Climate change effects on the storm surges of the Mediterranean coastal zone

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Abstract

This study aims to systematically assess the impacts of projected climate change on episodic events of sea level elevation in coastal areas of the Mediterranean Sea, induced by severe weather conditions identified as atmospheric deep depressions. We try to add new insight in the long-term, climatic timescale, identification of vulnerable parts at the Mediterranean coastal zone correlated to low atmospheric pressure patterns, indicative of the Mediterranean basin during the 21st century. An integrated quantitative assessment is proposed to achieve this goal by combining projections from available, established, climate change scenarios (based on Representative Concentration Pathways; RCP 4.5 and 8.5) with advanced numerical modelling and statistical post-processing for the definition of cyclonic weather impacts on exposed coastal zone hotspots. To this end, climate projections and outputs from several Regional Climate Models (RCMs) of the Med-CORDEX initiative at the Mediterranean basin scale are used after their evaluation. These atmospheric datasets feed a robust storm surge model (MeCSS) for the simulation of barotropic hydrodynamics (sea level elevation and currents) validated against *in situ* sea level observations by tide-gauges. Results corroborate a projected storminess attenuation for the end of the 21st century, yet local differentiations of storm surge maxima around the Mediterranean coastal zone is discussed. The analysis leads to quantification of deep depression systems' effect on the coastal sea level elevation due to storm surges towards 2100.

Keywords Storm surge, Climate change, Mediterranean Sea, Deep depression.

1 INTRODUCTION

In this paper, we attempt to systematically assess the impacts of projected climate change on episodic events of sea level elevation in coastal areas of the Mediterranean Sea, induced by severe atmospheric weather conditions identified as "deep depressions" (Lionello et al. 2019). Thus, our aim is to add new insight in the climatic-scale identification of vulnerable parts of the coastal zone correlated to peculiar atmospheric patterns indicative of the Mediterranean basin during the 21st century, assisting on the address of the European Challenges to Coastal Management from storm surges (Boyes and Elliott 2019). An integrated quantitative assessment is proposed to achieve these goals by combining projections from available established climate change scenarios (based on Representative Concentration Pathways; RCPs 4.5 and 8.5) with numerical modelling of storm surges and statistical post-processing for the identification of cyclonic weather impacts on exposed coastal zone hotspots (Makris et al. 2023).

2 METHODS AND DATA

To this end, historical data and climate projections are used for a Reference (1971–2000) and a Future (2071–2100) 30-years Period, respectively (Skoulikaris et al. 2021). The atmospheric parameters used as forcing of the hydrodynamic ocean model consist of wind (velocity and direction) and Sea Level Pressure (SLP) fields by three high-resolution Regional Climate Models (RCMs), developed and implemented by three institutions (CMCC, CNRM and GUF; Makris et al. 2023) in the framework of the Med-CORDEX initiative (Ruti et al. 2016; Reale et al., 2021). We simulated the storm-driven hydrodynamic circulation throughout the entire Mediterranean basin with special focus on the meteorologically induced sea level variations on the coastal zone (Androulidakis et al. 2023), based on a robust storm surge model (MeCSS; Androulidakis et al. 2015). The *in-situ* sea level observations use for comparisons with MeCSS results to validate the model's performance for the Control Run during the Reference Period refer to field data from the tide gauge network of the Hellenic Navy Hydrographic Service (HNHS; http://www.hnhs.gr/portal/page/portal/HNHS) in five Greek stations, i.e., Thessaloniki, Alexandroupoli, Heraklion, Chios (Aegean Sea), and Lefkada (Ionian Sea). The available data cover the 11-years period of 1995-2005 (Makris et al. 2015; Androulidakis et al. 2023).

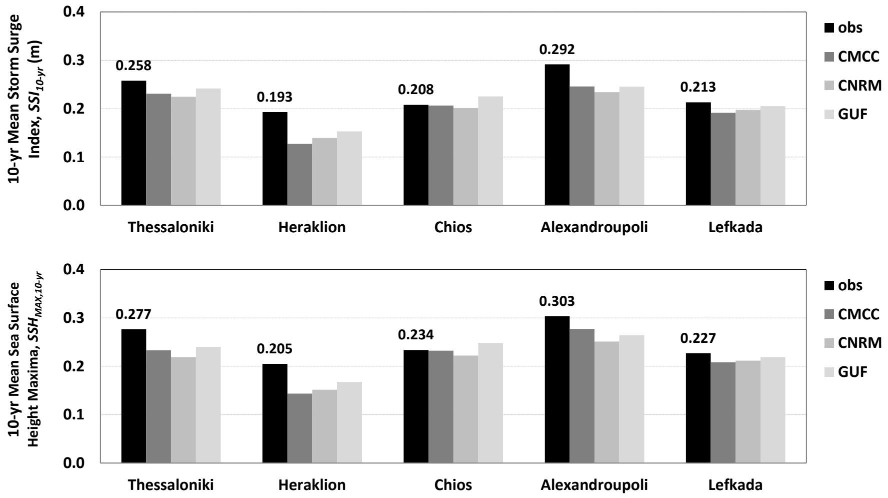

Figure 1 Comparisons of the decadal (1995-2005) average SSI (m) and SSH_{max} (m) [upper and lower graphs, respectively] in five Greek stations for field (obs) and model (mod; CMCC-, CNRM-, and GUF-MeCSS) data

Table 1 Statistical measures and skill metrics of the comparison based on decadal (1995-2005) averages of SSI (m) and SSH_{max} (m) at five Greek stations for field and model (CMCC-, CNRM-, and GUF-MeCSS) data

	RCM	**Pearson Correlation**	**Willmott Skill Score**	**RMSE (m)**	**RMSE/SSI (%)**
SSI	CMCC	0.849	0.735	0.039	17.98%
	CNRM	0.840	0.664	0.039	17.97%
	GUF	0.793	0.816	0.029	13.10%
	RCM	**Pearson Correlation**	**Willmott Skill Score**	**RMSE (m)**	**RMSE/SSH_{max} (%)**
SSH_{max}	CMCC	0.884	0.780	0.037	15.69%
	CNRM	0.828	0.582	0.043	18.70%
	GUF	0.810	0.802	0.030	12.65%

3 RESULTS

3.1 Model Validation

Thorough evaluation of the used climatic datasets against CERA-20C re-analyses (Laloyaux et al. 2019) is provided by Makris et al. (2023). Figure 1 presents the relevant comparisons of modelled and observed values for the decadal (1995–2005) average of Storm Surge Index (SSI, m) and Sea Surface Height maxima (SSH_{max}, m). All MeCSS model implementations follow the same geographical pattern as the one referring to field observations, i.e., higher storm surge levels in the northern part of the studied area and lower SSHs towards the south. Table 1 presents the aggregate estimation of MeCSS model's performance by a set of statistical measures and skill metrics. The results support the good performance of MeCSS model during the Reference Period. Even though the model underestimates SSI in all stations, the errors are generally acceptable and differences between modelled and observed SSI values are plausible. Overall, the cumulative comparisons reveal quite high Pearson correlation coefficients (>0.8), with a Root-Mean-Square-Error (RMSE) ranging from only 3 to 4.3 cm, namely a rough 12%–18% of the average SSH_{max} and <7% of the absolute observed SSH_{max}. The calculated Willmott Skill Scores also reveal a high agreement of GUF-forced MeCSS model output (>0.8) with field data in terms of the interdecadal SSH extremes.

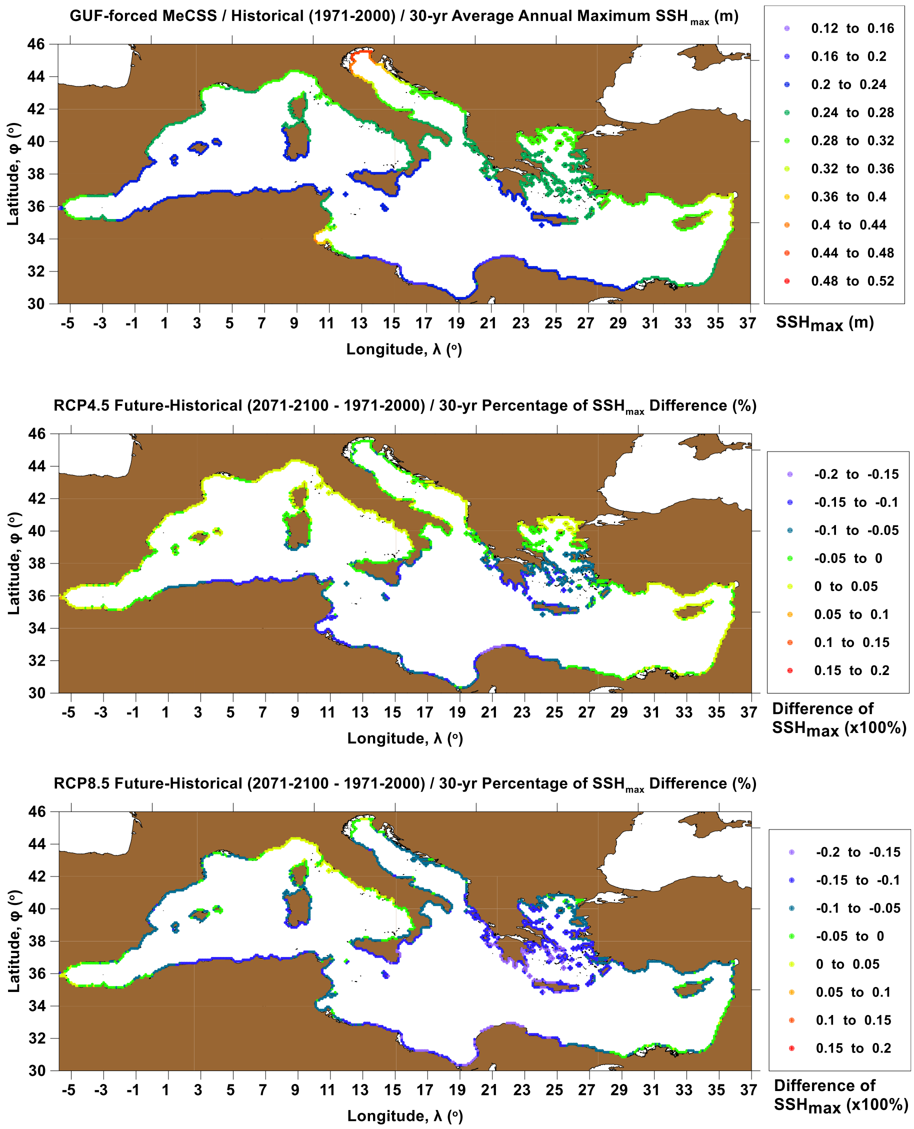

Figure 2 Map of 30-year averaged annual maxima of SSH (m) during the Reference Period (1971-2000; top graph); differences of SSH_{max} (×100%) between Future Period (2071-2100) and Reference Period for the RCP4.5 and RCP8.5 scenarios (mid and lower graphs, respectively) by the GUF-forced MeCSS model

3.2 Climate change impact on storm surges

Figure 2 presents maps of the horizontal distribution of 30-years SSH_{max} during the Reference Period and the calculated differences between it and the Future Period for both RCP4.5-8.5 scenarios for the GUF-forced MeCSS simulations. Figure 3 portrays the respective spatial distributions of the statistically significant Pearson correlation minima for SSH_{max} to identified Deep Depression centers (SLP minima) along the Mediterranean coastline. Differences of correlation between the Future-Reference Periods is also provided. Extreme storm surge magnitudes range between 0.35 and 0.50 m in the Mediterranean basin with higher values along parts of its northern coasts (Venice lagoon, Gulf of Lions, northern Adriatic and Aegean Seas, etc.) and the Gulf of Gabes in its southern part. Overall, the spatial distributions of surge maxima are estimated to remain similar to those of the past throughout the entire Mediterranean coastal zone. Differentiations between the two scenarios (RCP4.5-8.5) used are obvious, not so much related to the spatiotemporal distribution of storm surge maxima, which shows a very stable pattern, but more in terms of their magnitudes. Indicatively, a decrease of surge maxima from -30% to -2% can be observed towards the end of the 21st century, especially for RCP8.5-driven MeCSS simulations. This is a spatially averaged estimation, yet for some specific coastal sites in Croatia, Spain Italy, and France, such as Rovinj, Bakar, Toulon, Trieste, Ajaccio, Genova, Marseilles, Naples, Venice, Cagliari, Ancona, Ibixa, and Barcelona, the storm surge maxima might increase from 1% to 22% under different RCM/RCP combinations towards the end of the 21st century. The strongest correlations of deep depression events to high sea levels are observed in several parts along the N Mediterranean (Gulfs of Valencia and Lions, Ligurian and northern Adriatic Seas). They are followed by mid-latitude areas around Corsica, Sardinia, the mid-zonal Italian Peninsula and the Adriatic, and N Aegean Sea. The influence of deep depressions on storm surges is lower for Sicily, South Italy, Peloponnese, Crete, S Aegean, and Alboran Sea. The only exceptions in the generally unaffected S Mediterranean littorals are the Gulfs of Gabes and Alexandretta. These apply to the 20th century; however, they seem to repeat for the 21st century estimations, with even more pronounced differentiations between the southern and the northern parts. A projected northward shift of the main deep depression centers over the Mediterranean towards 2100, is likely the reason for the latter.

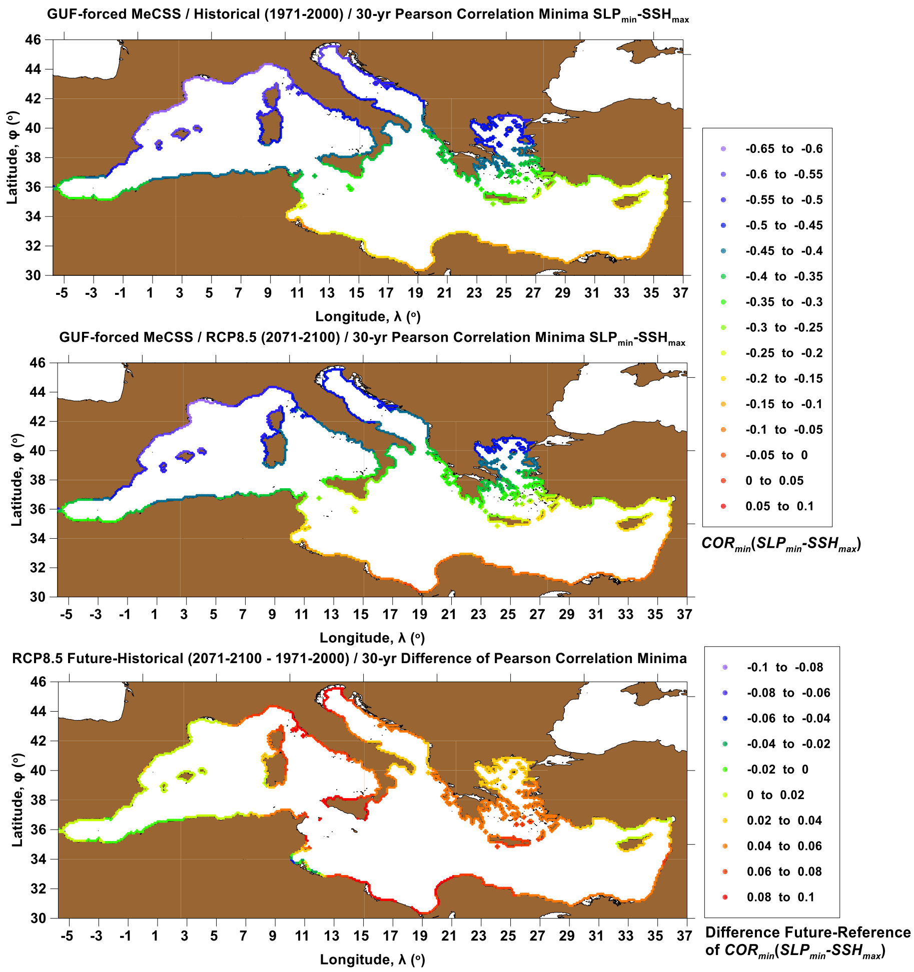

Figure 3 Spatial distribution along the Mediterranean coastline of statistically significant (p_{value}<0.01 by Mann-Kendall test) Pearson correlation minima for SSH_{max} (m) to the identified Deep Depression centers (SLP_{min}, hPa) during Reference (1971-2000; top graph) and Future (2071-2100; mid graph) Periods for RCP8.5 scenario

The climate change signal (difference of Future–Reference Period) of the deep cyclones' effect on the episodic increases of coastal sea level seems to have a very clear pattern of slight attenuation in certain regions, i.e., Sardinia, Corsica, the Ligurian and Adriatic Seas, and the entire Italian peninsula for all RCM-fed implementations towards the end of the 21st century. Conditionally, this is the case for the Gulf of Valencia, the north-western African coasts, the Alboran, Ionian, Aegean, and Libyan Sea coasts, under specific combinations of RCM/RCP forcings. On the other hand, a possible increase of the Mediterranean deep depressions' influence on the coastal storm surges might be the case for the Gulf of Lions, the Ionian, Aegean, and Levantine Sea basins, covering the north-central and north-eastern coasts of Africa.

4 CONCLUSIONS

The implemented storm surge model (Krestenitis et al. 2014; Makris et al. 2019) proved to be quite robust in reproducing the main patterns of evolution for the meteorological residual of sea level in coastal areas. Our results further corroborate a projected storminess attenuation for the end of the 21st century, yet local increases in storm surge maxima around the Mediterranean coastal zone are also pinpointed. Moreover, a slight reduction of average storm-induced Mean Sea Level (MSL; component attributed solely to the meteorological residual of SSH) is also apparent towards the end of the 21st century (Makris et al. 2023). The produced results can be used in focused studies for integrated hydrologic/hydrodynamic modelling and coastal management under projected climate change conditions until 2100 (e.g., Katirtzidou et al. 2023).

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