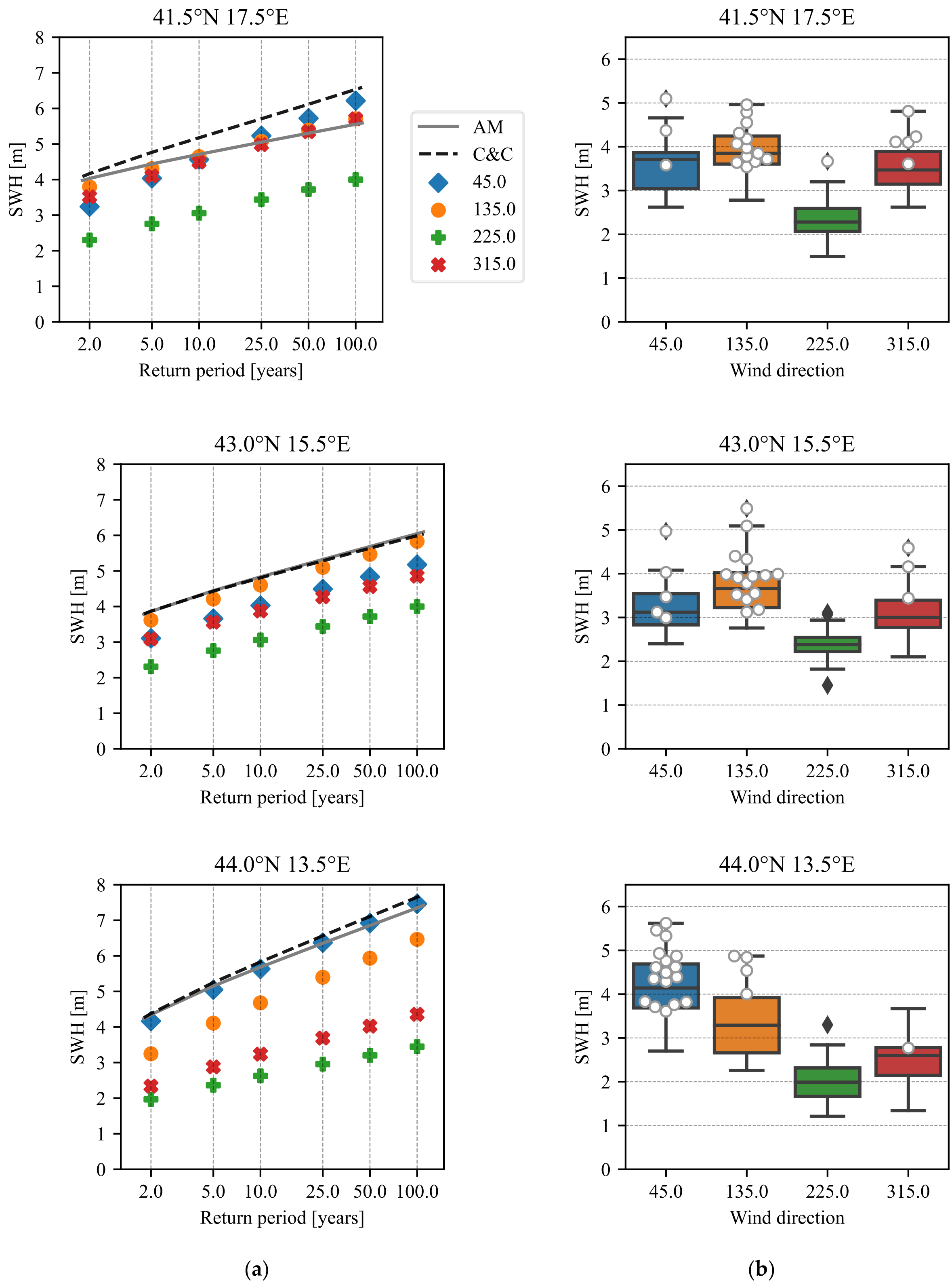
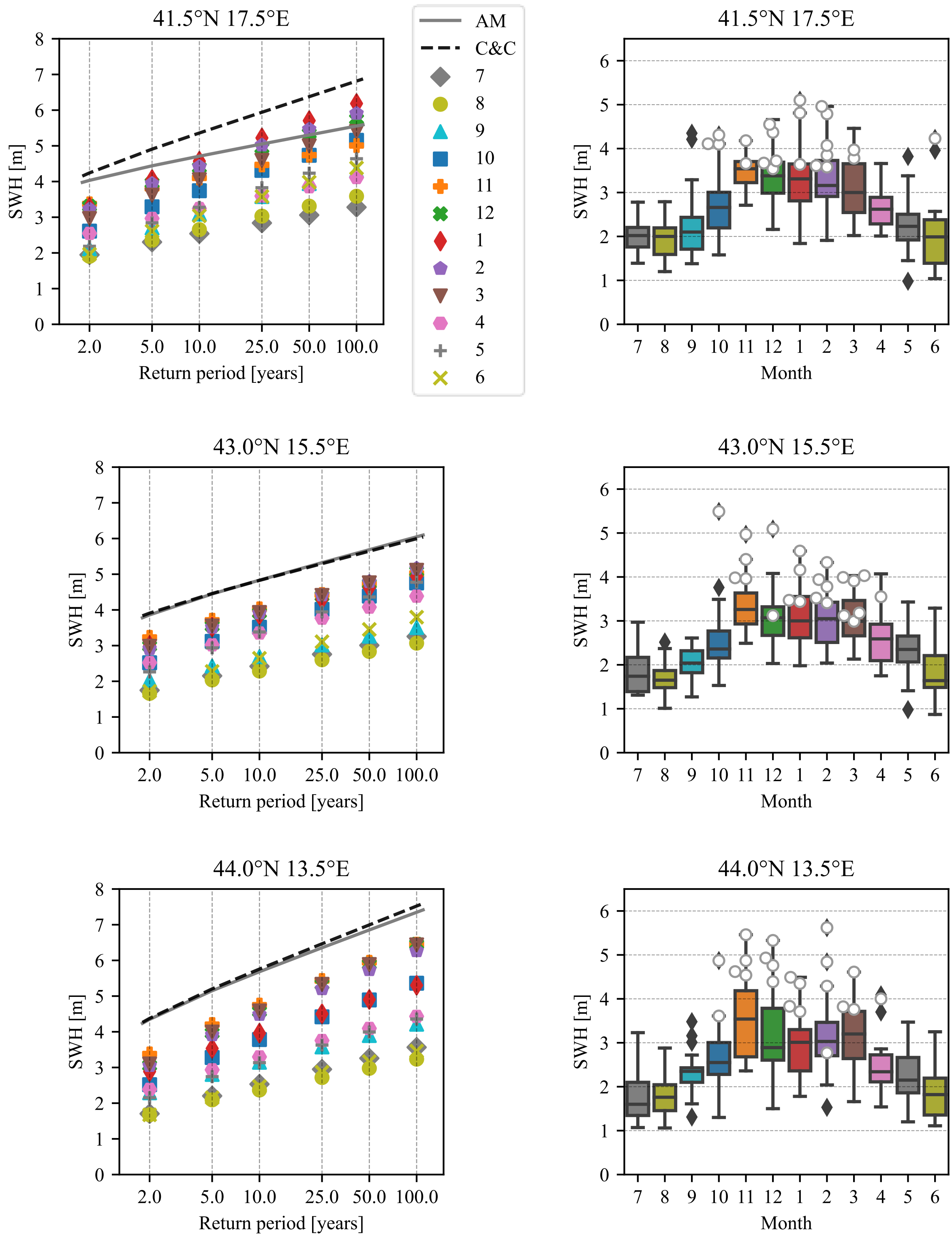


Figure 6. Directionality effect for three characteristic locations: (**a**) The extreme SWHs calculated based on different return periods. Markers represent results from individual directions, while the dashed black line displays values obtained by the C–C approach combining DM; (**b**) Box plot describing the dispersion of maxima that occurred in a given direction. White circles highlight the values that are also the annual maxima that occurred in a given direction.



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

Figure 7. Seasonality (Within-year climate variability) effect for three characteristic locations: (**a**) The extreme SWHs calculated based on different return periods. Markers represent results from individual months, while the dashed gray line displays values obtained by the C–C approach combining MM; (**b**) Box plot describing the dispersion of maxima that occurred in a given month. White circles highlight the values that are also the annual maxima that occurred in a given month.

Directionality effects across the Adriatic Sea are also examined in Figure 8, revealing the distribution of the number of yearly maxima across four studied directions. Analysis suggests domination of *Bura* waves in the north and along the west coast of the Adriatic, while *Jugo* dominates the remaining locations across the basin. In the southernmost locations, close to the Strait of Otranto, there is a strong influence of the Ionian Seas, causing a mixture of different wind and wave systems. Consequently, in those locations, it could be that extreme waves are not predominantly influenced by *Jugo* or *Bura*.

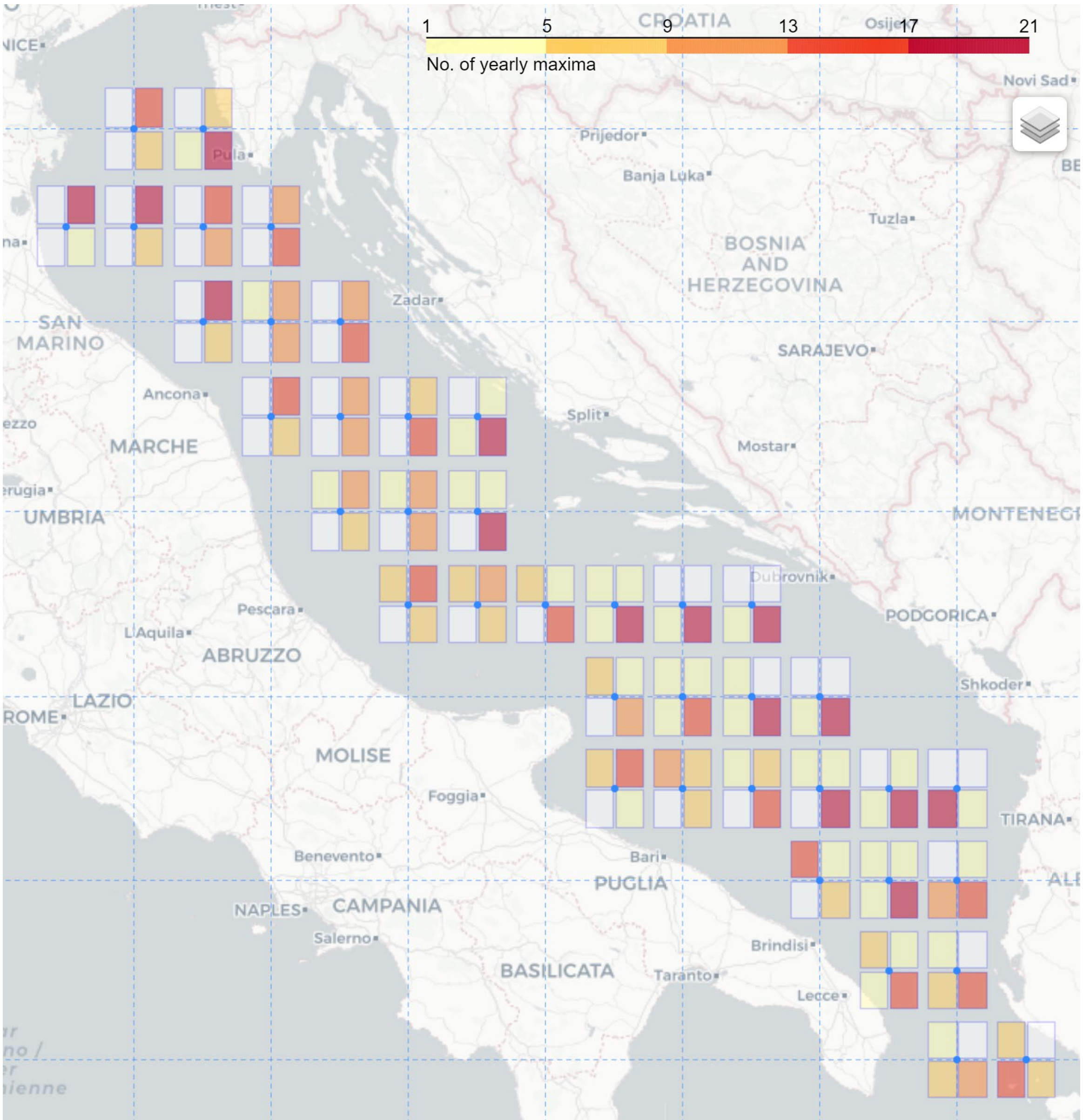


Figure 8. Distribution of yearly maxima from four main quadrants across the Adriatic Sea. Each location is represented by a blue dot and four quadrants suggesting the direction of the waves. The color scale presented in the upper left corner indicates the number of yearly maxima that occurred in a direction.

4. Discussion

Results presented in Figure 8 are direct consequences of the wind and terrain properties, as the Adriatic is encompassed by the Apennines to the West, the Alps to the north, and the Dinarides to the East. *Jugo*, being a strong wind with the longest fetch, expectedly generates the highest waves through the Adriatic basin. Waves generated by *Bura* prevail in the north, alongside the western coast, where it had some time and length to develop some rough seas. Although having longer fetch, *Maestral*, due to moderate power and short duration, evidently cannot produce any significant influence except in a few locations in the southwest. *Lebić*, as a wind of short duration, while also having a shorter fetch, can hardly produce waves higher than the previous three winds. Therefore, only a few locations in the south, already outside the Adriatic Sea, are observing higher impact from that direction due to influence from the rest of the Mediterranean.

Blowing through the whole year, it is more common in the south of the Adriatic, which is characterized by strong winds and rough seas. *Jugo* reaches its peak strength after two to three days of persistent blowing and usually lasts up to days. Sometimes, however, especially during the winter season, it can last up to a week.

A very cold, dry wind *Bura* (N–NE to E–NE, Italian bora) blows from the northeast over the coastal Dinaric Mountain slopes. Characterized by violent gusts, it brings accelerating cold air that meets the seawater with great force, spreading it in the shape of a fan. With powerful blows and rapid changes of direction, *Bura* generates short but very high waves with a lot of foam and spray [3].

In the uppermost graph in Figure 6, for location 41.5° N 17.5° E, there are at least three wind systems influencing extreme values of significant wave heights, i.e., *Bura*, *Jugo*, and *maestral*. As seen in the uppermost Figure 6a, for return periods of 25 years and higher, predictions from three directions overshoot AM predictions, therefore, confirming a high difference in the C–C approach. As seen from Figures 5 and 6, these relatively large differences between the AM and C–C methods are characteristic of the southern locations close to the Strait of Otranto.

A large overestimation of the C–C method compared to the AM for location 41.5° N 17.5° E is also evident for MM in the uppermost Figure 7a. Comparably, December, January, and February overshoot the AM approach for the same return periods, while AM are almost evenly distributed from October–March. It is interesting to observe in the uppermost right graph in Figure 7 that some extreme events occur outside the October–March season, which is characteristic of *maestral*. This spread of extreme event occurrence throughout the year is the likely reason for differences between the C–C and AM method.

Location 43.0° N 15.5° E (middle graphs in Figures 6 and 7) in the middle Adriatic displays slightly less scattered values between distributions of both DM and MM. Namely, for a DM, *Jugo* is clearly a predominant wind pattern, regarding both the number of extremes and their values. Therefore, no difference between the AM and the C–C methods is observed. However, the explicit dominance regarding the number of extremes or their values is not displayed by any particular month. Only a somewhat lower dispersion between monthly predictions of the three analyzed locations can be exhibited (Figure 7b), resulting in almost equal values from both AM and the C–C method, i.e., negligible within-year climate variability effect.

In the northern part of the Adriatic Sea, location 44° N 13.5° E (the lowest graphs in Figures 6 and 7), the C–C predictions slightly exceed the AM predictions. *Bura* exerts a significant influence on both the frequency of occurrence and values of extremes. *Jugo* produces several annual extremes but with obviously lower values and frequency of occurrence. Encountering the dominance of a particular month is much harder as the influence is almost evenly distributed from November up till March. However, a general trend can be observed in Figures 4 and 5, where discrepancies between the C–C and the AM method are being reduced as we move from the south towards the north Adriatic.

Additional graphs are presented in Appendix A, comparing extremes obtained for individual directions (Figure A1) and months (Figure A2) with extremes obtained by AM and C–C methods. For a substantial number of locations, extremes for individual directions and months exceed those obtained by the AM method. However, these results never exceed the predictions obtained by the C–C method, representing a safe and conservative envelope of individual results. This exceedance of AM is the most frequent for individual directions and the return period of 100 years.

It is well known that both choices of the theoretical extreme value distribution and fitting method may influence the prediction. The choice of Gumbel extreme value distribution is based on the recommendations of the classification societies for fitting annual extreme SWHs [1]. The choice is also confirmed by a comparative analysis of three extreme value distributions performed in [6], where it was found that the Gumbel distribution is the most appropriate. Histograms and fitted extreme value distributions are shown in Appendix B, Figure A3, for three locations analyzed in Section 3. Fitting distributions for individual wave directions and months are presented in Figure A3 sides, respectively. Appropriate fitting is observed for most cases. In some rare instances, e.g., for September for loc. 43.0° N 15.5° E (middle graphs in Figure A3, Appendix B), fitting is not adequate as the tail of the distribution function likely overestimates extremes.

However, the shape of the histogram is such that other probability distribution and fitting methods would hardly improve this fitting. It should be mentioned that the present study includes a large number of directions, months, and locations, aiming to draw the conclusion from the whole dataset. In such a case, it would be rather inconvenient to fit different distributions with different methods on a case-by-case basis.

The general discussion about the accuracy of wave data contained in the wave databases is given in [13], where some effects like the quality of the wind forcing model, scarcity of the satellite altimeter data, and the resolution in space and time are emphasized as highly important. The comparison performed in [15] has found that extreme heights in storm conditions predicted by the WWA are higher compared to the ERA5 reanalysis database, hence supporting the usage of WWA, confirming the statement in [13] that ERA5 tends to underestimate extreme wave heights.

The study presents results of the extreme value analysis of wave heights in the Adriatic Sea by considering simultaneously physically similar processes, i.e., waves generated by *bora* and waves generated by *Jugo* for directional analysis and waves generated in each month for within-year variability analysis. The main advantage of the proposed method lies in having directional and seasonal maxima that, as we could observe, can sometimes exceed the ones derived from the whole dataset. Also, extreme values obtained by system probability, i.e., combining distributions from individual directions, are always conservative. The approach is slightly more complex than the conventional analysis and requires a large dataset containing many years of uninterrupted records with high temporal resolution. Since a lot more fitting is performed compared to the conventional method, the proposed methodology is more sensitive considering distribution fitting uncertainty.

The method presented is general and can be employed for any location where long-term continuous data about sea states are available from either measurements or numerical reanalysis. It is of particular interest to investigate the applicability of the method to the North Atlantic, which is the design wave environment for ship structures. Although wave databases are considered in the development of the design wave climate, the effects of wave directionality and inter-annual variability are currently not considered in ship structural design, which means that wave data are probabilistically considered on an annual basis without considering the variability of wave conditions through the months [24]. The effect of the intra-annual variability in the North Atlantic is analyzed by [6], where a moderate increase of design significant wave height is obtained. Wave directionality is also currently not considered, and it is assumed that waves from all directions are equally probable. The effect could be potentially important, as indicated by [25]. Namely, the dominant storm conditions in the North Atlantic are storms being generated in the regions around Newfoundland, which then travel across the ocean towards the Azores islands and Portugal. For ships crossing from Europe towards the USA, the storms will be on the starboard side, but in the other direction, the storms would be on the port side of the ships. Therefore, it would be reasonable to investigate this effect in the North Atlantic for implementation in ship design. It is to be mentioned that results obtained for the Adriatic Sea should not be mapped to other regions, as wave generation processes occurring in the Adriatic basin are peculiar and strongly controlled by the relationship between basin geometry and variations in wind intensity and directions.

5. Conclusions

Extreme significant wave height statistics are developed for the Adriatic region by considering wind patterns and within-year climate variability. Results are based on the WorldWaves database, containing 23 years of continuous wave records. The analysis of extreme values is based on the system probability method proposed by Carter and Challenor [4]. Results are compared to the ones neglecting wind directionality and wave climate seasonality effects, suggesting the following:

- *Bura* is the wind pattern generating extreme wave heights in the north part of the Adriatic and along the west coast. Across the remaining part of the Adriatic Sea, *Jugo* is a dominating wind pattern. The only exception is the southernmost part of the Adriatic, where extreme waves may be generated by other wind patterns;
- The extreme value prediction considering wave directionality is, on average, 4% larger compared to the predictions when this effect is neglected;
- The extreme values predictions from individual directions can overshoot the ones derived from the whole dataset, i.e., by neglecting directionality. However, extreme values obtained by system probability, combining distributions from individual directions, are always conservative;
- The yearly maxima predominantly occur inside one or two directions, *Bura* in the north and along the west coast, and *Jugo* across the remaining part of the basin. The importance of wave directionality is increased near the Strait of Otranto because of the influence of other wind and wave patterns from the Ionian Sea;
- The extreme value prediction considering within-year climate variability appears as a more important effect, leading to, on average, 8% larger extremes compared to the prediction when this effect is neglected;
- Similar to the wave directionality, the within-year climate variability effect is more influential in the southern part of the Adriatic;
- The study reveals that neglecting wave directionality and within-year wave climate variability effects for the Adriatic Sea, in general, leads to an underestimation of the long-term extreme SWHs. Therefore, it is recommended to consider these effects when defining extreme environmental conditions for the design and analysis of marine structures operating in the Adriatic Sea.

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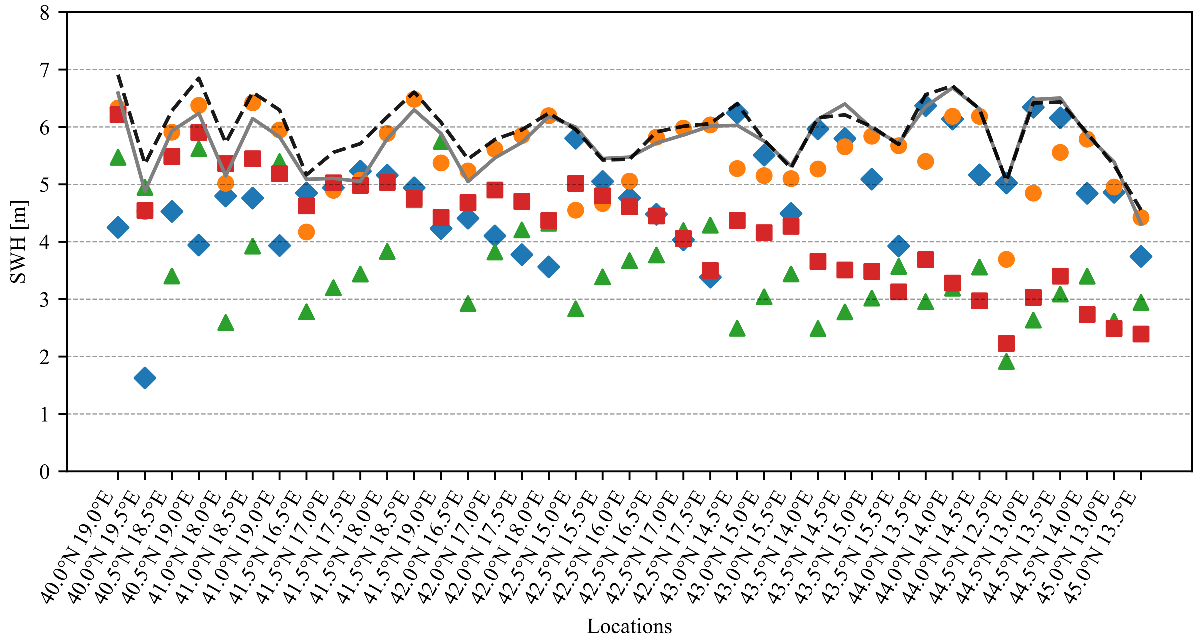
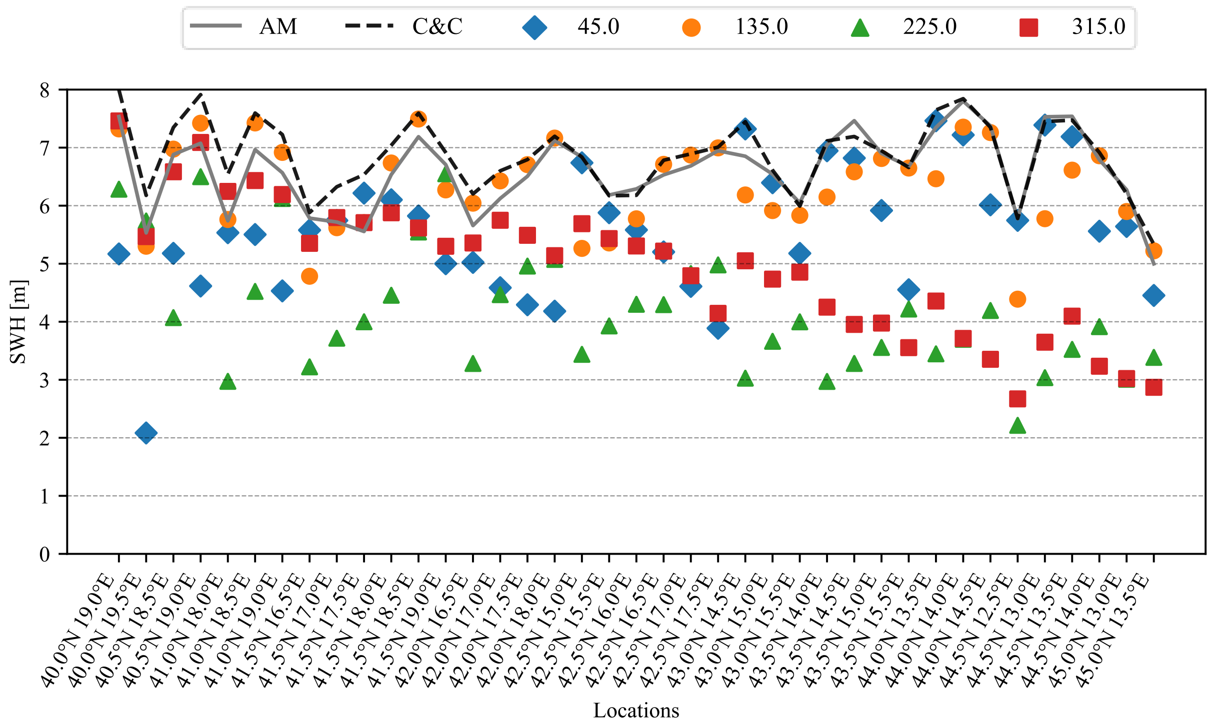
Appendix A

Comparison of maxima for individual directions and months with maxima obtained by AM and C–C method.

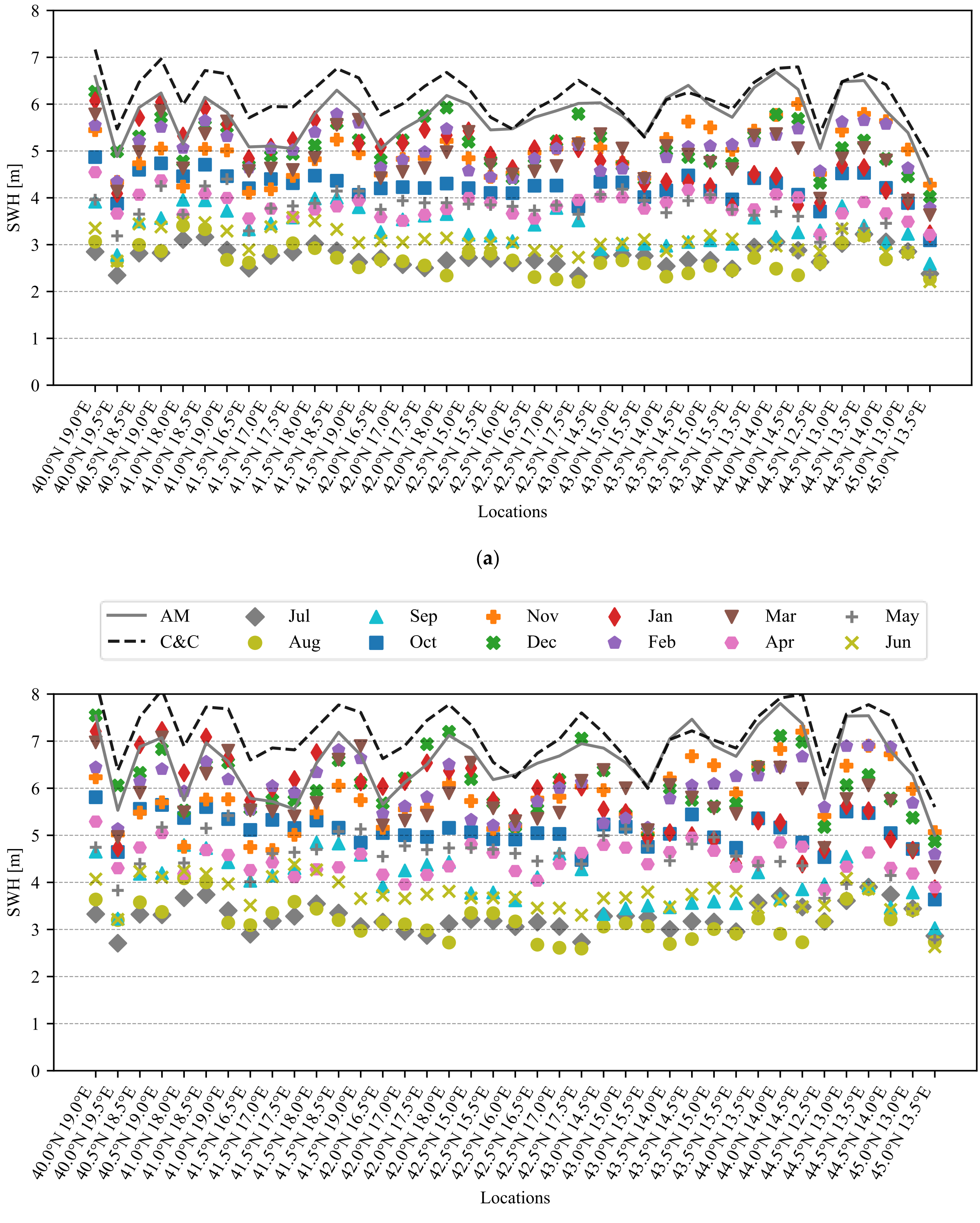


(**a**)



(**b**)

Figure A1. The extreme SWHs predictions calculated based on the return period: (**a**) 25 years; (**b**) 100 years. Markers represent results from individual directions, while the dashed gray line displays values obtained by the C–C approach combining DM.



(**a**)

(**b**)

Figure A2. The extreme SWHs predictions calculated based on the return period: (**a**) 25 years; (**b**) 100 years. Markers represent results from individual months, while the dashed gray line displays values obtained by the C–C approach combining MM.

Appendix B

Histograms and probability density plots of fitted Gumbel distributions for three characteristic locations: (a) Directional maxima; (b) Monthly maxima.

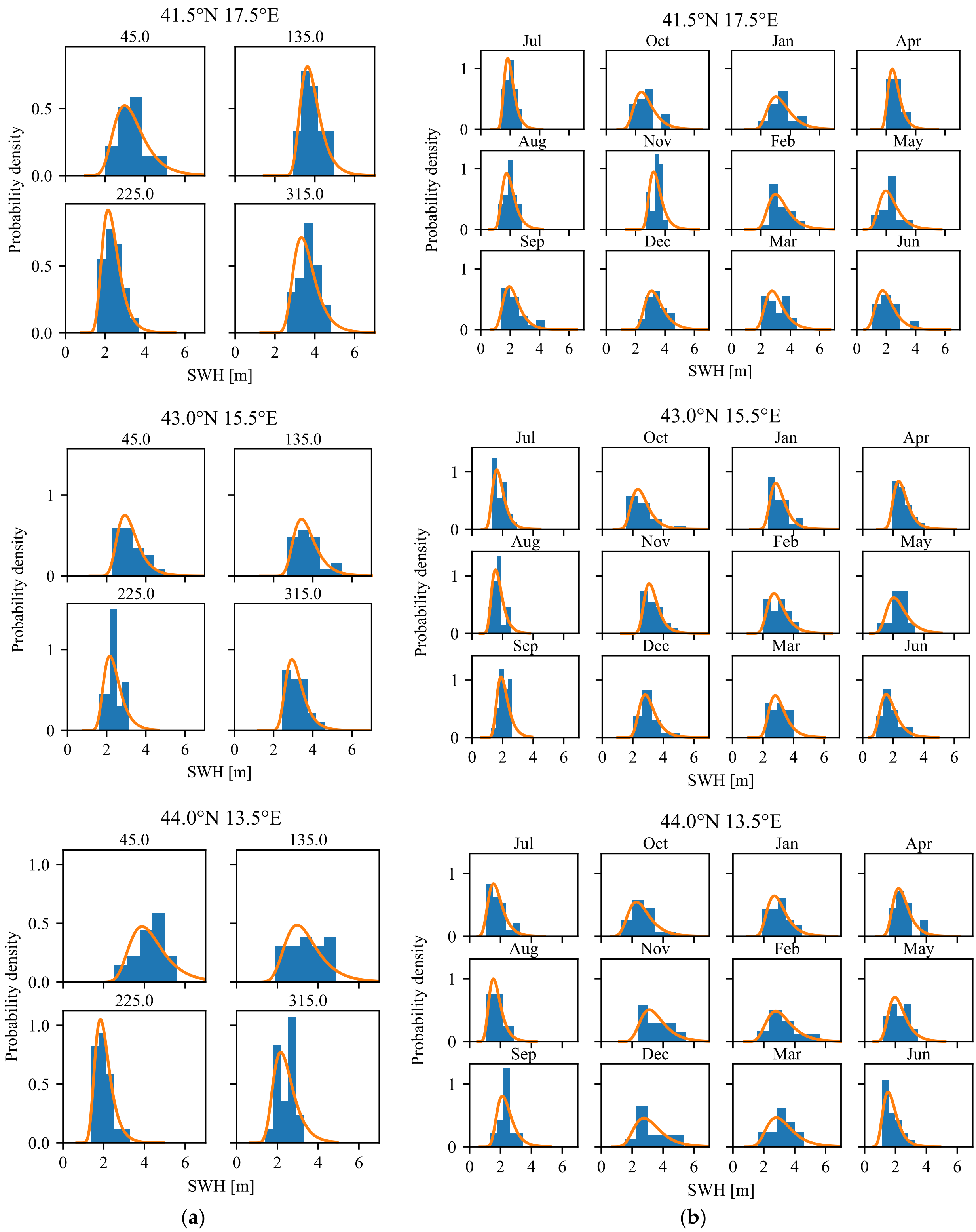


Figure A3. Histograms of SWH maxima and PDF plots of fitted Gumbel distributions for three characteristic locations: (**a**) Directional maxima; (**b**) Monthly maxima.

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