Climate change effects on extreme total water levels of the Greek coastal zone

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Abstract

The nonstationary univariate extreme value theory is implemented on data of sea state characteristics at selected Greek coastal areas of the Aegean Sea to provide reliable estimates of design total water levels (TWLs) on the coast and to assess their temporal variability in the future climate, by adopting a compound event approach. Long-term time series of deep water significant wave height and associated peak spectral wave period corresponding to sea states affecting the coast are used to estimate the wave run-up at the selected coastal areas by means of established empirical formulas. Wave-induced run-up is then added to concomitant five-day maxima of sea level heights due to storm surge, mean sea level rise and astronomical tide records. The resulting structure variable is modeled using a nonstationary Generalized Extreme Value (GEV) distribution to extract time-dependent estimates of extreme TWLs at the shoreline, providing more reliable design values for coastal areas and structures.

Keywords Total Water Level, Nonstationary extremes, Coastal zone, Climate change

1 INTRODUCTION

Global climate change is expected to cause significant long-term changes in storm variability regionally, leading to consequent shifts in mean sea level (MSL), wave climate and storm surge regime. Changes in frequency and severity of future marine conditions can significantly affect vulnerability and exposure of coastal areas to inundation, flooding and erosion hazards. During the last decade climate change effects on the variability and long-term trends in MSL, as well as changes in extreme wave climate and extreme storm surges in the Mediterranean have gained significant interest (*i.e.* Adloff et al. 2015, Tsimplis et al. 2013, Makris et al. 2016).

Estimation of extreme total water level (TWL) at a coastal area assessing the contributions of various components of the marine climate, can provide the boundary conditions for flooding and erosion hazard studies and estimation of the related coastal risks. Very recently, studies focusing on the estimation of TWL at the shoreline started including components to simulate seasonality and interannual variability of the marine climate, as well as considering dependencies between the different variables of TWL (*i.e.* Serafin and Ruggiero 2014, Serafin et al. 2017, Galiatsatou et al. 2019).

Climate change being one of the prominent causes of long-term nonstationarities inherent in marine signals, especially when their extreme levels are of interest, necessitates the use of a nonstationary approach to assess reliable future extremes of TWL on the coast, to be used as input for various impact studies. However, many of the studies in this field assume stationarity of the marine climate variables and/or do not consider their combined impact on coastal areas. In the present work extreme TWLs on the coasts of Greece are assessed by the use of a nonstationary approach to approximate the coastal flooding hazard under climate change conditions. Wave characteristics, sea level heights due to storm surges (SLH), MSL rise, and astronomical tidal range of the study areas are considered in the analysis.

2 METHODOLOGY

Coastal flooding, caused by the combined effect of high water levels (storm surges and astronomical tides), MSL rise and wave action of rough sea states, can result from the combination of large values of more than one of its constituent processes. Therefore, a compound extreme TWL can be a combination of variables that are not necessarily extreme events of themselves (Serafin et al. 2017) and extreme source is not equivalent to extreme impact (Leonard et al. 2014). Therefore, in the present work an impact-based definition of multivariate sea storm events is used, adopting a compound event approach to estimate extreme TWL at the shoreline. Long-term time series of deep water significant wave height H_s and associated peak spectral wave period T_p corresponding to sea states affecting the coast are primarily used to estimate the wave-induced run-up $R_{2\%}$ on the shoreline at selected coastal areas by means of the Stockdon et al. (2006) empirical formula:

$$R_{2\%} = 1.1\left(0.35tan\beta(H_sL_o)^{1/2} + \frac{\left(H_sL_o(0.563tan^2\beta+0.004)\right)^{1/2}}{2}\right) or\ R_{2\%} = 0.043(H_sL_o)^{1/2}, \xi < 0.3 \quad (1)$$

where H_s[m] is the deep water significant wave height, L_o[m] is the deep water wave length associated to the peak spectral wave period T_p[s], $\tan\beta$ is the beach face slope and ξ is the Iribarren number. The TWL at the shoreline results from adding the wave-induced run-up at the shoreline, $R_{2\%}$, the sea level height due to storm surge, SLH, the MSL rise, $MSLR$, and the maximum astronomical tidal range, TR_{max} at the selected study area:

$$TWL = R_{2\%} + SLH + MSLR + TR_{max} \quad (2)$$

Annual maxima of the sum of the two stochastic components of TWL, $R_{2\%}$ and SLH, are extracted and the univariate Extreme Value Theory (EVT) is used to assess extremes of the response variable. The nonstationary Generalized Extreme Value (GEV) distribution is then utilized to model the distribution function of the aforementioned structure variable ($TWL_{stoch} = R_{2\%} + SLH$). All time-dependent distributions are fitted using a 50-year moving time window with an annual time step. The derived parameter estimates correspond to the last year of each 50-years period.

Linear and nonlinear parametric trends are then fitted to extracted parameter estimates and best-fitted models are selected using the Akaike and the Bayesian Information Criterion, as well as tests for statistical significance of the coefficients of the fitted trends (Galiatsatou et al. 2019). Nonstationary design $TWLs$ are then defined as a conditional sum of extracted return level estimates of the structure variable (with or without the fitted parametric trends), astronomical tide, and MSL rise estimates at the selected coastal areas.

3 AVAILABLE DATA

The wave (H_s and T_p) and SLH data used in this paper cover a period of 150 years (1951-2100) and are derived from 3-hourly simulation results for the Greek Seas produced by SWAN wave model and the high-resolution two-dimensional, barotropic, storm surge model GreCSS (Makris et al. 2016). Forcing of wind and atmospheric pressure fields are derived from dynamically downscaled simulations with Regional Climate Model RegCM3, and future climate projections are based on IPCC-A1B emissions scenario (IPCC 2007). After extracting $R_{2\%}$ for all waves heading to the coastal areas of interest, a five-day window (by 2.5 days bilaterally) of concurrent SLH is implemented in the analysis, in order to estimate the largest possible response to particular storm events, which usually have a maximum duration of 120 hours in the Mediterranean basin.

Three representative Greek study areas (Makris et al. 2018) have been selected, one in the North Aegean (Area 1) containing the coastal zone of Alexandroupolis city, one in the Central Aegean (Area 2) containing the coastal area of Eresos in the southern Lesvos Island, and one in the South Aegean (Area 3) containing the coastal area of the city of Heraklion in northern Crete. An adequate number of representative cross-shore profiles, with distances 800 to 1000m from each other, were selected at each study area: namely 21, 5 and 18 beach slope profiles for Areas 1, 2 and 3, respectively. Three profiles were studied in each of these areas, corresponding to the maximum (17.1% for Area 1, 16.2% for Area 2, 14.5% for Area 3), and the minimum slopes (1.2% for Area 1, 5.7% for Area 2, 3.0% for Area 3) as well as to slopes close to the median (7.5% for Area 1, 11.6% for Area 2, 8.5% for Area 3).

To assess the MSL rise in the Aegean Sea, both a steric and a component of mass addition due to ice melting were considered, resulting to a total value of 25cm by 2100 (Makris et al. 2016), corresponding to about 2.5mm/year, averaged over the whole Mediterranean. The maximum astronomical tidal range, TR_{max}, is considered equal to 0.66m, 0.44m and 0.40m for the coastal areas of Alexandroupolis, Eresos and Heraklion, respectively (HNHS 2011).

4 RESULTS

The nonstationary analysis of TWL_{stoch} extremes using 50-year moving time windows for all selected cross-shore profiles in all three study areas (see Sect. 2) resulted in obtaining time-dependent estimates of GEV parameters (location, scale and shape) from 2000 to 2100. All parameter estimates were obtained using the L-moments approach. Figure 1 presents such estimates for cross-shore profiles with slopes close to the median value for each study site. Statistically significant (5% significance level) linear trends, as well as best-fitted nonlinear trends for all parameters are also shown in Figure 1. Similar plots were also produced for maximum and minimum slopes, not presented here for the sake of brevity.

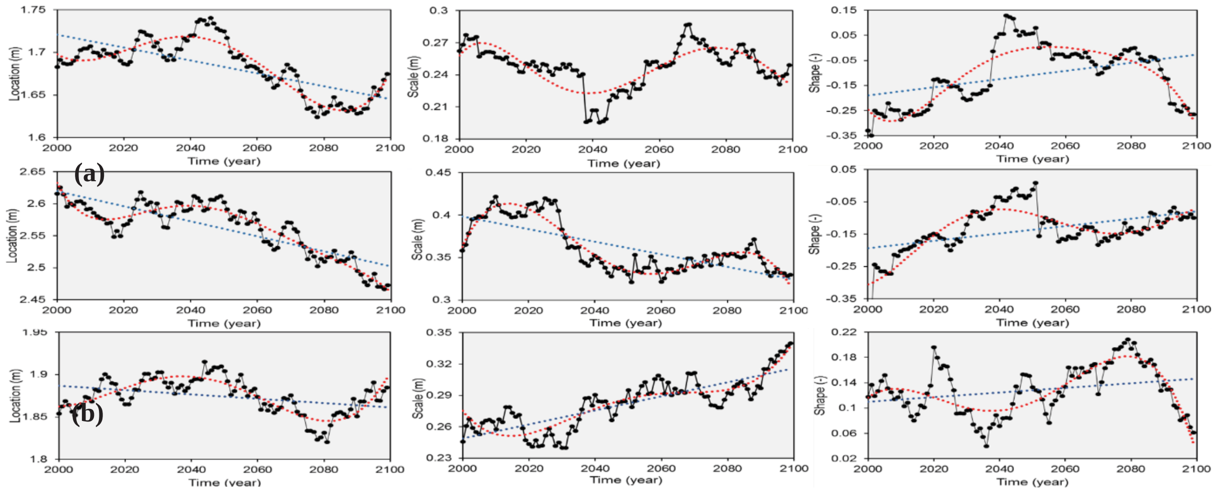

Figure 1 Time-dependent estimates of the GEV location (m), scale (m), and shape (-) parameters fitted to the sum of stochastic components of TWL for cross-shore profiles with slope close to the median for the coastal areas of: a) Alexandroupolis (Area 1), b) Eresos (Area 2), c) Heraklion (Area 3). Blue and red dashed lines represent statistically significant linear and best-fitted nonlinear trends, respectively.

Statistically significant linear trends have been detected in almost all GEV parameters for all three study areas (except the scale parameter for Area 1). Such trends are decreasing for the location and increasing for the shape parameter in all areas, identifying distribution functions with progressively lower means and heavier tails during the future period. GEV distribution functions seem to present progressively lower variances (represented by the scale parameter) in the future in Area 2, and higher ones in Area 3.

Statistically significant polynomial trends have been also detected in all parameters of the GEV fitted to TWL_{stoch} for all three study areas. In the present work the maximum order of the fitted polynomial trends was set equal to five. All resulting polynomial trends are of order four or five, identifying quite high variability of the GEV parameter estimates with time in all study areas. Larger differences in variations over time among the study coastal areas are observed for the scale parameter, which shrinks or stretches the TWL distribution and the shape parameter, which dictates its limiting behavior. In Area 1 the scale parameter presents a bimodal behavior, peaking at the beginning and after the middle of the 21st century, while during the latter period the shape parameter presents its highest values. In Area 2 the scale parameter decreases considerably after 2020, while highest values of the shape parameter are obtained around the middle of the 21st century. Finally, in Area 3, the scale parameter presents an increasing trend, while heavy tails characterize the distribution of TWL throughout the 21st century.

Figure 2 presents time-dependent 100-years return levels of TWL (Eq. 2) for the period 2000-2100 for cross-shore profiles with slopes close to the median value in all three study areas. Most likely 100-years return levels are presented, together with their associated 95% confidence intervals estimated using a parametric bootstrap approach. Figure 2 also includes most likely 100-years TWL estimates assessed by considering best-fitted nonlinear parametric trends for all GEV parameters. Similar plots were also produced for maximum and minimum slopes, not presented here for the sake of brevity.

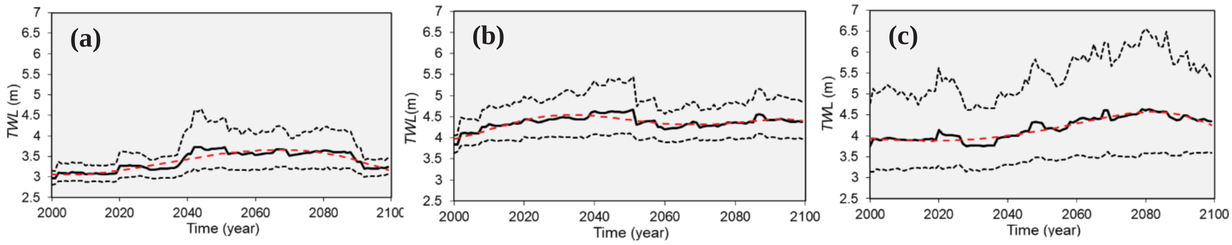

Figure 2 Time-dependent estimates of 100-years *TWL* for cross-shore profiles with slope close to the median for the coastal areas of: a) Alexandroupolis (Area 1), b) Eresos (Area 2), c) Heraklion (Area 3). Solid black lines represent most likely estimates, and dashed back lines represent their associated 95% confidence intervals. Dashed red lines are most likely 100-years *TWL* estimates considering nonlinear trends in all GEV parameters.

TWL extremes in Area 1 appear increased in the second half of the 21st century, while uncertainty almost doubles in this interval (apart from the last ten years), with respect to the period 2000-2040. Considering nonlinear trends in GEV parameters, most likely TWL extremes peak in the interval 2065-2070 to the value of 3.6m (2.7m to 6.0m considering minimum and maximum slope). In Area 2 extreme $TWLs$ seem to increase in the first half of the 21st century and decrease in the second one, presenting their highest values (4.7m) around the middle of the century (2.8m to 5.3m considering minimum and maximum slope). When including parametric trends in the GEV parameters, highest values of 100-years TWL estimates appear around 2035. In Area 3 extreme $TWLs$ present their highest values (4.6m) around 2080 (2.8m to 6.6m considering minimum and maximum slope), appearing highly uncertain throughout almost the entire study period. Variability of most likely 100-years TWL estimates in all study areas exceeds 20% in the 21st century, while it increases to more than 35% when upper 95% confidence intervals are considered.

Figure 3 presents TWL return level estimates from 2000 to 2100 corresponding to return periods from 2 to 200 years in the three coastal areas of the northern (Area 1), central (Area 2), and southern (Area 3) Aegean Sea. Estimates shown were produced for cross-shore profiles with slopes close to the median value in all three study areas, considering best-fitted nonlinear parametric trends in the GEV parameters. Similar plots were also produced for maximum and minimum slopes of the cross-shore profiles.

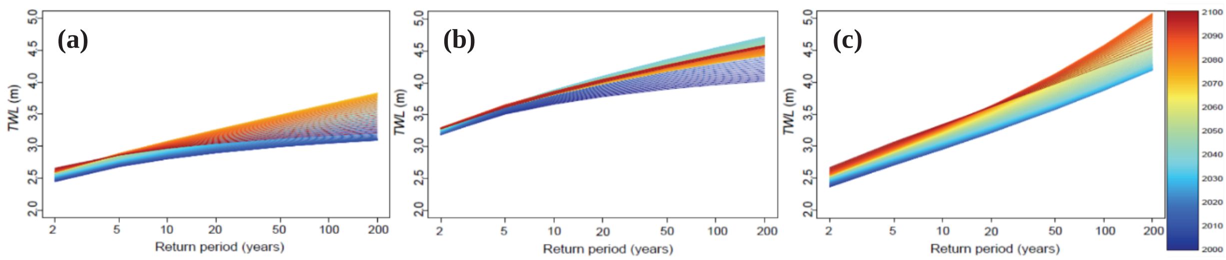

Figure 3 Return level estimates of *TWL* for cross-shore profiles with slope close to the median for the coastal areas of: a) Alexandroupolis (Area 1), b) Eresos (Area 2), c) Heraklion (Area 3) for the period 2000-2100 considering best-fitted nonlinear trends in all GEV parameters.

In Area 1 TWL return level estimates present an increasing trend until 2065-2070 and a decreasing trend afterwards, for the entire range of probabilities considered. Differences are more pronounced for high return periods. The decrease in TWL values is quite sharp especially for high return periods, leading to short-tailed distributions in the last thirty years of the 21st century. In Area 2 TWL return level estimates associated with low probabilities of occurrence present an abrupt increase in the first half of the 21st century, and decrease slightly afterwards. Short-tailed GEV distribution functions are assigned to the entire study period, enabling the extraction of design values of the response for different impact studies. In Area 3 TWL return level estimates progressively increase during the period 2000-2080. Extreme $TWLs$ are fitted to GEV distribution functions with progressively heavier tails, turning to upper-bounded distribution functions in the last twenty years of the 21st century.

5 CONCLUSIONS

In this study multivariate extreme sea states (storm waves and surges) at selected areas of the Greek coastal zone, representing a possible realization of the future marine climate, are statistically treated via EVT, considering nonstationarity on time scales longer than the seasonal or interannual, possibly attributed to climate change. Furthermore, they are combined with other sources of the coastal flooding hazard, *i.e.* astronomical tides and MSL rise, allowing for a robust derivation of extreme values, which is mainly focused on the associated response function of the TWL in coastal areas of the Aegean Sea. This hopefully allows for safer estimations of the coastal flooding hazards, more reliable design values for coastal protection works and more efficient management of the coastal zone.

The nonstationary analysis of the response function of TWL revealed statistically significant nonlinear trends in all GEV parameters and identified quite a high variability in its estimates in all study areas. TWL peaks appearing after 2060 in northern Aegean Sea imply the rise of extreme southerly winds in the area towards the middle of the 21st century and beyond (Vagenas et al. 2017). Progressive increase of TWL extremes in southern Aegean Sea could be possibly combined with a mild rise of northerly extreme winds after the first half of the 21st century detected in the Aeolian patterns (Galiatsatou et al. 2019). Finally, the projected significant increase in extreme Etesians (*i.e.* local strong meridional winds called "Meltemia"; Maheras 1980) in the first half of the 21st century could possibly explain peaks in TWL extremes in the central Aegean Sea during this period.

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