Galiatsatou, Panagiota; Prinos, Panayotis

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Analysing the Effects of Climate Change on Wave Height Extremes in the Greek Seas

P. Galiatsatou & P. Prinos
Department of Civil Engineering, A.U.Th., Thessaloniki, Greece

ABSTRACT: In the present work the effects of climate change on extreme values of the significant wave height are studied and analysed in selected areas of the Greek Seas. The available wave height data are divided in groups of equal size, corresponding to the present, the short-term and the long-term future climate. The analysis is conducted utilizing a non-stationary GEV model that simulates the variability within a year of wave height monthly maxima. The parameters of the model are simulated using harmonic functions of time representing the annual and the seasonal cycle. To determine the appropriate number of parameters in each point and time period and to avoid overparameterisation, the Akaike Information Criterion with correction for small sample size (AICc) is utilized and the selection is performed among twenty six candidate models. After selecting an appropriate model for the extremes, time-dependent quantiles of significant wave height within an one year period are assessed for each period and point considered. Apart from time dependent quantiles, annual return levels are also approximated by means of numerical integration of the fitted non-stationary model. The data used for extreme value analysis, are first corrected for bias using significant wave height data resulting from a wave prediction system forced with meteorological observations of the necessary atmospheric factors.

Keywords: Climate change, Bias correction, Non-stationary GEV, Monthly maxima, Time-dependent quantiles, Annual return levels

1 INTRODUCTION

Analysing and extrapolating extreme values of marine variables comprises a contemporary field of research and constitutes one of the basic components in estimating coastal flooding and erosion risks, in forming a modern framework for designing and upgrading coastal and marine structures and in understanding the basic physical processes in coastal areas. The former combined with the existing strong evidence for a possible change of the global climate associated with extreme events of higher intensity and frequency, intensify the interest in the field of extreme events analysis.

Most marine variables, like the majority of environmental signals, are characterised by phenomena of non-stationarity. The existence of a seasonal cycle in the studied variables, as well as the possible existence of long-term trends are some evident causes of the above mentioned non-stationarities. These phenomena should be incorporated in the extreme value models, for the process of extrapolation to be more reliable and unbiased. Morton et al. (1997) present a model framework for incorporating seasonality in the analysis of extreme significant wave height, based on the POT (Peaks Over Threshold) model. Separate POT models characterised by the use of seasonal thresholds are applied for each season of the year and finally return levels are extracted by an aggregation procedure. Caires et al. (2006) introduce a non-stationary and non-homogeneous Poisson process to model significant wave height extremes with parameters dependent on sea level pressure covariates. Méndez et al. (2006) develop non-stationary POT models to simulate significant wave height extremes, taking account of climate covariates, such as the NAO index, harmonic functions for periodic variations and long-term trend components. Méndez et al. (2008) present respective models, focusing on the harmonic functions of interannual variability for wave height extremes, but also on the duration of wave storm events. Brown et al. (2008) analyse changes in observed daily temperature anomalies since 1950 by utilizing an extreme value distribution function with time-varying parameters, considering time trends and the influence of the NAO. Menéndez et al. (2009) study monthly wave height extremes, considering a non-stationary GEV (Generalized Extreme Value) model with parameters described by means of harmonic functions. Frías et al. (2012) utilize the above mentioned model to analyse extreme values of atmospheric temperature resulting from a regional climate model (RCM).

In the present work, extreme value analysis of significant wave heights in selected areas of the Greek Seas is performed for the present and the future climate. In Section 2, bias correction methods utilized for the wave data in the selected areas are presented. Section 3 presents the basic characteristics of the non-stationary GEV distribution function, fitted to the monthly maxima of wave height data, according to the methodology presented in Menéndez et al. (2009). Section 4 of the present work introduces shortly the data utilized in the present work and presents some indicative results. Finally, extreme values of the studied variables for present and future climatic conditions are intercompared and basic conclusions are extracted regarding the effects of climate change on the wave climate of the Greek Seas.

2 BIAS CORRECTION METHODS

Significant wave height simulations resulting from the use of wave prediction systems forced by RCMs are often subject to phenomena of bias, possibly due to the limited process understanding, the incomplete conceptual representation of the atmospheric processes leading to the generation of climate data, the incomplete discretisation, the spatial averaging in each cell of the model grid and other parameters. Bias represents the error component of the model that is independent of time (Haerter et al. 2011) and imposes the processing of the data before using it to estimate the effects of climate change in any domain of study. Particularly, when referring to extreme events, it has been pointed out that if the output of RCMs is not corrected for bias, they lead to unrealistic exceedance probabilities, rendering the analysis of extreme events unreliable (Durman et al. 2001). However, it should be noticed that incorrect representation of the different processes involved in a physical system cannot be rectified by means of bias correction. Within the framework of bias correction methods, the error of the climatic model is considered stationary and the correction techniques and parameterisation for the present climate are also considered valid for the future climate. Therefore, for future projections the bias component is assumed unchangeable (Berg et al. 2012).

Among the bias correction techniques, recent studies mainly using precipitation and temperature data, indicate the quantile mapping methods as the most efficient, even for the most extreme part of the distribution of the studied variables (Themeßl et al. 2011). The above mentioned techniques include the development of transfer functions between the cumulative distribution functions of the data that need to be corrected for bias (modelled data) and of the "control" or the observed dataset. Quantile mapping (also referred to as quantile-quantile transformation) results in a new distribution function for the modelled variable almost equal to the one of the observed variable. The main limitations of the quantile - quantile transformation focus on the preservation of the temporal autocorrelation properties of the data, the independent correction of different variables with biases that might not be independent and the inability to correct the spatial autocorrelation of different variables (Boé et al. 2007).

The methods used in the present work include the development of parametric, as well as non-parametric quantile - quantile transformations. The former transformations include linear, polynomial and scale functions. All parametric transformations are fitted by minimizing the residual sums of squares. Within the non-parametric framework, the empirical distribution functions of the "control" or observed data and of the data resulting utilizing the forcing of the RCMs, are represented by means of tables of empirical percentiles, while the values between them are assessed by means of a monotonic tricubic spline function (Gudmundsson et al. 2012). In this case, if the model values of the future projections are larger than the training values, the correction found for the highest quantile of the training period is utilized.

3 ANALYSIS OF EXTREME WAVE EVENTS

The univariate Extreme Value Theory (EVT) includes models for block maxima and exceedances over high thresholds (POT models). The first correspond to the family of GEV distributions (Generalized Extreme Value) including the Gumbel (Type I), the Fréchet (Type II) and the Weibull (Type III) distributions (Jenkinson, 1955). The cumulative distribution function of the GEV for $\xi \neq 0$ is given by the following formula (Coles, 2001):

$$G(x) = \exp[-\{1+\xi\frac{(x-\mu)}{\sigma}\}^{-1/\xi}],\ \ 1+\xi\frac{(x-\mu)}{\sigma} > 0 \tag{1}$$

where μ, $\sigma>0$ and ξ = the location, scale and shape parameters, respectively. The special case with $\xi=0$ corresponds to the Gumbel distribution function. To simulate non-stationary phenomena, the parameters of the GEV distribution function can be modelled as functions of time. To incorporate the seasonal component in the model, the parameters of the GEV can be represented as harmonic functions of time of the following form (Menéndez et al. 2009):

$$\begin{aligned} \mu(t) &= \mu_0 + \sum_{i=1}^{p_\mu} \mu_{2i-1}\cos(i\omega t) + \mu_{2i}\sin(i\omega t) \\ \sigma(t) &= \exp(\sigma_0 + \sum_{i=1}^{p_\sigma} \sigma_{2i-1}\cos(i\omega t) + \sigma_{2i}\sin(i\omega t)) \\ \xi(t) &= \xi_0 + \sum_{i=1}^{p_\xi} \xi_{2i-1}\cos(i\omega t) + \xi_{2i}\sin(i\omega t) \end{aligned} \tag{2}$$

where p_μ, p_σ, p_ξ = the number of harmonics in the parameters μ, σ and ξ of the GEV, respectively, $\omega=2\pi/T$ and T = the number of data within a year used for the fitting of the GEV distribution function. The parameters of the GEV distribution function can be estimated by means of the Maximum Likelihood Estimation procedure (MLE). The optimum number of harmonics used in each of the three parameters of the model is assessed by minimizing the Akaike criterion with correction for small sample sizes (AICc) (Hurvich and Tsai, 1989), as well as by the deviance statistic function, D (Coles, 2001). In the present work, the maximum number of harmonics within each parameter is set to two. After selecting the best model, probability-probability and quantile-quantile plots applied to a standardized version of the data, conditional on the fitted parameter values, are utilized for model diagnostic.

Within a non-stationary context, the return level x_p corresponding to a return period of $1/p$, is assessed as a function of time and it represents the quantile of the distribution function of the studied variable in a given year:

$$x_p(t) = \mu(t) - \frac{\sigma(t)}{\xi(t)}[1-\{-\log(1-p)\}^{-\xi(t)}] \tag{3}$$

The variance of the quantile estimates is calculated using the delta method. When applying the non-stationary GEV distribution function to monthly maxima, annual return levels corresponding to a certain exceedance probability, p, can be assessed by iteratively solving the following equation (Menéndez et al. 2009):

$$p = \exp\{-12\int_0^1 [1+\xi(t)(\frac{x_p[0,1]-\mu(t)}{\sigma(t)})]^{-1/\xi(t)}dt\} \tag{4}$$

The 95% confidence interval of the annual return level can be approximated by means of simulating a number of parameters of the selected non-stationary GEV model. The three GEV parameters are assumed to follow a multivariate Normal distribution function. In the present work, for each dataset analysed, 1000 samples of parameters are generated from the fitted non-stationary GEV distribution functions, constituting a sample from the approximate sampling distribution of the maximum likelihood estimator (Coles, 2001).

4 WAVE DATA AND RESULTS

The marine data used in the present work are predictions of significant wave height in selected locations (Figure 1) of the Greek Seas. The datasets used cover selected areas of the Aegean Sea, such as the Thracian Sea (area 1), the marine areas of Katerini (area 2), Lesvos (area 3), Chania (area 4), Heraklio (area 5), as well as selected areas in the Ionian Sea, near the coasts of Parga (area 6) and Katakolo (area 7). The wave data result from a wave prediction system formulated for the Greek Seas, based on the wave model SWAN (Ris et al. 1999, Booij et al. 1999) and cover a period of 150 years (1950-2099). The atmospheric forcing of the model consists of wind (wind velocity and direction) fields of the RCM model

RegCM3 (Dickinson et al. 1989). The spatial resolution of the model is 10 x 10km. The future predictions of the model are based on the A1B SRES emissions scenario (Jacob et al. 2007).

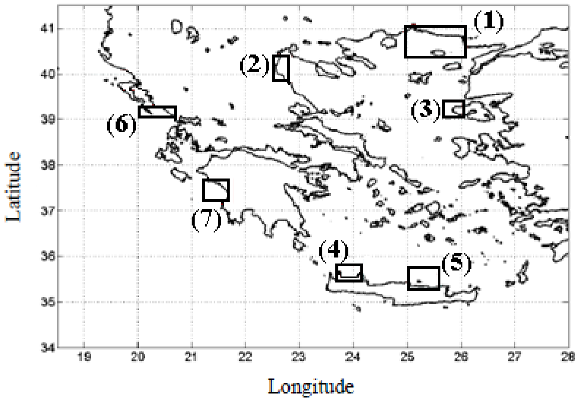

Figure 1. Locations of the seven study areas

The selection of representative points of the SWAN grid in the study areas, is performed utilizing the homogeneity measures of Hosking and Wallis (1997). The homogeneity measures represent the variability of the L-moments of the datasets of the selected points compared to the respective variability expected for a homogeneous region. The homogeneity measure (*H*-statistic) includes three components, *H*(1), *H*(2) and *H*(3). The homogeneity measure *H*(1) refers to the standard deviation of the L-CVs (L-coefficients of variation) of the data in the selected data points. Measures *H*(2) and *H*(3) refer to the mean distance of the coordinates of the selected points from a mean regional estimate, in a diagram of L-CV with L-skewness and L-skewness with L-kurtosis, respectively. If all the above mentioned measures are lower than unity, then the studied area can be characterised as adequately homogeneous. In the present work, the homogeneity measures are assessed based on the annual and also on the monthly maxima of the significant wave height in the period 1950-1999, for all the studied grid points and for all the study areas. In the studied area of the Thracian Sea (1), based on the above mentioned homogeneity measures, two distinct groups of grid points are formed. These two groups are separated in space by the island of Samothrace. In the marine areas of Katerini (2), Lesvos (3), Chania (4), Heraklio (5) and Katakolo (7), the wave data are considered almost homogeneous for all the grid points considered. In the marine area of Parga (6), the analysis of homogeneity of the wave data results in two distinct homogeneous groups.

Before performing extreme value analysis using the methodologies described in Section 3 of the present paper, the wave data from representative grid points of all the formed homogeneous regions are corrected for bias. The wave height datasets used for bias correction cover a period of ten years. This data result from the wave prediction model WAM forced with the non-hydrostatic model ETA for the Thracian Sea and with SKIRON (Papadopoulos et al. 2002) for all the other data points. The ten year datasets used for bias correction cover the interval 1995-2004 for the Thracian Sea and 2001-2010 for all the other locations. To perform bias correction of the significant wave height, the parametric and non-parametric techniques described in Section 2 are utilized. For the grid points where the largest values of the significant wave height are observed during the training period, a non-parametric technique is preferred. In the rest of the cases, a suitable parametric quantile transform is utilized.

Following the correction of wave data for bias, the available significant wave height time series are separated in three parts of equal size (fifty years each), in order to represent the fifty years of the current (1950-1999), the short-term (2000-2049) and the long-term future (2050-2099) climate. For each one of these three periods, the monthly maxima of the significant wave height are selected. The selected monthly values should be separated by a time interval of at least two to three days, to be considered to belong to separate storm events. After defining the samples of monthly maxima, twenty six non-stationary GEV distribution functions with up to two harmonic functions in all the parameters of the model, are fitted to the data at each location and time period. For each case considered, the model that corresponds to the lowest AICc is selected. Apart from the Akaike criterion, to avoid overparameterisation of the fitted distribution, the deviance statistic, *D*, is also assessed. Table 1 presents the number of harmonics in the parameters μ, σ and ξ of the selected best fitted non-stationary GEV models for all the grid points and for all the three time periods considered. It should be noted that the majority of the selected models for wave height extremes analysed in the Ionian Sea (areas 6 and 7) presented one single harmonic in the location and two harmonics in the scale parameter of the GEV distribution function for all three time periods considered. Considering the two locations in the South Aegean Sea (areas 4 and 5), they seem to show similar model structures for each one of the three time periods examined. In the areas of the North Aegean Sea, harmonic functions appear also in the shape parameter of the GEV distribution function, modifying the tail behaviour of the wave height within the year.

Table 1. Number of harmonics in the parameters of the non-stationary GEV model

Area - Point Coordinates	Number of harmonics in μ, σ, ξ (p_μ - p_σ - p_ξ)		
	1950 - 1999	2000 - 2049	2050-2099
Thracian Sea (area 1) - (25.30°, 40.65°)	2 - 2 - 1	2 - 2 - 2	2 - 2 - 2
Thracian Sea (area 1) - (25.70°, 40.65°)	1 - 2 - 0	2 - 1 - 0	2 - 1 - 2
Katerini (area 2) - (25.85°, 40.10°)	2 - 2 - 0	2 - 1 - 2	2 - 1 - 1
Lesvos (area 3) - (25.75°, 39.00°)	1 - 1 - 1	2 - 1 - 0	2 - 2 - 2
Chania (area 4) - (24.00°, 35.80°)	1 - 1 - 0	2 - 1 - 0	2 - 1 - 0
Heraklio (area 5) - (25.15°, 35.70°)	1 - 1 - 0	2 - 1 - 0	2 - 1 - 0
Parga (area 6) - (20.30°, 39.00°)	1 - 2 - 0	1 - 1 - 0	1 - 1 - 0
Parga (area 6) - (20.10°, 39.30°)	1 - 2 - 1	1 - 2 - 0	1 - 2 - 0
Katakolo (area 7) - (21.35°, 37.40°)	1 - 2 - 0	1 - 2 - 0	1 - 2 - 0

Figures 2, 3 and 4 present wave height quantile levels for a return period of 50 years in a time interval of one year and for all the three time periods considered, for points in areas 1 (25.30°, 40.65°), 3 (25.75°, 39.00°) and 7 (21.35°, 37.40°), respectively. The mle of the quantiles is represented with a continuous line, while the shaded areas correspond to the 95% confidence intervals estimated using the delta method. Figures 2, 3 and 4 also include the monthly maxima of each sample in each month in chronological order.

For the three representative points in Figures 2, 3 and 4 it is obvious that the quantile levels of wave height are increased in the intermediate time period for the whole year and especially for the winter period. In the last time period considered (2050-2099), the prediction uncertainty appears increased in a large proportion of the year for the representative grid points in the Thracian Sea and in the marine area of Lesvos island. From Figures 2 and 3 it can be noted that in this last future period, the highest wave height quantiles are observed apart from the winter period, in the spring and at the end of the autumn season for the Thracian Sea and in the spring season for Lesvos island. Table 2 presents the annual return levels (mles and 95% confidence intervals) for significant wave height corresponding to return periods of 50 and 100 years, for all the locations considered.

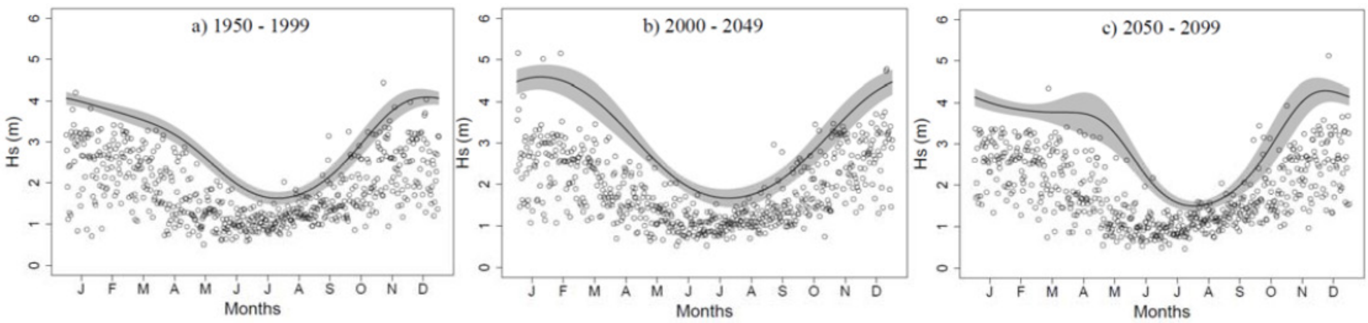

Figure 2. 50-year return period quantiles within a year for a grid point in the Thracian Sea (25.30°, 40.65°)

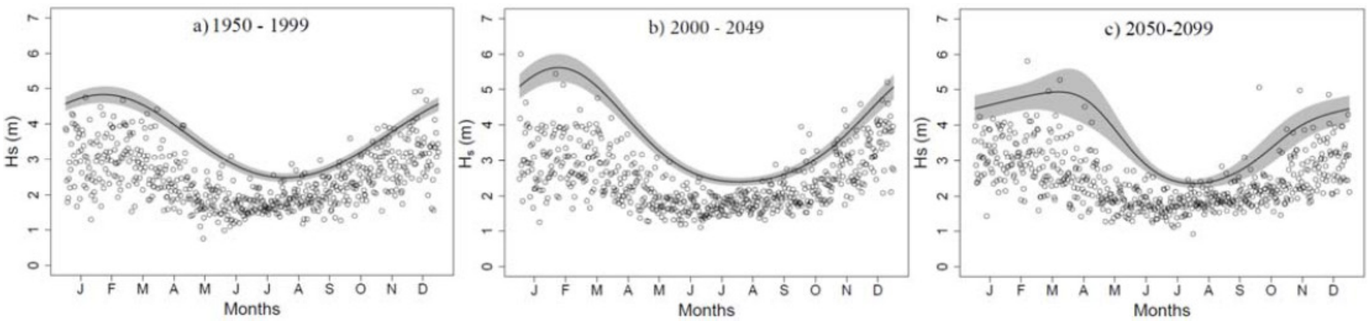

Figure 3. 50-year period quantiles within a year for a grid point in the marine area of Lesvos island (25.75°, 39.00°)

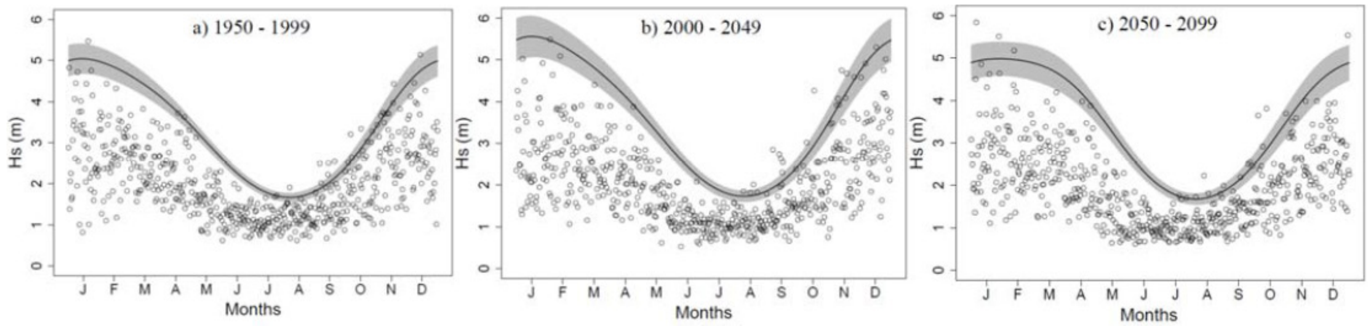

Figure 4. 50-year period quantiles within a year for a grid point in the marine area of Katakolo (21.35°, 37.40°)

Table 2. Annual H_s return levels for return periods of 50 and 100 years

Point Coordinates - Area	T (years)	Annual H_s Return Levels (m)		
		1950 - 1999	2000 - 2049	2050-2099
Thracian Sea (area 1) - (25.30°, 40.65°)	50	4.23 (4.03, 4.55)	4.83 (4.59, 5.26)	4.67 (4.31, 5.38)
	100	4.37 (4.12, 4.76)	5.07 (4.74, 5.53)	5.00 (4.51, 6.05)
Thracian Sea (area 1) - (25.70°, 40.65°)	50	3.80 (3.48, 4.26)	4.34 (3.93, 4.85)	3.81 (3.40, 4.64)
	100	4.03 (3.66, 4.58)	4.68 (4.19, 5.32)	4.22 (3.62, 5.47)
Katerini (area 2) - (25.85°, 40.10°)	50	3.00 (2.73, 3.39)	3.15 (2.81, 3.70)	2.89 (2.83, 3.67)
	100	3.21 (2.87, 3.69)	3.40 (2.95, 4.14)	3.07 (2.97, 4.12)
Lesvos (area 3) - (25.75°, 39.00°)	50	5.00 (4.75, 5.32)	5.96 (5.54, 6.52)	5.47 (5.08, 6.41)
	100	5.15 (4.86, 5.53)	6.28 (5.79, 6.95)	5.84 (5.36, 7.27)
Chania (area 4) - (24.00°, 35.80°)	50	6.87 (6.20, 7.66)	6.69 (6.15, 7.25)	7.12 (6.48, 7.98)
	100	7.34 (6.55, 8.30)	7.06 (6.45, 7.75)	7.64 (6.88, 8.20)
Heraklio (area 5) - (25.15°, 35.70°)	50	6.69 (6.07, 7.51)	6.73 (6.12, 7.42)	6.43 (5.88, 7.12)
	100	7.22 (6.47, 8.23)	7.19 (6.47, 8.02)	6.85 (6.20, 7.71)
Parga (area 6) - (20.30°, 39.00°)	50	5.13 (4.79, 5.59)	5.91 (5.43, 6.53)	5.49 (5.05, 5.96)
	100	5.39 (5.01, 5.94)	6.31 (5.74, 7.04)	5.85 (5.35, 6.41)
Parga (area 6) - (20.10°, 39.30°)	50	5.35 (4.92, 6.05)	6.02 (5.52, 6.65)	5.82 (5.28, 6.52)
	100	5.68 (5.15, 6.59)	6.40 (5.82, 7.14)	6.20 (5.56, 7.06)
Katakolo (area 7) - (21.35°, 37.40°)	50	5.37 (5.00, 5.85)	6.13 (5.61, 6.85)	5.70 (5.20, 6.29)
	100	5.61 (5.19, 6.18)	6.54 (5.91, 7.42)	6.05 (5.48, 6.82)

From Table 2 it can be concluded that especially in the area of the North Aegean and in the Ionian Sea, an increase in the severity of extreme wave height events is obvious in the period 2000-2049. In the marine area of Lesvos island in the Aegean Sea, this increase reaches 19% and 22% for return periods of 50 and 100 years, respectively, compared to the present climate conditions. In the Thracian Sea, the respective increases reach 14% and 16%. In the Ionian Sea, 50-years annual return levels for the period 2000-2049 appear increased compared to the ones of the period 1950-1999 up to 15%, while the increase for 100 years return period reaches 17%. In the studied locations of the South Aegean Sea, climate change effects are not so evident. In the last 50-years period (2050-2099), a decrease in extreme wave heights is observed, compared to the intermediate period. For a return period of 50 years, this decrease reaches 14% in the Thracian Sea, 9% for the marine areas of Katerini and Lesvos, 5% for Heraklio and almost 8% for the locations in the Ionian Sea. For a return period of 100 years the respective decreases are up to 11% in the Thracian Sea and Katerini, 8% in Lesvos, 5% in Heraklio and 8% in the Ionian Sea. However, for the marine area of Chania, mean return levels of the last future period appear increased by 6% and 8% for return periods of 50 and 100 years, respectively. Regarding the estimates of the upper 95% confidence interval for extreme wave height predictions, an increase is also observed in the area of the North Aegean and the Ionian Sea for the intermediate interval (2000-2049), compared to the present climate extreme conditions. In the area of Lesvos island, a maximum increase is estimated at 22% and 26% for return periods of 50 and 100 years, respectively. In the Thracian Sea, the respective proportions are up to 16%, while for the Ionian Sea they reach 17% and 20%, for return periods of 50 and 100 years, respectively.

Figure 5 presents a comparative return level plot representing annual wave height return levels for the intervals of the present (1950-1999) and the short-term future climate (2000-2049) for the points represented in Figures 3 and 4 in the Aegean and the Ionian Sea, respectively. It is obvious that for both cases, annual return level estimates (mles and 95% confidence intervals) are increased for the latter time period. Uncertainty, represented by the range of the confidence interval, appears also higher for the future period.

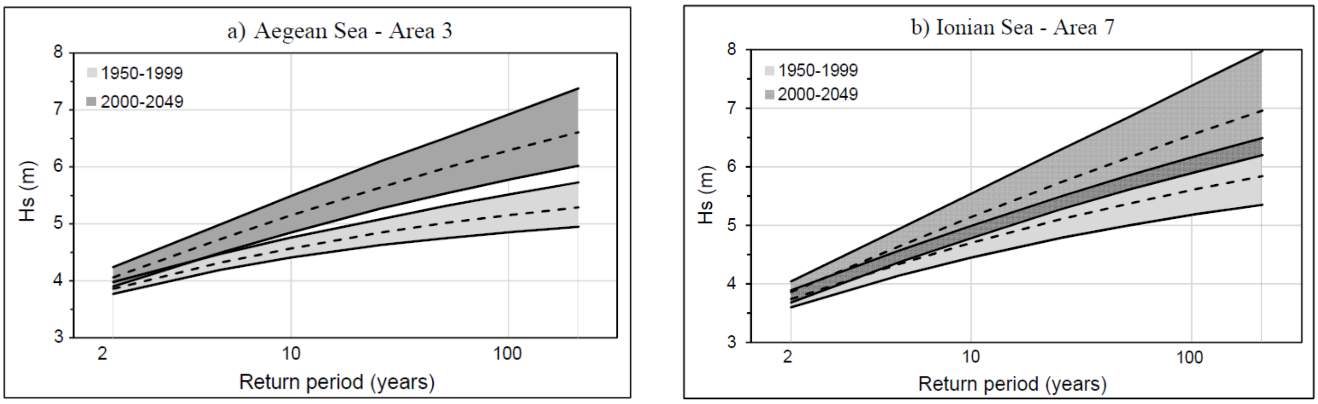

Figure 5. Comparison of annual wave height return levels for area 3 in the Aegean Sea and area 7 in the Ionian Sea

5 CONCLUSIONS

In the present work the effects of climate change on extreme values of the significant wave height are studied and analysed in selected areas of the Greek Seas. The analysis is conducted utilizing a non-stationary GEV model that simulates the variability within a year of the wave height monthly maxima. The parameters of the model are simulated using harmonic functions of time representing the annual and the semiannual cycle. To determine the appropriate number of parameters in each time period (present, short-term and long-term future climate) and area considered, the Akaike Information Criterion with correction for small sample size (AICc) and the deviance statistic function, are utilized and the selection is performed among twenty six candidate models. After selecting an appropriate distribution function for wave extremes, time-dependent quantiles of significant wave height within an one year period are assessed for each period and point considered. Apart from time dependent quantiles, annual return levels are also approximated. It should be emphasized that the data used for extreme value analysis, are first corrected for bias using significant wave height data resulting from a wave prediction system forced with meteorological observations of the necessary atmospheric factors

The non-stationary GEV distribution function used in the present work is able to model the entire variability of extreme events within a year, taking account of such events in all seasons. It considers more than a single event per year, it uses information from neighbouring months and thus includes natural variability in the simulation procedure and it is threshold independent. The model represents the seasonal variability of extremes in the Aegean and in the Ionian Sea fairly well for present and future climate conditions. Especially for the North Aegean Sea, the pattern of oscillations in the GEV parameters appears modified between present and future climate conditions and even between the two future time periods.

From the analysis conducted, an increase of the extreme wave climate in the North Aegean and in the Ionian Sea for the intermediate time period 2000-2049, compared to the present climate (1950-1999) conditions, can be observed. In the marine area of Lesvos island in the Aegean Sea, this increase reaches 19% and 22% for return periods of 50 and 100 years, respectively. In the Ionian Sea, 50-years annual return levels for the period 2000-2049 appear increased compared to the ones of the period 1950-1999 up to 15%, while the increase for 100-years return period reaches 17%. In the last 50-years period (2050-2099), a decrease in mean extreme wave heights is observed, compared to the intermediate future period. For the points examined in the South Aegean Sea, the effects of climate change on the marine climate are not so evident using the model for monthly wave height maxima.

NOTATION

AICc	Akaike Information Criterion with correction for small sample size
D	Deviance statistic function
H	Homogeneity measures of Hosking and Wallis (1997)
MLE	Maximum Likelihood Estimation
p_μ	number of harmonics in the location parameter
p_σ	number of harmonics in the scale parameter
p_ξ	number of harmonics in the shape parameter
x_p	quantile corresponding to a probability of exceedance, p

μ location parameter of the GEV distribution function
σ scale parameter of the GEV distribution function
ξ shape parameter of the GEV distribution function

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