Modeling storm surges in the Mediterranean Sea under the A1B climate scenario

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Low-elevation areas along the Mediterranean coastline are under high inundation risk in cases of extreme storm surge events. We explore the trends of sea level extremes for a period of 150 years (1950-2100) under a future climate scenario that considers increasing concentrations of atmospheric greenhouse gases, scenario A1B; this scenario is applied on the 3rd version of the Regional Climate Model (RegCM3) and, in turn, RegCM3 forces the hydrodynamic Mediterranean Climate Surge Model (MeCSM). In situ measurements from several areas are used to evaluate the storm surge results; spatial distribution of extreme values from both historical data and modeling and statistical comparisons support the good performance of the model. Morphological differences between the Mediterranean regions reveal significant respective differences on the sea level height evolution and especially on the magnitude and occurrence frequency of extreme events. The atmospheric distribution of pressure and winds on the storm surge extremes variation and evolution are also under investigation.

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1 Introduction

Low-elevation areas along the Mediterranean coastline are at high risk as a result of extreme storm surge events. Coastal flooding is often caused by extreme storm surge events, inducing significant problems on coast populations, infrastructures and environment. Storm surges reveal significant differences between Mediterranean regions, due to the topography, storm magnitude and direction characteristics of each area. Nicholls and Hoozemans (1996) showed that coastal management at Mediterranean region needs to address long-term problems and especially, the impact of climate change on the sea level rise. Conte and Lionello (2013) based on a climate change study covering the period 1951-2050 found that the climate change in the Mediterranean Sea may bring a likely attenuation of storminess. We seek to explore the trends of sea level extremes for a period of 150 years under a future climate scenario (A1B) with highly increasing concentrations of atmospheric greenhouse gases.

2 Data and Methodology

The A1B emission scenario is applied on the 3rd version of the Regional Climate Model version (RegCM3); fields from the RegCM3 model force the hydrodynamic Mediterranean Climate Surge Model (MeCSM), for a period of 150 years, starting from 1951. RegCM3 is used extensively for climate simulations to investigate past and/or future evolution of several atmospheric parameters such as rainfall, air temperature and winds over smaller (i.e. Sahara, Caribbean) or broader (i.e. Africa, Indian Ocean) regions (e.g. Sylla et al. 2010, Ozturk et al. 2012). MeCSM is a 2-dimensional hydrodynamic model (Krestenitis et al. 2011) that solves the depth averaged shallow-water equations and it is used to provide the sea level for the entire Mediterranean basin on a 1/10°×1/10° horizontal grid (Fig. 1). 6-hourly atmospheric forcing (winds at 10 m and Sea Level Pressure-SLP) are provided by the RegCM3 simulations for the entire study period (1950-2100). The RegCM3 domain covers the entire Mediterranean region (15°W-40°E and 30°S-60°N) with a resolution of 25km×25km; interpolation is performed for the forcing of MeCSM. Daily averaged Sea Level Height (SLH) measurements from four gauge stations are compared with respective simulation data.

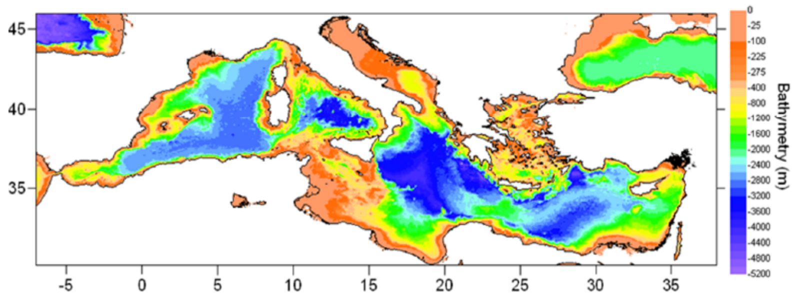

Fig. 1. Mediterranean Sea bathymetry (m) and MeCSM model domain (Atlantic and Black sea excluded).

3 Results

The largest sea level anomalies that may occur every year can be investigated with the Storm Surge Index (SSI), which has been calculated along the available measured periods. The SSI is defined as the mean of the 3-highest storm surge maxima per-year (Conte and Lionello 2013) and has been calculated from both modeled and observed time-series for 5 Greek stations (Fig. 2a); the Percent Error E (%) has also been computed (Fig. 2b). The Error Index EI that compares errors with the variability of the anomalies and provides information about the error significance between the entire model and in situ time-series is also presented.

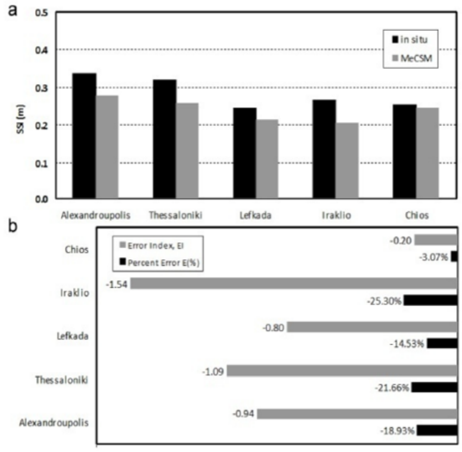

Fig. 2. a) Storm Surge Index (SSI) values, b) Percent Error (%) and Error Index values at Chios (Central Aegean), Iraklio (South Aegean), Lefkada (Ionion Sea), Thessaloniki (North Aegean) and Alexandroupolis (North Aegean) between MECSM and in situ time-series for the 2002-2012 period.

11-year daily observations of the maximum values from five stations along the Greek coastal zone were used to evaluate the model performance over this topographically complicated region. The lowest SSI values were computed for the Ionian (Lefkada) and S. Aegean Sea (Fig. 2a) as derived from both simulated and observed time-series. The highest levels (~30 cm) were observed at N. Aegean stations; although the model slightly underestimates the respective extremes, it also shows the highest values (~27 cm) over the same region. The largest EI were calculated for Iraklio station (EI=-1.54; Fig. 2b). Conte and Lionello (2013) presented similar high errors at several Mediterranean stations in all their climate simulations (their Fig. 3c). The rest of the Greek stations reveal smaller E (<25%) and EI (<1), indicating the low significance of the simulation errors in comparison with the observed data. As defined by Jaffe and Sallenger (1992), the events that may exceed a critical value are called coherent extreme events. A coherent event is defined as $SLH_{max} \geq (m_{\max} + \sigma_{\max})$, where SLH_{max} is the daily maximum of the time-series, m_{max} is the mean of the SLH_{max} time-series over the entre study period (11 years in the case of the Greek stations), and σ_{max} is the respective standard deviation (Cox and Kobayashi 2000). The exceedance probability (p_{coh}) of the critical value for all Greek stations is presented in Table 1, derived from both simulated and observed time-series. Moreover, the statistics of intense events (p_{int}), which are defined as $SLH_{max} \geq (m_{\max} + 2\sigma_{\max})$, are also presented in Table 1, describing the frequency of occurrence of significantly extreme and rare events of each station's time-series (Cox and Kobayashi, 2000). Simulated values approach the measured ones at all stations, with low intense events frequencies over N. Aegean (Thessaloniki and Alexandroupolis) and higher values over Ionio (Lefkada) and S. Aegean (Iraklio). Although Lefkada and Iraklio show the lowest SSI values their p_{coh} and p_{int} probabilities reveal the highest values of all locations. It is noted, that these two areas show low but frequent SSH extremes. Both model and in situ values support this finding, indicating the spatially good performance of the model.

Table 1. Exceedence probability (%) of coherent and intense storm surge events.

Station	Pcoh (%)		Pint (%)	
	model	in situ	model	in situ
Alexandroupolis	14.0	15.0	3.5	3.2
Thessaloniki	15.0	15.0	3.3	3.6
Lefkada	15.4	14.6	3.7	4.0
Iraklio	14.7	14.6	3.9	3.4
Chios	14.3	14.0	3.6	3.5

The inter-annual evolution of the annual maximum SLH for all 28 stations covering a large part of the Mediterranean coastal zone (Fig. 1c) were derived from the entire 150-year MeCSM simulation after daily averaging; it is noted that the MeCSM results are 3-hourly, while the field data are daily averages. Generally, the SLH values are inversely correlated with the respective SLP values (Fig. 3). The Pearson correlation coefficients between the time-series of annual maximum SLH and the temporal respective SLP for all study stations are negative, indicating the relevance between the two parameters. The low pressure systems may affect directly the sea level of coastal regions, while the accumulation of waters near the shore due to direct wind effect is of lower influence; morphology and orientation of the coastline in relation with wind direction may also affect the sea level rise over coastal areas. The French Mediterranean coast (e.g. Marseilles), the central western Italian coast (e.g. Naples) and the N. Aegean coastal region (e.g. Thessaloniki) reveal strong dependence of extreme SLHs by the pressure with correlation coefficients of around -0.6. Southerly winds show low occurrence frequencies along the French coast, while the northerly winds, that may drag surface waters offshore, are very common. Moreover the low wind correlation coefficients along the N. Aegean coastline indicate the low wind effect on the SLH maximum appearance in relation with the domination of northerly winds. Although the correlation between pressure and sea height during extreme events is low over the N. Adriatic coasts, the computation of the correlation coefficients between the entire time series (all values) revealed high relevance between the two parameters (r=-0.72; grey square points in Fig. 3). It seems that strong southeasterly Scirocco winds may accumulate surface waters over the enclosed N. Adriatic coastal region, producing sea surges (Pirazzoli and Tomasin 2002) but during periods of higher pressures and lower winds (high pressure systems) the sea level may follow the variation of SLP.

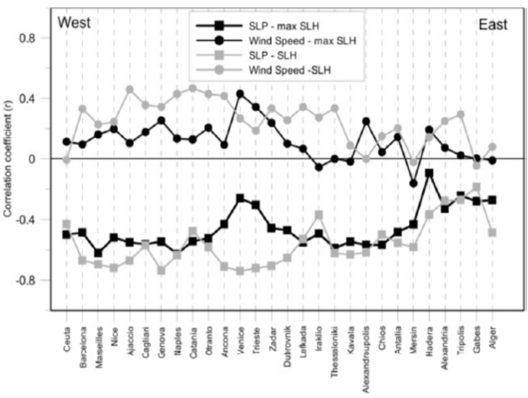

Fig. 3. Distribution of correlation coefficients (r) between the annual maximum SLH and the respective SLP (black circles) and wind speed (black circles) values for 28 stations. The respective correlations for the entire SLH, SLP and wind speed time-series are indicated with grey color.

3.1 General trends

The study period is divided in three sub-periods in order to investigate the general trends of the annual maximum and average SLH during the past period (1951-2000), the first (2001-2050) and second (2051-2100) half of the 21^{st} century under the A1B climate scenario (Fig.4).

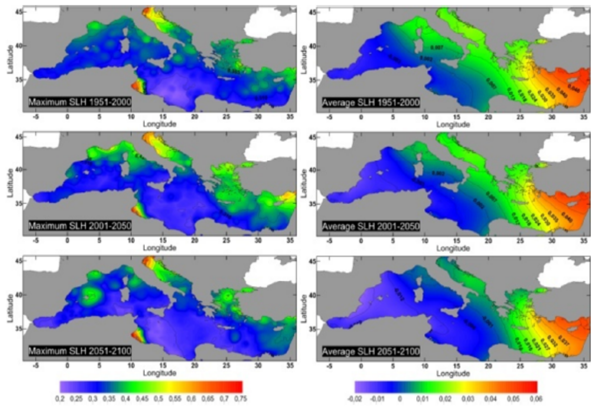

Fig. 4 Horizontal minimum (left) and average (right) SLH (m) distribution as derived from the MeCSM simulation results.

The maximum extreme values were observed over the N. Adriatic, Aegean, N. Levantine and Central African coastline during all periods. However, the highest values were calculated during the 2001-2050 in all of these areas. On the contrary, the average SLH is lower during the first half of the 21st century in comparison with the second half of the 20th century, indicating an attenuation of the storminess, especially over central and eastern Mediterranean region. The attenuation is also appeared during the last 50 years in agreement with a significant reduction also at the maximum SLHs in comparison with the 2001-2050 period. Although Balearic Sea is the only region that may reveal higher values in the end of 21st century, the general SLH trend (average) is decreasing.

4 Conclusions

The contribution of the wind and SLP combination on the SLH variability varies from region to region, depending on topographic features and atmospheric low pressure system propagation. There is a clear difference on the initiating cause of the extreme SLH events between Aegean and Adriatic regions, especially over extensive low-elevation areas, where the high sea-surge levels may induce significant flooding. Although higher maximum SLHs may appear during the first half of the 21st century over several risky areas, the general trend is decreasing, supporting the storminess attenuation under the A1B scenario.

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