Analysis of extreme storm surges at the Mediterranean coastline under climate change

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Abstract

This study examines the effects of climate change on extreme storm-induced sea levels in the coastal zone of the entire Mediterranean Sea. The analysed extreme sea surface heights resulted from high-resolution simulations with a robust storm surge model (MeCSS) fed by atmospheric circulation data from the COSMO-Climate Limited-area Modelling (CCLM) Regional Climate Model (RCM) of the Med-CORDEX initiative (implemented in Goethe Universität Frankfurt, GUF), with future estimations based on Representative Concentration Pathways, RCP 4.5 and 8.5. Extreme value theory is utilised to analyse and extrapolate extreme storm surges along the Mediterranean coastline in three 35-year intervals, corresponding to the reference and two future periods. The analysis reveals local differentiations in storm surge extremes among the different areas of the Mediterranean Sea, while a projected storminess attenuation is found, especially in the second half of the 21st century for both RCPs.

Keywords Extreme value theory, Storm surge, Mediterranean Sea, Climate change.

1 INTRODUCTION

Global climate change is associated with extreme marine events of higher intensity and frequency and mean sea level rise, increasing vulnerability and exposure of coastal areas to flooding and erosion phenomena. Extreme wave and surge storm events constitute the primary sources of coastal risks, rendering a reliable estimation of their extreme levels urgent, especially for future weather conditions. Intense storm surge events threaten low-elevation coastal areas of the Mediterranean Sea with inundation risk, resulting in human casualties, severe damages to properties and infrastructure, as well as deterioration of the coastal environment. Many researchers have shown that the extreme storm surge climate varies significantly among different regions of the Mediterranean coastline, especially due to the diverse topographical characteristics of its regional seas (Šepić et al. 2012; Cid et al. 2016; Makris et al. 2016, 2018, 2023; Galiatsatou et al. 2019, 2021; Lionello et al. 2019, 2021; Calafat et al. 2022).

2 STUDY AREA AND CLIMATE CHANGE DATA

The data of storm-induced sea level (Sea Surface Height, SSH) in coastal regions of the Mediterranean Sea resulted from high-resolution simulations with Mediterranean Climate Storm Surge (MeCSS) model, a 2-DH barotropic simulator of hydrodynamic ocean circulation based on the depth-averaged shallow water equations (Androulidakis et al. 2015). Simulations covered the reference (1971-2005), the short-term (2021-2055) and the long-term (2066-2100) future climate (Makris et al. 2023). The atmospheric forcing of the model consists of wind (velocity and direction) and sea level pressure fields by a high-resolution Regional Climate Model (RCM), i.e., the COSMO-Climate Limited-area Model (CCLM) with Nucleus for European Modelling of the Ocean (NEMO) by Goethe Universität Frankfurt (GUF), implemented within MED-CORDEX initiative (https://www.medcordex.eu/; Ruti et al. 2016).

The GUF-CCLM-NEMO is an atmospheric-ocean circulation ensemble model collaboration based on a finite difference, hydrostatic, primitive equation ocean general circulation model, with free sea surface and non-linear equation of state. Historical climate data for the reference period were validated by Makris et al. (2023) against ECMWF (European Centre for Medium-Range Weather Forecasts) reanalyses, based on assimilation system fields produced under CERA-20C. Future estimations of the

GUF RCM are based on two climatic scenarios of the Representative Concentration Pathways, RCP 4.5 and RCP 8.5.

3 METHODOLOGY

Extreme value methods are powerful statistical techniques for analysing the highest values of a process and for extrapolating to levels more rare compared to any previously observed or simulated. In this work the Generalised Extreme Value (GEV) distribution is fitted to annual maximum storm surge events of all three 35-year periods (reference and two future periods) for all the littoral grid cells of the GUF-forced MeCSS model along the entire Mediterranean coastline. The cumulative distribution function of the GEV is expressed as (Coles 2001):

$$G(x;\mu,\sigma,\xi)=\begin{cases}\exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} & \xi\neq 0\\ \exp\left\{-\exp\left[-\left(\frac{x-\mu}{\sigma}\right)\right]\right\} & \xi=0\end{cases} \quad (1)$$

where μ is the location, σ, is the scale, and ξ is the shape parameter of the distribution, the latter also determining its limiting behaviour. Considering the small size of the 35-year annual maxima samples for the reference and future periods, the method of L-moments is used in this work to estimate the parameters of the GEV distribution function (Galiatsatou and Prinos 2016). The quantiles, X_T, corresponding to a defined return period, T, represent the T-years SSH return levels (Coles 2001):

$$X_T=\begin{cases}\mu-\frac{\sigma}{\xi}\left\{1-\left[-\ln\left(1-\frac{1}{T}\right)\right]^{-\xi}\right\} & \xi\neq 0\\ \mu-\sigma\ln\left[-\ln\left(1-\frac{1}{T}\right)\right] & \xi=0\end{cases} \quad (2)$$

Storm surge 95% confidence intervals (CI) are also calculated by means of a parametric bootstrap approach (Shao 1996). A large number of samples (500 samples) of length equal to 35 years is first generated from each fitted GEV model. GEV models are then fitted to the simulated samples using L-moments approach. Return levels are then estimated for all simulated samples using Eq. 2, to finally assess CI using the percentile method. Extrapolated storm surge return levels corresponding to return periods of 50 and 100 years are therefore extracted and intercompared among the different areas of the Mediterranean Sea. Stationarity and independence of the 35-years annual maxima for both the historical and future climate conditions are checked using the Mann-Kendall trend and the Wald-Wolfowitz tests (Galiatsatou et al. 2019).

4 RESULTS

The non-parametric Wald-Wolfowitz test, implemented to storm surge annual maxima along the Mediterranean coastline for all study periods, reveals very few samples not satisfying the null hypothesis of stationarity and independence, at a 1% significance level (i.e., less than 2% of the coastal points in all study periods). Implementation of the Mann-Kendall trend test did not identify statistically significant linear trends (1% significance level) in storm surge extremes of the Mediterranean coastline.

Figure 1 presents maps of horizontal spatial distribution of 50-years SSH return levels along the Mediterranean coastline for the reference (1971-2005) and the two future (2021-2055 and 2066-2100) periods for scenarios RCP 4.5 and 8.5. Local differentiations in storm surge extremes around the Mediterranean coastal zone are evident in all study periods, however their spatial distribution remains almost similar in the reference and the future climate. Highest storm surges are detected along parts of the northern Mediterranean coasts (Venice lagoon, Gulf of Lions, northern Adriatic and Aegean Seas, etc.) and the Gulf of Gabes in its southern part. In the reference period maximum storm surge return levels, 0.75m (upper 97.5% CI =1.05m) and 0.85m (upper 97.5% CI =1.33m) for return periods 50 and 100 years, respectively, are assessed in the Gulf of Gabes. The same area provides maximum storm surge return levels in the short-term future period for RCP 4.5 ($SSH_{50years}$ = 0.63m and $SSH_{100years}$ = 0.69m), and in the long-term future period for RCP 8.5 ($SSH_{50years}$ = 0.71m and $SSH_{100years}$ = 0.80m). The Gulf of Gabes and the northern Adriatic Sea along the coastlines of Croatia and Slovenia accommodate the largest storm surge return levels in the long-term future period for RCP 4.5 ($SSH_{50years}$ = 0.58m and $SSH_{100years}$ = 0.62m), and in the short-term future period for RCP 8.5 ($SSH_{50years}$ = 0.57m and $SSH_{100years}$ = 0.61m).

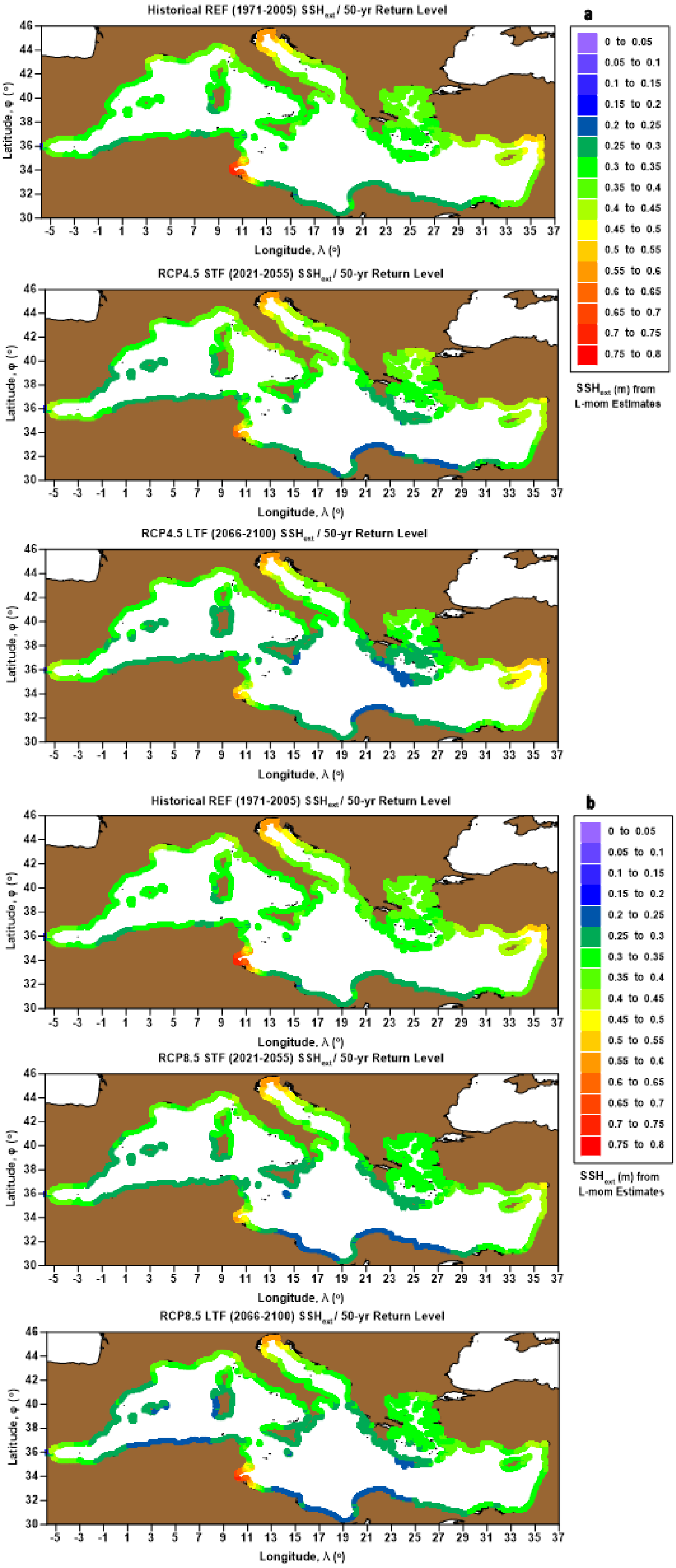

Figure 1. Map of horizontal spatial distribution of 50-year SSH (m) along the Mediterranean coastline during the Reference (1971-2005) and Future Periods (2021-2055 and 2066-2100) for scenarios: **(a)** RCP4.5, **(b)** RCP8.5

Figure 2 presents maps of horizontal spatial distribution of differences (×100%) of 50-years SSH return levels between the two future and reference periods for scenarios RCP 4.5 and 8.5. A projected storminess attenuation is evident for both RCPs and for both future periods, with more extended and pronounced effects for the long-term future period for scenario RCP 8.5. The climate change signal (difference of Future–Reference Period) reveals a decrease in 50-years storm surges up to -23% (2021-2055) or -30% (2066-2100), and -29% (2021-2055) or -28% (2066-2100), for RCP 4.5 and 8.5-driven simulations, respectively. There exist apparent differences between the climate change signals of the two scenarios (RCP4.5-8.5), not so much related to the spatial distribution of projected storm surge extremes, which presents a quite stable pattern, but more in terms of their magnitudes. Despite the general projected storminess attenuation along the Mediterranean coastline, due to a probable northward shift of the cyclogenesis centers and deep depression areas over the basin, extreme storm surges are expected to increase at specific coastal sites in south and northeastern Spain, the western and east-central coasts of the Italian Peninsula, certain gulfs and coastal inlets in south France, north-western African littorals, north Aegean coasts, Lebanon, Syria, and Israel, with more obvious increases assessed for RCP 4.5-driven simulations. Such increases range from almost 10% up to more than 30% locally for the two future periods.

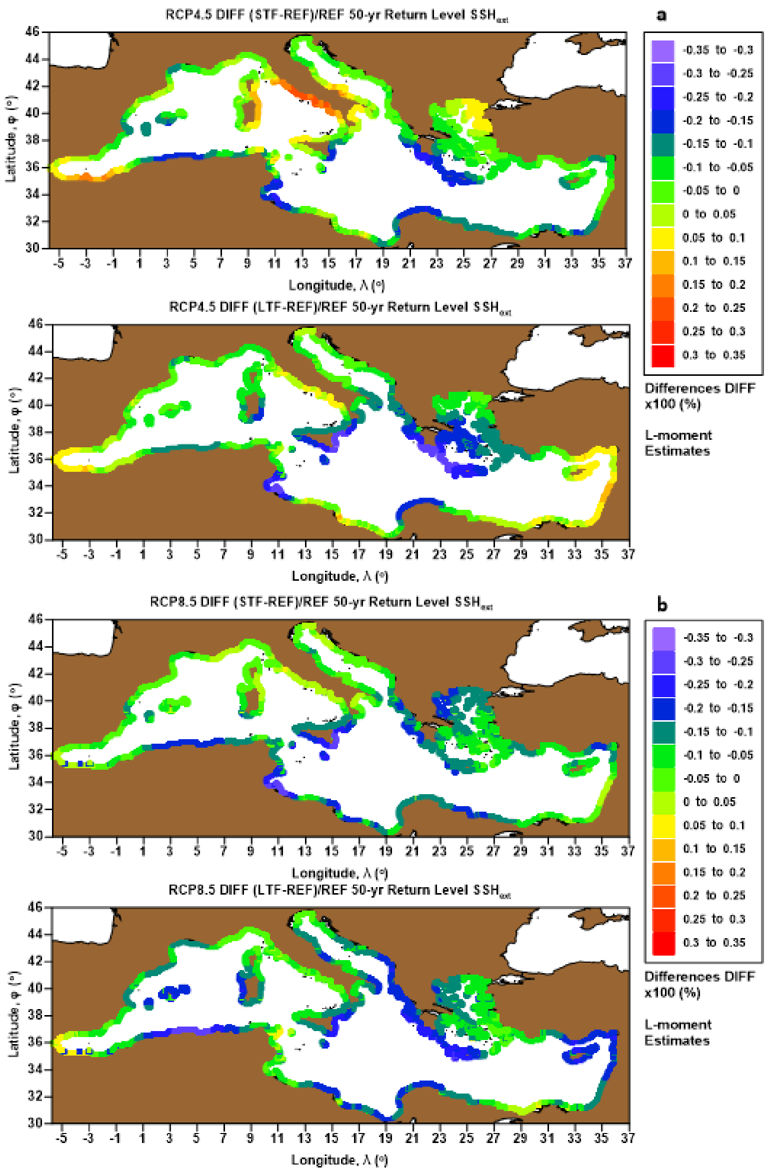

Figure 2. Map of horizontal spatial distribution of differences (×100%) of 50-year SSH (m) between the Future (2021-2055 and 2066-2100) and Reference Periods for scenarios: **(a)** RCP4.5, **(b)** RCP8.5

For RCP 8.5-driven simulations, increases in projected storm surge levels hardly reach 10% for the short-term future period and are mostly detected locally at coastal sites in Croatia, Spain, Italy, France, north-western Africa, Syria, and Lebanon, while increases in storminess and coastal surges are quite reduced in the long-term future period confined to a few coastal sites in north-western/-eastern Africa.

5 CONCLUSIONS

A projected storminess attenuation is estimated to occur in the Mediterranean basin affecting the storm surges on the coastline under the considered climate scenarios (RCP 4.5-8.5) with more extended and pronounced effects for the long-term future period for scenario RCP 8.5. The climate change signal for the long-term future period reveals a decrease in 50-years storm surges up to -30% and -28%, for RCP 4.5 and RCP 8.5-driven MECSS simulations, respectively. However, the magnitudes of storm surge extremes are estimated to increase up to 30% locally in certain regions (mainly gulfs, bights, and coastal inlets) during the 21st century. The peculiarities of topographic characteristics of the regional seas (e.g., northern Adriatic and Aegean Seas, south Libyan and eastern Levantine Seas, etc.) in the Mediterranean basin have a significant influence on the variability of storm surge extremes for all study periods.

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