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Influence of the North Atlantic Oscillation on Extreme Waves Forecasting - Study Region in the Moroccan Coast

Hosny BAKALI, Ismail AOUICHE, Najat SERHIR, Mostafa BAHLOUL

Abstract
Extreme wave height generally considered for maritime structures design is the one hundred years return period wave. It is determined by forecasting from available wave data over few decades. Research carried out since the 1990s has shown the presence of a cyclical variation in north Atlantic meteorology, this variation is correlated with the sea states. In this work, we present the significant impact of the North Atlantic Oscillation (NAO) on the frequency and magnitudes of storms in the study area located in the Atlantic coast of northern Morocc. The NAO cyclical variation of sea states implies the variation of forecasted extreme waves obtained by statistical analysis. Consideration of the NAO in the choice of wave data is essential for a correct choice of a representative sample of sea state variation and obtaining forecasted extreme waves for a safe design of maritime structures.

Keywords: North Atlantic Oscillation; wave recording; extreme analysis method; hundred years return period wave; sea state

1. Introduction

Over the past decades, understanding the long-term variation of wave climate in the North Atlantic has been the subject of several discussions. Most studies show that inter-annual changes in waves heights are linked to climatic factors represented mainly by the North Atlantic Oscillation Index. The authors of (Hurrell and James W. 1995), (Hurrel and Van Loon 1997), (W. Hurrell et al. 2003) presented the impact of the North Atlantic oscillation index on the climate in the northern hemisphere: Precipitation, temperatures, storms. Also, the European project (WASA Group 1998) concluded that the variation in sea state in the East Atlantic and North Sea is in part related to the North Atlantic Oscillation. The study of the spatial variation of the relationship between the NAO index and the mean parameters of sea states indicates a positive correlation in high latitudes (Dodet et al. 2010); (Bacon and Carter 1993).

The NAO index represents the pressure difference at sea level between the subtropical high atmospheric pressures (Azores and Gibraltar areas) and low pressures in Reykjavik (Iceland) (Jones et al. 1997). It could be the most important factor influencing wave heights in the Atlantic Ocean (WASA Group 1998). Several works have studied the relation between the variation of the NAO index and ocean storms in the North Atlantic which have shown a strong correlation between the variation of the NAO index and the heights of waves in the coasts of Norway and Scotland and a less important correlation in Portuguese coast (Bauer 2001).

In coastal engineering, the prediction of significant wave heights for different return periods is a crucial step in the design of maritime structures, therefore, authorities and designers must have a precise description of the statistical properties of sea states to avoid damages caused by storms. The influence of the NAO index variation on the wave height may have a significant impact on the prediction of significant wave heights used in the design of coastal structures. Hence, it is necessary to identify this impact by studying the correlation between wave data and the cyclic variation of the NOA index.

In sea states studies, the availability, as well as the precision of wave data over long periods is crucial. Therefore, a large number of approaches have been explored for studying sea state variation, they are based on: visual observations, buoys recordings, satellite measuring, and finally numerical modeling. Based on measurements at the Hamburg site in Germany, the authors of (Grevemeyer et al. 2000) indicate an increase in heights and occurrences of extreme waves over the period from 1954 to 1998. Analysis of satellite wave data in the North Atlantic over the period from 1985 to 1999 has shown that the inter-annual variation of the NAO index may be the main source of the variation in sea state (Woolf et al. 2002). The work of (Wanner et al. 2001) provides a general description of the meteorology in the North Atlantic, indeed, according to the sign of the NAO index, a positive NAO index characterizes rainy winters in northern Europe and dry and cold winter in northern Africa. Opposite meteorological states are observed and more storms are directed to the south over periods with negative NAO index.

Available studies provide considerable information in the North Atlantic higher latitudes over 40° N where most developed countries are located, however, less information is available in low latitudes. The study area is located in the northern Moroccan coast (between Kenitra and Safi cities), this region is the leading urban zone and the economic hub of Morocco. The socioeconomic interest of the study area characterized by the largest port infrastructures in the country as well as the availability of wave data from the Spanish measurement network and wave recordings by buoys make this region particularly relevant and interesting for studying the influence of the variation of the NAO index on extreme waves forecasting.

2. Methodology

2.1 Study area and data subdivision

The first waves measurements by buoys were carried out in the sixties (Walden and Nasmyth 1970), these measurements enabled for studying the evolution of sea state in the north Atlantic and indicated a worsening of the sea state during the 1970s compared to the 1960s (Draper 1986). Since the 1990s, the inter-annual change in sea states has been justified by factors as the North Atlantic Oscillation and climate change (Alcock et al. 2003); (WASA Group 1998).

Recent studies of the relationship between wave height and the NAO index concluded that the correlation between the two parameters varies both: spatially and temporally. Indeed, satellite data indicated a maximum correlation in western Ireland (Dodet et al. 2010), the correlation is more significant in winter than in summer (Woolf et al. 2002). No study has focused on evaluating this type of correlation in the south between latitude 30° and 35°.

The impact of the NAO index variation on extreme waves forecasting is studied by (Gleeson et al. 2019) on the coast of Ireland; results obtained indicate that periods with a positive NAO index are associated with higher values of forecasted extreme waves. The spatial variation of the correlation between the NAO index and sea states requires other local studies of the NAO impact on extreme waves forecasting.

The study area is located between the cities of Kenitra and Safi on the Atlantic coast in northern Morocco. The choice of this area is related to:

- The concentration of the country's major port infrastructures: Future Port of Kenitra Atlantique, Port of Mohammedia, Port of Casablanca, Port of Jorf Lasfar, Several fishing ports and marinas;
- The concentration of more than the third of the Moroccan population, with a strong littoralisation of this coast,
- Fig. **1** shows the concentration of the population and the big cities of Moroccan north Atlantic coast;
- Availability of sea state data over a long period of 62 years (1958-2019);
- The traffic of ports in the study area represents about two-thirds of the overall traffic of Moroccan ports (Fig. 2).

Fig. 1: Main cities and port infrastructures in the study area – Source: Ezilon Maps.

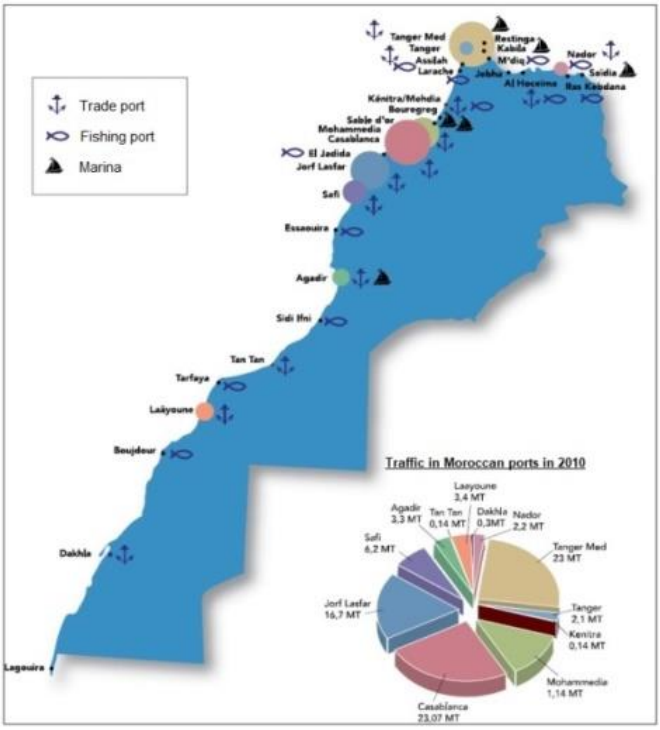


Fig. 2: Map from the National Port Development Plan for 2030, illustrating the volumes of traffic in the main ports Morocco in 2010 – Source: 2030 National Port Strategy.

This paper aims to identify the impact of the NAO index on the values of predicted extreme waves. Two statistical approaches are adopted: The annual maxima method (MA) and Peak Over Threshold method (POT). The two approaches are applied to 62-years of SIMAR-44 database generated by Puertos del Estado, wave parameters (significant height Hs, peak period Tp, and direction) were obtained from the WAM model forced by the wind. We split the 1958-2019 data period into three samples according to the variation of the NAO index as shown in Fig. 3. In the Moroccan Atlantic coast, maximum waves occur mainly during the winter months, consequently, we analyzed only the NAO index and wave heights during the winter months.

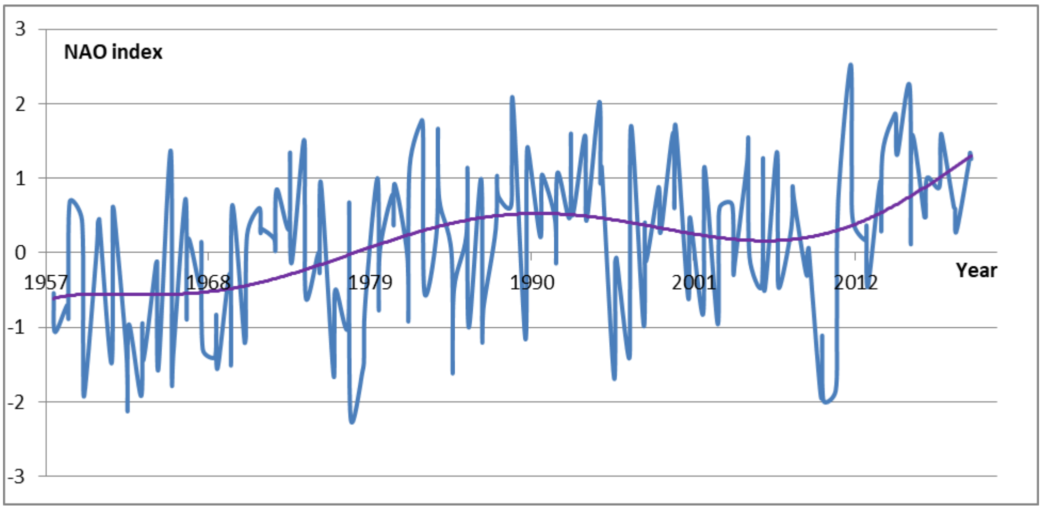


Fig. 3: Curve of variation of the NAO index for the winter months of the period 1958 to 2019 "National Center for Environmental Information (NCEI)".

- Period 1: From 1958 to 1979: Negative trend in the variation of the NAO index,
- Period 2: From 1979 to 1999: Trend curve towards positive values of NAO index,
- Period 3: From 1999 to 2020: Trend curve in positive values of NAO index, with values lower than the previous period over the first decade and an increase over the last decade

Analysis is carried out in the three above-mentioned periods. The data ranges will be analyzed for:

- Studying the impact of the NAO index variation on sea state: For each period, we will study the correlation between the NAO index and the storms number occurrence as well as their magnitudes,
- Studying the impact of the variation of the NAO index on extreme wave forecasting: We will analyze the wave data for each data period to determine the 100 years return period extreme wave,
- Studying the spatial variation of the influence of the NAO index on extreme wave forecasting: 62 years of wave data will be analyzed in three points N°1052038, N°1050036, and N°1042030 representing the three regions; Kenitra, Mohammedia, and Safi, as indicated in Fig. 4.

Fig. 4: Locations of the three points of the study area.

2.2 Extreme analysis method

2.2.1 Maxima Annual Method

The Maxima Annual method is the former method (Ferreira and De Haan 2015), it consists in subdividing data into periods of identical sizes and retaining the maximum value of each period. For the case of the study of natural phenomena (waves, rainfall, etc.) and considering the seasonal variation of these phenomena, the period of the subdivision is equal to one year, in this particular case the approach is designated by the Maxima Annual method.

2.2.2 Peak Over Threshold (POT)

The Peak Over Threshold method was developed by (Pickands 1975), it consists of retaining independent and identically distributed values exceeding a censoring threshold set by the user. In comparison with the Maxima annual method that can neglect large values and retain smaller ones. The POT method has the advantage of retaining all the maximum values exceeding the pre-fixed threshold (Ferreira and De Haan 2015).

2.3 Software used

To carry out the statistical analysis of the data, we used the HYFRAN-PLUS software. It is developed for the analysis of hydraulic data that allows the adjustments by several statistical models and the comparison between different fittings by graphical method and the goodness-of-fit tests (EL adlouni and Bobée 2014).

2.4 Method for selecting wave heights for the POT method

2.4.1 Independence condition

The condition of independence of two successive storms is considered to be verified if the autocorrelation function of the wave recording calculated for time step DT is between 0.3 and 0.5, DT is the time between two extreme values of successive storms (Mathiesen et al. 1993). More practical methods allow the development of an algorithm for the selection of maximum values of storms. (Mazas and Hamm 2010) recommends the verification of three criteria for the choice of extreme waves, these criteria are fixed for each site depending on local sea conditions:

- Criterion 1: The minimum duration of the storm above the chosen threshold u_0 is greater than or equal to N_H,
- Criterion 2: The recorded values of Hs can fall below the threshold u_0 during a duration n_H ($n_H < N_H$). Parameters N_H and n_H are fixed for each ocean condition, for example, for Mediterranean Sea N_H = 12 h and n_H = 6 h (Mazas and Hamm 2010).
- Criterion 3: A minimum interval of 1 to 3 days is observed between two extreme values of two successive storms to verify the criterion of independence of events.

According to (Caires and Sterl 2005) two maximum values of Hs belong to the same storm if they occur within an interval of less than 48 hours. In our analysis, and to ensure the independence of the events, we will adopt the criterion of minimum interval between two successive extreme wave heights of 48 hours.

2.4.2 Determination of the threshold

The POT method proposes different approaches to estimate a censoring threshold beyond which observations will be considered as extreme values. The threshold must be large enough to select significant extreme events, but not too large to keep a sufficient number of observations to obtain a good approximation of the theoretical model parameters (Coles 2001). The mean excess function (MEF), which describes the prediction of exceeding the threshold u when an excess occurs, is defined by:

$$\hat{e}_n(u) = \frac{\sum_{i=1}^{n}(X_i - u)_{\{X_i>u\}}}{\sum_{i=1}^{n} 1_{\{X_i>u\}}}$$

A linear trend of the Mean Excess Function from a threshold u_0 indicates a stabilization of GPD model parameters σ_u and ξ. We, therefore, assumed that the fitted model to studied samples is the GPD, we will see later that other models fit with the analyzed data, this hypothesis requires a demonstration of its validity.

2.5 Calculation of empirical probabilities of non-exceedance

The general formula for determining the empirical probabilities of non-exceedance is (2):

$$P_k = \frac{k-\alpha}{n+1-2\times\alpha} \quad (2)$$

We will retain the compromise distribution retained by (Cunnane 1978), with $\alpha = 0.4$.

2.6 Method for selecting the best-fitted statistical model

The choice of best-fitted model to study samples is made by a multi-distribution analysis. The models examined are Gumbel, GEV, Weibull, Gamma, Gamma inverse, Log normal, Pearson type III, and exponential. The choice of the best-fitted model is made by following two steps:

- Step 1: Graphical examination: We will keep the models that graphically fit the sample and in particular with the extreme quantiles
- Step 2: Final choice: The goodness-of-fit tests are used as a decision aid, we will make sure that the chosen model minimizes the value of Chi2-squared test (Pearson 1900) and the values AIC-BIC tests proposed by (Hirotugu 1974) and (Schwartz 1978).

For M/N <40 (N is the size of the sample and M is the number of freedom degrees of the model), we will correct the value of AIC by the formula (3) (Hurvich and Tsai 1989)

$$\text{AICc} = \text{AIC} + \frac{2\times(M+1)\times(M+2)}{(N-M-2)} \quad (3)$$

3. Results & Discussion

3.1 Relation between NAO index and wave occurrence

We analyzed the occurrences of storms in the study area in the winter months (December, January, February) according to the values of the average monthly NAO index (It will be designated in this paper by NAO_m). Figure 5 shows the number per month of storms with H_s>5m as a function of the NAO_m. We chose a threshold value H_s=5m because it is near to the values of thresholds determined by the MEF (Par. 3.2).

The graphical analysis indicates that a threshold of NAO_m = 0.5 presents an upper limit describing the months with the majority of storms.

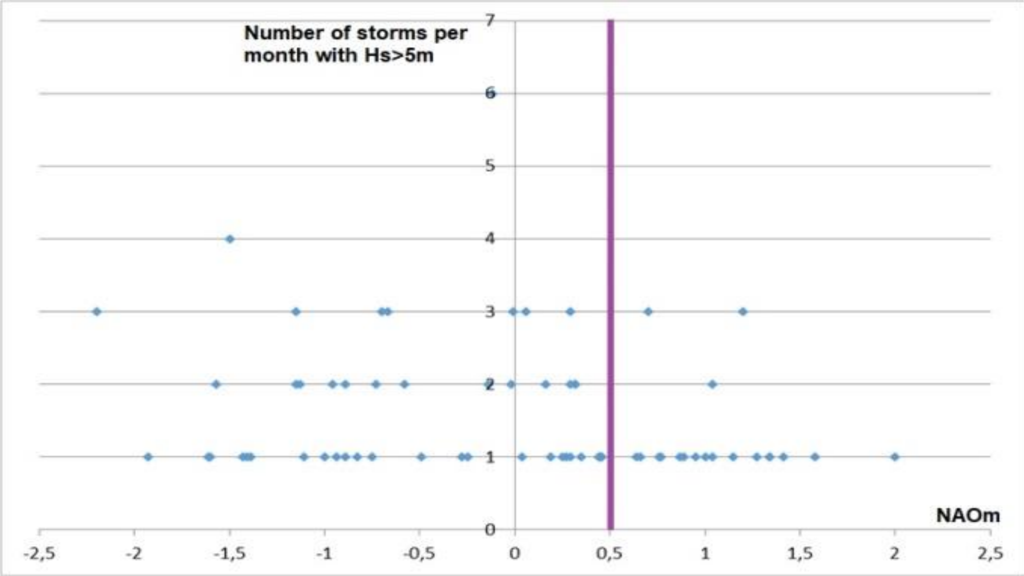


Fig. 5: Number of storms with Hs>5m by month as a function of the NAOm.

Subsequently, we distributed the storms according to the NAO_m and the three periods considered 1958-1978, 1979-1999, and 2000 to 2019. Figures 6, 7, and 8 illustrate the results obtained, the results highlight the following points:

- Over the period from 1958 to 2019, the number of months with NAO_m <0.5 is 114 (60% of winter months), and the number of months with $NAO_m \geq 0.5$ is 72 (40% of winter months);
- Over the entire period from 1958 to 2019, 70% of significant storms (greater than 5 m) are concentrated in the months characterized with NAO_m <0.5;
- The period from 2000 to 2019 is characterized by the lowest number of extreme events (storms greater than 7 m) compared to the four previous decades;
- 90 % of extreme events with a significant wave height superior to 7 meters occur in months characterized by a NAO_m <0.5;
- The probability of significant storms occurrences (with Hs>5m) during months of NAO_m <0.5 is 40% greater than during months of NAO_m> 0.5.

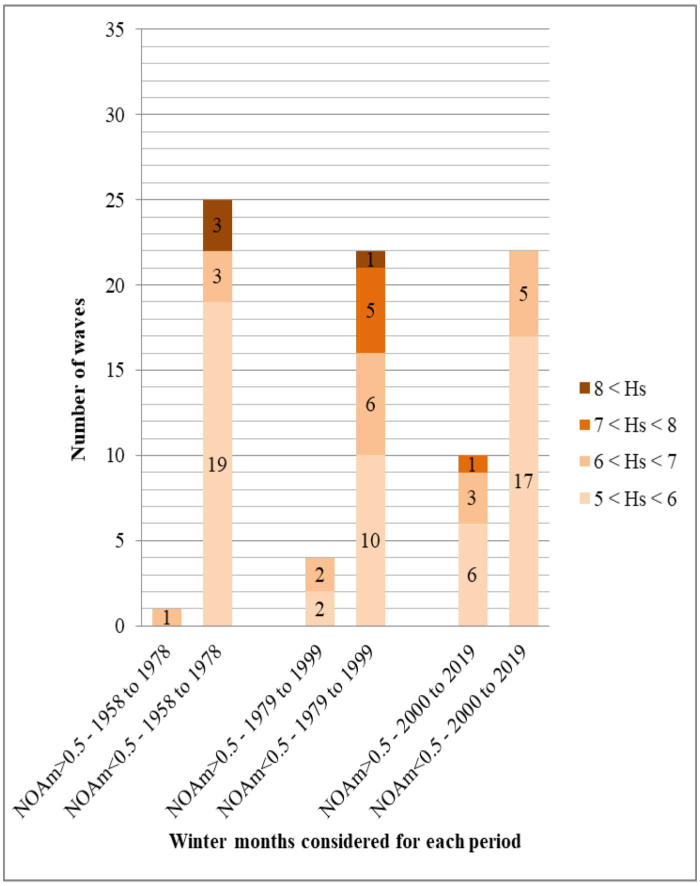


Fig. 6: Distribution of storms according to the value of the monthly NAO index over the three periods of wave data on the coast of KENITRA.

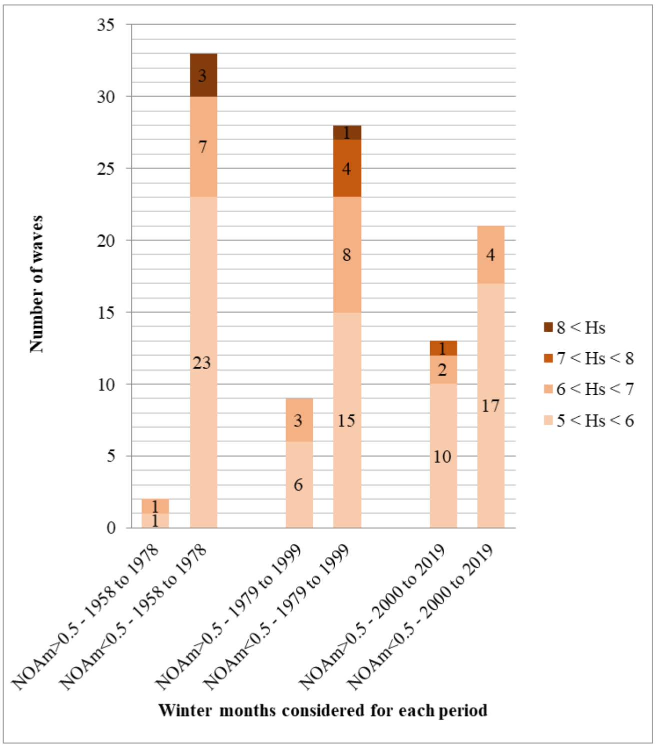


Fig. 7: Distribution of storms according to the value of the monthly NAO index over the three periods of wave data on the coast of Mohammedia.

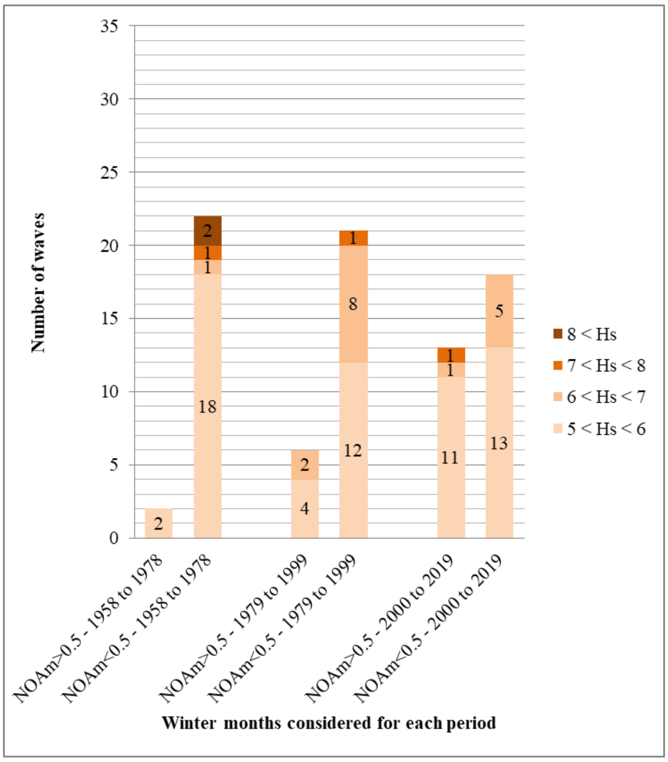


Fig. 8: Distribution of storms according to the value of the monthly NAO index over the three periods of the wave data on the coast of SAFI.

Therefore, the variation of sea state in the study area depends on the NAO cycle, most extreme waves with Hs>7m occur in months with NAO_m<0.5. Furthermore, the overall comparison of waves occurrence dependency on the NAO_m indicates that there is an increasing trend in extreme wave occurrence during months with NAO_m> 0.5 and a decrease in the frequency of extreme waves overall the period from 1958 to 2019, these trends could be linked to other climate change factors. The decrease of the frequency of extreme events complies with other studies concerning the evolution of sea state during the 21st century; the study achieved by (Alvaro et al. 2013) indicates a decrease in average and extreme wave heights in the middle and low latitudes of the North Atlantic.

We find that periods characterized by low NAO_m include most of the extreme storms in the study area, other studies have indicated the same trend in the mid-latitudes of the North Atlantic (Dodet et al. 2010); (Bacon and Carter 1993). The concentration of storms in periods of low NAO_m could be due to their directions of origin. Indeed, by examining the directions of extreme waves we find that they are located between 300°N and 320°N. This direction is explained by the fact that lesser overpressures during the low NAO_m period in the Azores favor the deviation of storms towards the Moroccan Atlantic coast (Wanner et al. 2001) following the observed direction of extreme waves origin.

In the following section, we will study the forecasted extreme waves for each period according to the NAO cyclic variation, our objective is to study the impact of the variation of the NAO_m on the values of the 100 years return period wave height which is very used in designing coastal structures

3.2 Statistical analyses

3.2.1 Example of determining the optimal censorship threshold for the POT method

In figure 9, we present the Mean Excess function for the wave data for the period from 1958 to 2019 at the point in Mohammedia's coast, the thresholds are determined from the linearity of the Mean Excess Function (Coles 2001).

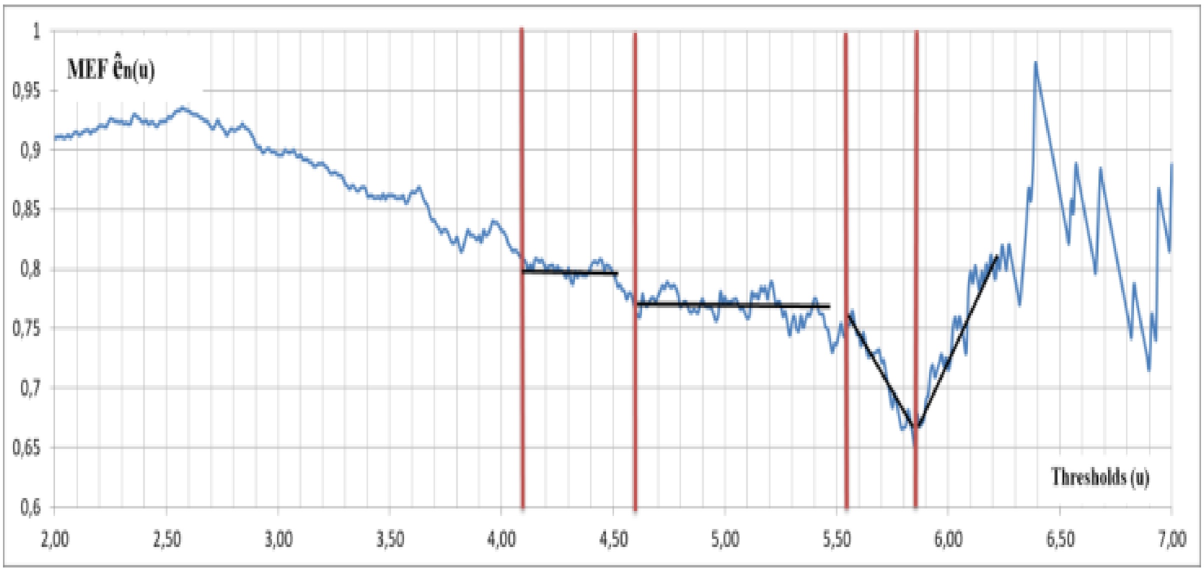


Fig. 9: Mean Excess function for wave data for the period 1958 to 2019 at the point on the coast of Mohammedia.

We present in table 1 the four thresholds that can be chosen according to the Mean excess method. The threshold to be chosen should allow the selection of a total number of storms which corresponds to an average number per year between 2 and 5 (Mazas and Hamm 2011). Consequently, the optimal threshold retained is $u_0 = 4.60$ m.

Table 1: thresholds that can be chosen according to the Mean excess method.

Threshold	Value	Number of events considered	Average number of waves per year Na
U_{01}	4,10 m	447	7,21
U_{02}	4,60 m	226	3,64
U_{03}	5,55 m	72	1,16
U_{04}	5,85 m	55	0,89

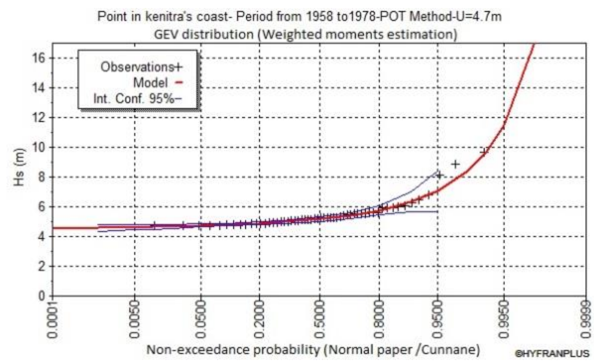
3.2.2 Results of the graphical adjustments of models adopted for the POT method

Figures 10, 11 and 12 present the results of the graphical adjustments for data analyzed by the POT method. For each sample, we present the most fitted model determined by a multi-distribution analysis as indicated in par. 2.6. Thresholds determined in the three points are:

- Point in Kenitra's coast: u_0 varies from 4.5 to 5 m
- Point in Mohammedia's coast: u_0 varies from 4.6 to 5.1 m
- Point in Safi's coast: u_0 varies from 4.5 to 4.8 m

All determined thresholds are between 4.5 and 5.1 meters, their values vary slightly by less than 10%. In the Safi point located at the south of the study area thresholds values are slightly less than the points in the north, it could be due to the fact that wave's heights are less important in this area. The 100 years return period waves determined by the POT method are:

- For the period from 1958 to 1978: The forecasted values are equal to 9.27m in Safi's coast and from 12 to 12.2 m in the two points in the north
- For the period from 1979 to 1999: The forecasted values are equal to 8.36 m in Safi's coast and from 10.44 to 10.7 m in the two points in the north
- For the period from 2000 to 2019: The forecasted values are equal to 8.72 m in Safi's coast and from 7.86 to 8.75 m in the two points in the north



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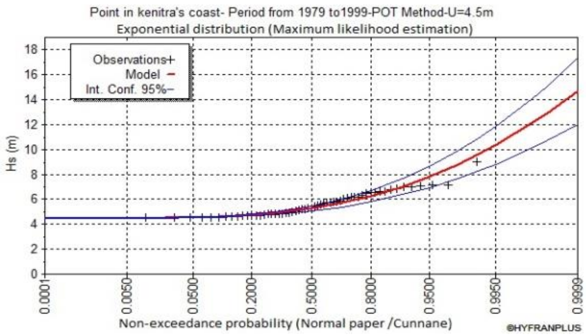

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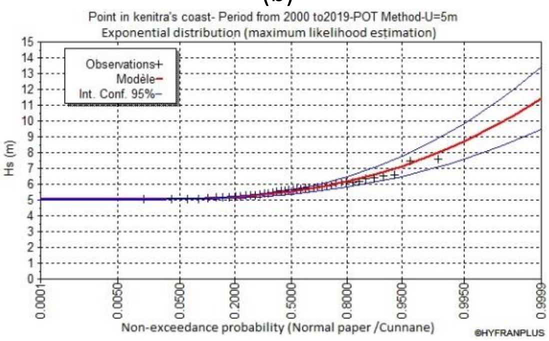

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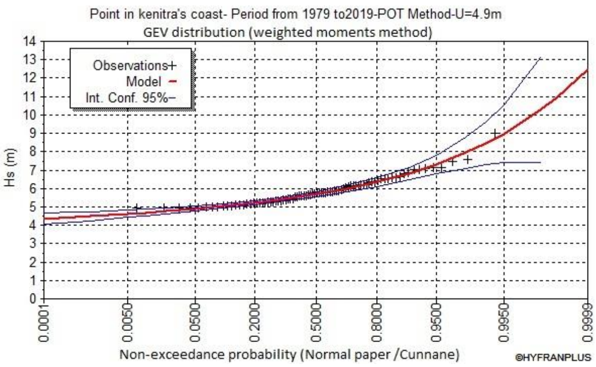

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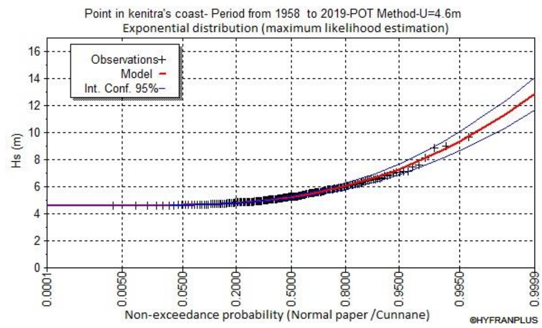
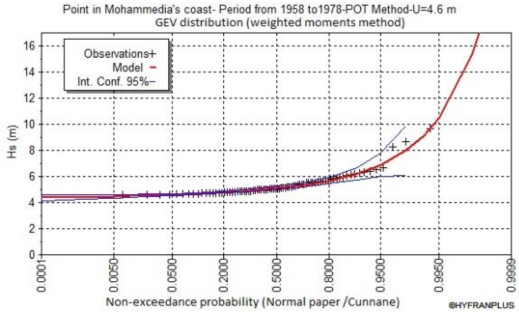


(e)

Fig. 10: Results of graphical adjustments of wave data selected by the POT method on the coast of Kenitra for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c)), 1979 to 2019 - Fig(d), and from 1958 to 2019 - Fig(e).



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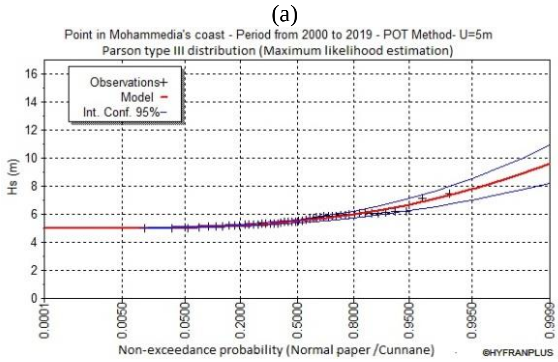

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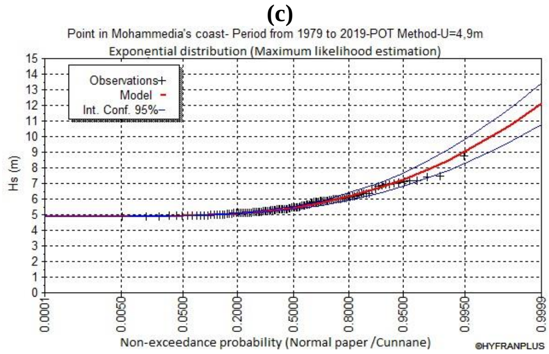

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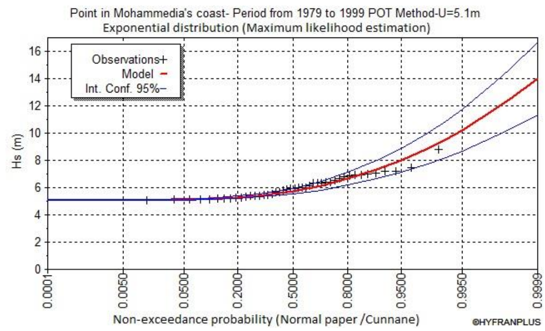

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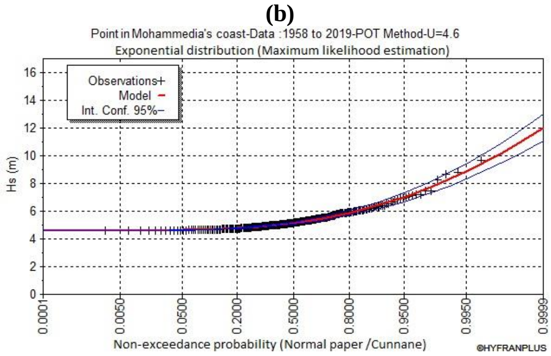
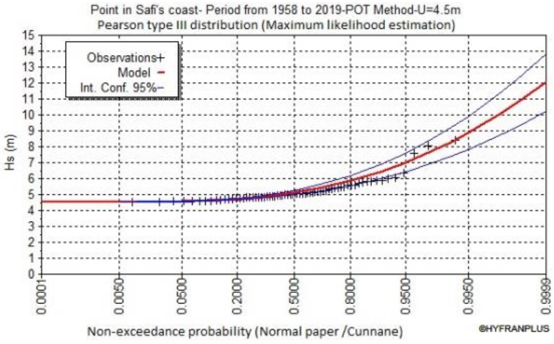


(e)

Fig. 11: Results of graphical adjustments of wave data selected by the POT method on the coast of Mohammedia for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c), 1979 to 2019 - Fig (d), and from 1958 to 2019 - Fig (e).



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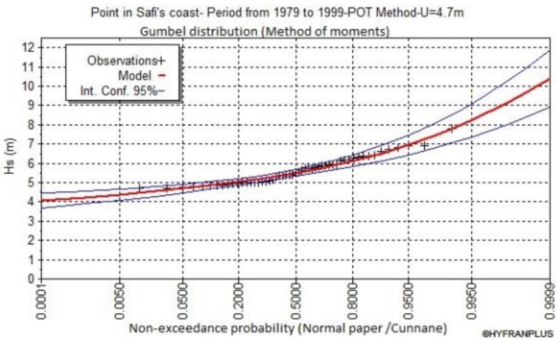

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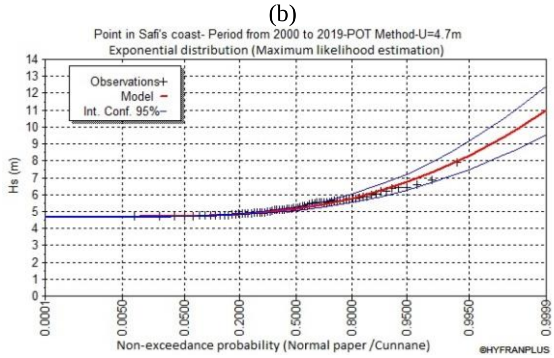

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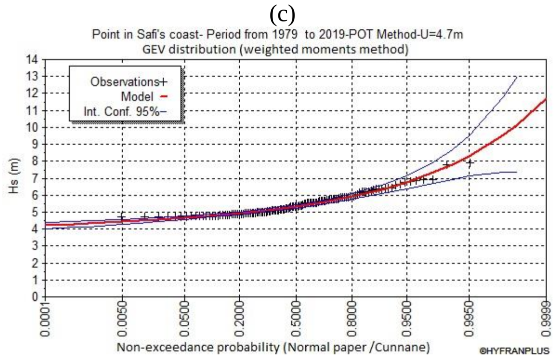

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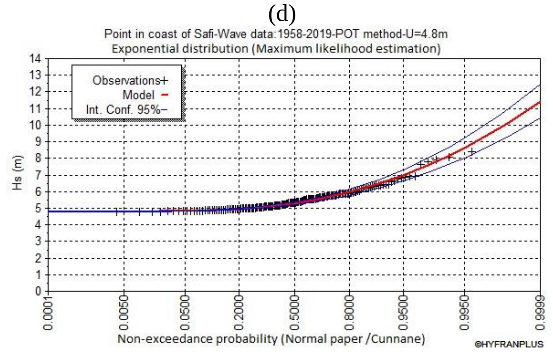


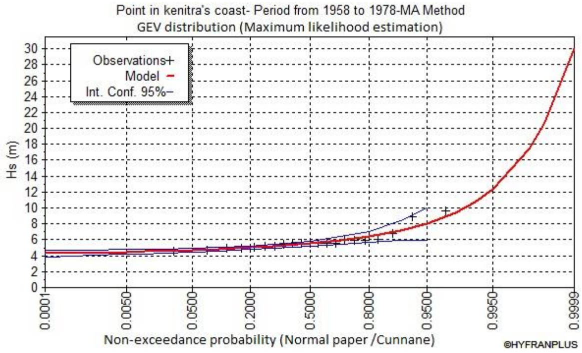
(e)

Fig. 12: Results of graphical adjustments of wave data selected by the POT method on the coast of Safi for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c), 1979 to 2019 – Fig (d), and from 1958 to 2019 - Fig (e).

3.2.3 Results of the graphical adjustments of models adopted for the MA method

The figures 13, 14 and 15 present the results of graphical adjustments of the models adopted for the MA method. The 100 years return period waves determined by the MA method are:

- For the period from 1958 to 1978: The forecasted values are equal to 8.83 m in Safi's coast and from 10.8 to 11.2 m in the two points in the north
- For the period from 1979 to 1999: The forecasted values are equal to 8.13 m in Safi's coast and from 8.62 to 9.25 m in the two points in the north
- For the period from 2000 to 2019: The forecasted values are equal to 8.51 m in Safi's coast and from 7.82 to 8.08 m in the two points in the north



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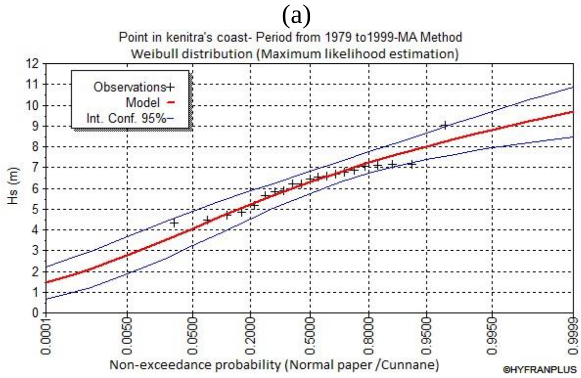
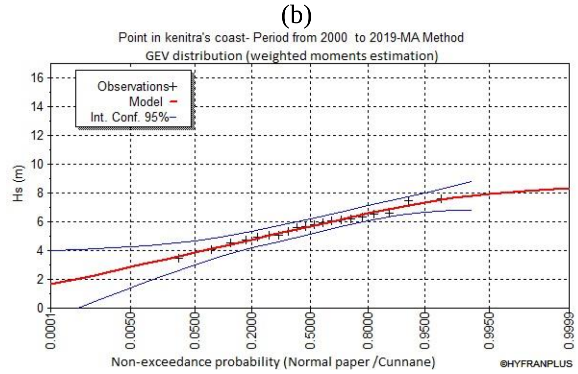
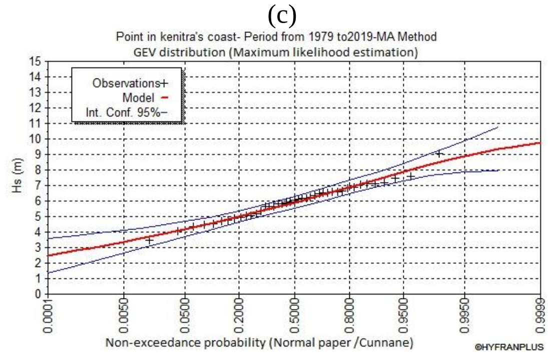


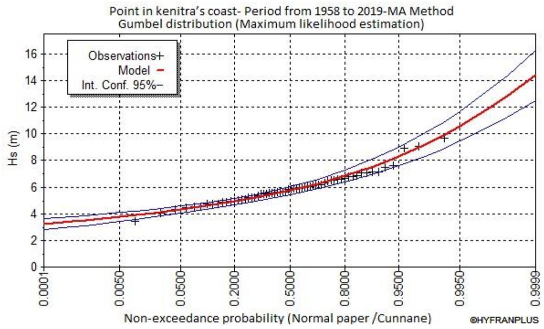
(b)



(c)

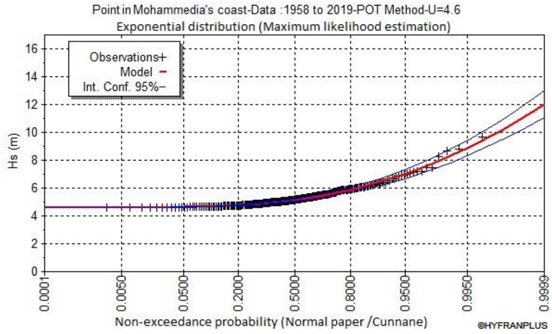


(d)



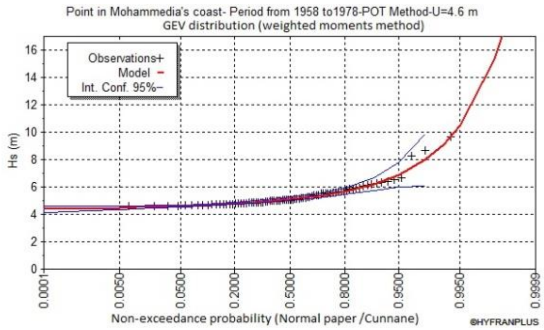
(e)

Fig. 13: Results of graphical adjustments of wave data selected by the MA method on the coast of Kenitra for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c), 1979 to 2019 – Fig (d), and from 1958 to 2019 - Fig (e).

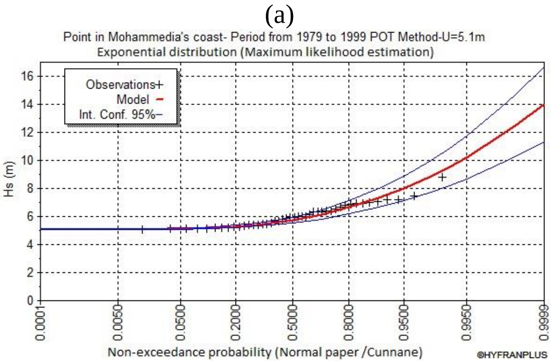


(e)

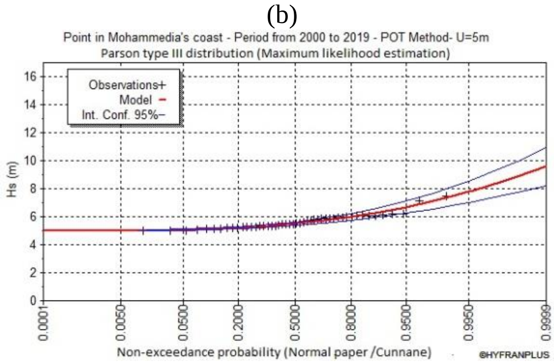
Fig. 14: Results of graphical adjustments of wave data selected by the MA method on the coast of Mohammedia for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c), 1979 to 2019 - Fig (d), and from 1958 to 2019 - Fig (e).



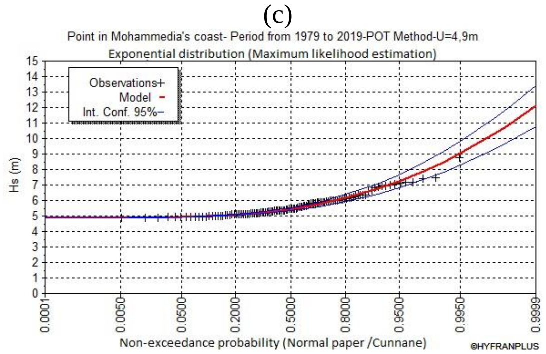
(a)



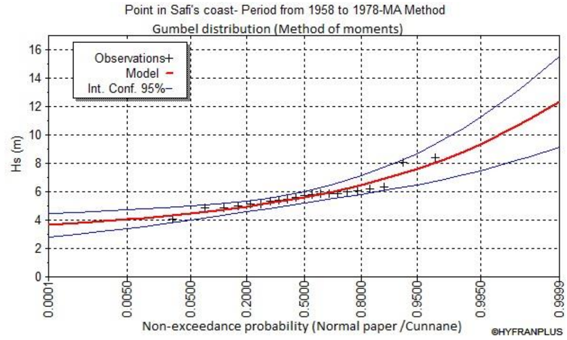
(b)



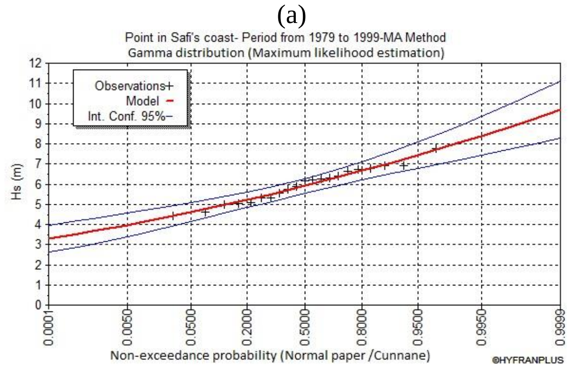
(c)



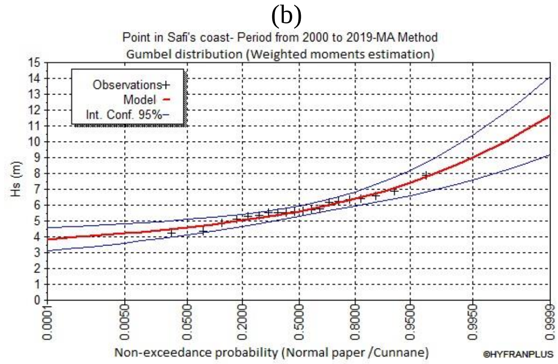
(d)



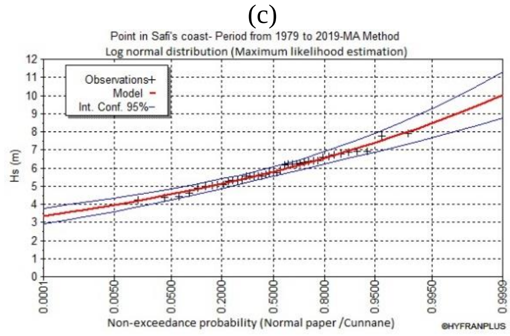
(a)



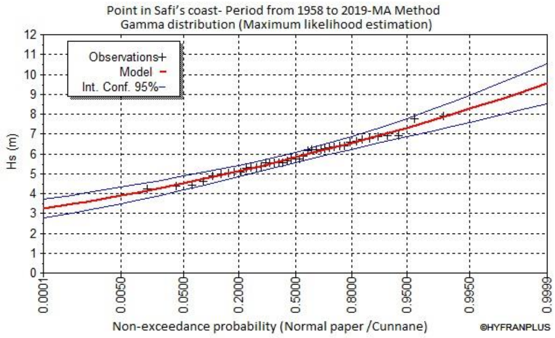
(b)



(c)



(d)



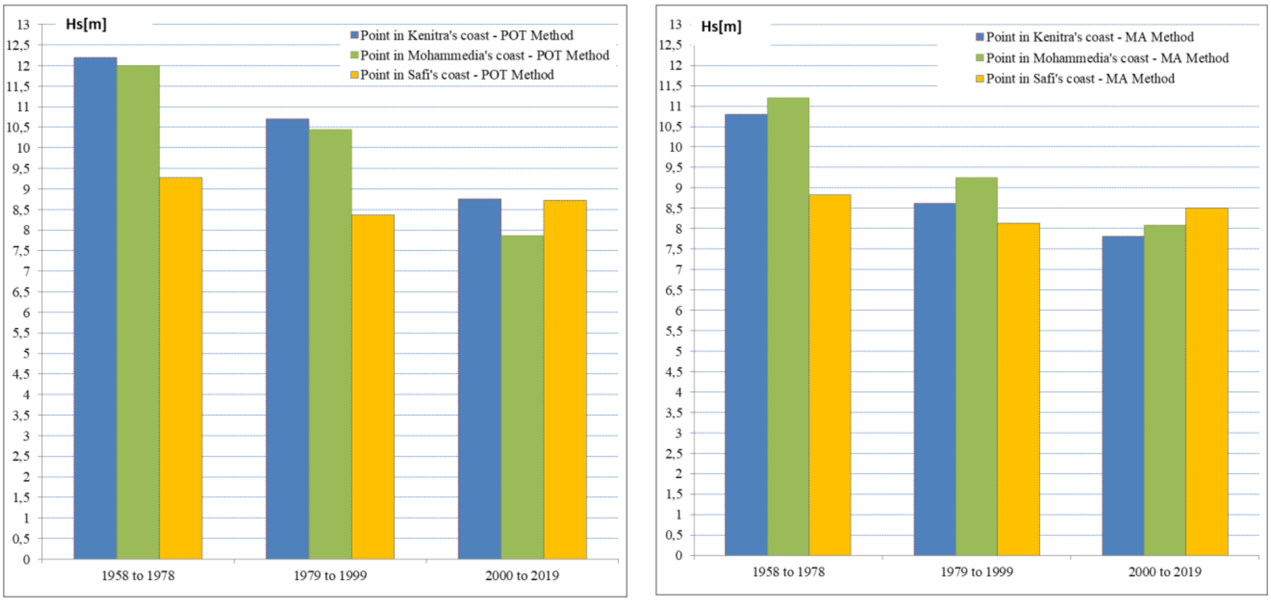
(e)

Fig. 15: Results of graphical adjustments of wave data selected by the MA method on the coast of Safi for periods from 1958 to 1978 - Fig (a), 1979 to 1999 - Fig (b), 2000 to 2019 - Fig(c), 1979 to 2019 - Fig (d), and from 1958 to 2019 - Fig(c).

3.3 Results of Statistical analysis for different periods

We present in Figure 16 the results of the 100 years return period waves (will be designated by 100y-Hs), for the three sub-periods from 1958 to 1978, 1979 to 1999, and 2000 to 2019, using the two methods POT and MA. We find that:

- The differences in the results between the MA and POT methods mainly concern the KENITRA point with a divergence of 10 to 20%, for other points the divergence of the results is less significant;
- Samples of waves of the period from 1958 to 1978 generate the maximum values of 100y-Hs, this is partly explained by the presence of three storms with significant height (Hs) superior to 8 m (recorded on 21-02-1966, 17- 01-1973, and 20-12-1973)
- 100y-Hs are minimal for the data period between 2000 and 2019 which is justified by the low number of extreme events recorded in this period in comparison with the previous four decades.
- The influence of the cyclic variation of the NAOm on 100y-Hs is most important in the points in the north of the study area. In fact, the difference of the 100y-Hs values between the two periods 1958-1978 and 2000-2019 is about three meters in the points in KENITRA's and MOHAMMEDIA's coasts. For the point in Safi's coast, the impact of the NAO cycle on the 100y-Hs is much less significant with a difference of less than 50 cm by comparing the two periods (1958-1978 and 2000 to 2019).



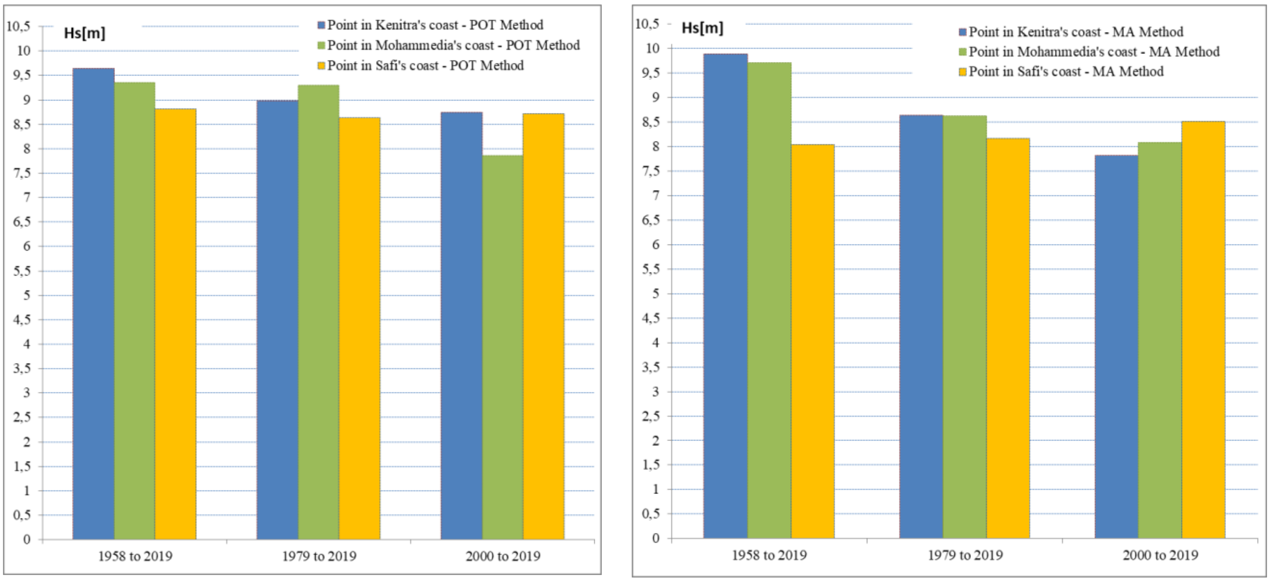
(a) **(b)**

Fig. 16: Results of significant wave's heights with a return period of 100 years for the three periods 1958-78, 1979-1999, and 2000-2019. (a) Results of statistical analysis with POT method, (b) Results of statistical analysis with MA method.

3.4 Impact of the data size on the variation of 100y-Hs

We saw in the previous section that periods with small values of NAO_m are characterized by the higher occurrence of extreme waves, this character has a consequence on the 100y-Hs independently of the calculation method (MA or POT). In this section we will study the variation of 100y-Hs depending on data size, our goal is to extend the data period to integrate the impact of the variation of the NAO_m on the 100y-Hs. We present in figure 17 the results of the 100y-Hs for longer data periods. From the results obtained for data durations of 62 years, 41 years, and 20 years we find that:

- Analysis of samples of the period from 2000 to 2019 gives the lower results for 100y-Hs for the two methods (MA and POT),
- The integration into the statistical analysis of wave data from the period 1958 to 1978 provides the safest wave results, this observation is valid for both methods (MA and POT),
- The impact of taking into account periods with a NAO_m <0.5 is more significant for the two points in the north of the study area (Points in KENITRA's and MOHAMMEDIA's coasts)



(a) **(b)**

Fig. 17: Results of significant wave's heights with a return period of 100 years for the three periods 1958-2019, 1979-2019, and 2000-2019. (a) Results of statistical analysis with POT method, (b) Results of Statistical analysis with MA method.

Considering a period of data characterized by a homogeneous NAO_m can lead to an overestimating or underestimating of the 100y-Hs. For example, taking into account the period from 1958 to 1978 overestimates the results of 100-y-Hs waves by 1 to 2 meters in comparison with the overall period, while considering the period from 2000 to 2019 implies an underestimation of the 100y-Hs by approximatively 1 meter.

4. Conclusions

In conclusion, we highlight that the occurrence probability of storms on the studied coast is partly explained by the NAO cycle, this observation is consistent with studies carried out in higher latitudes (Dodet et al. 2010) and (Bacon and Carter 1993). The study of wave data from 1958 to 2019 revealed that the occurrence probability of a significant storm (Hs> 5m) during a winter month with NAO_m <0.5 is 40% greater than during months with NAO_m> 0.5. Extreme storms of Hs greater than 7 meters are practically concentrated in winter months with NAO_m <0.5, indeed, during last 60 years, only one storm with Hs>7m occurred during a month with NAO_m> 0.5.

The correlation between the NAO cycle and storms occurrence in the studied coast requires consideration of the entire data period for forecasting 100y-Hs. Failure to take into account the period from 1958 to 1978 may imply an underestimation of the height of the 100y-Hs by about 1 meter in the north of the study area. In low latitudes, taking into account the period from 2000 to 2019 for forecasting 100y-Hs is sufficient, these conclusions should be validated by a global study of other points the mid-latitudes of the North Atlantic coast.

Over the entire 62-years period studied, we observe a general trend towards a decrease in the frequency and magnitude of wave heights, this trend is consistent with the results of studies of the evolution of sea states which have noted a general decrease in maximum annual wave heights during the 20th century (Wang et al. 2012). Hence, wave heights are non-stationary processes possibly due to long-term climate change. Rigorous estimation of the 100y-Hs must be determined by a non-stationary model as recommended by (Coles 2001). Even thought, the stationary model could be a safe hypothesis for the determination of the 100y-Hs generally considered for the design of maritime structures.

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