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NUMERICAL MODELLING OF STORM SURGES IN THE MEDITERRANEAN SEA UNDER CLIMATE CHANGE

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ABSTRACT

Extreme storm surge events pose a great threat to low-elevation coastal areas and can cause loss of land and property, damages to structures and defenses, and even human casualties. Hereby, we explore the trends of meteorologically induced extremes of sea level in the Mediterranean Sea, with a specific focus on the Greek seas, for a period of 150 years (1951-2100). The analysis is based on hydrodynamic simulations of storm surges with a couple of high spatial resolution model implementations for 2D shallow water equations, the Greek Climate Surge Model (GreCSM), which is nested to the coarser domain of the Mediterranean Climate Surge Model (MeCSM). The latter are implemented under IPCC's A1B climate scenario that considers increasing future concentrations of atmospheric greenhouse gases. In this framework, *in situ* measurements from several areas, during the last 50 years, are used to evaluate the models' results. Statistical indices and spatial distributions of extremes, from both historical data and modelling, show good agreement. This confirms the ability of our models to estimate the response of the sea surface to future climatic conditions. We also investigate the future trends, the variability and occurrence frequency of extreme sea level anomalies and the main forcing mechanisms that can induce strong surges in the Mediterranean basin and the Greek seas. Our results support that there is a general decreasing trend in storminess under the considered climate scenario. However, this is mostly related to the occurrence frequency of sea-surface maxima and the spatial coverage of storm surges, yet not to the actual magnitudes of sea level maxima that can increase during the 21st century. We show that the different morphological characteristics of the regional Seas in the Mediterranean basin have a significant influence on the variability of extreme events, and there are also clear distinctions in the seasonal variability of extremes under the A1B scenario. The significant storm surge extremes, along the Mediterranean and the Greek coastlines, are predicted until 2100, through the use of recently proposed Indices. The impact of Climate Change on the evolution of storm surge extremes on the Greek coastal zone is also investigated.

Keywords: Storm Surge; Climate Change; Mediterranean; Greek Seas; Hydrodynamic Modelling

1. INTRODUCTION

Low-elevation areas along the Mediterranean coastline are at high risk in cases of extreme storm surge events; extreme storms may induce significant direct (e.g. flooding, coastal erosion, damage to property) and indirect (e.g. salt intrusion, land subsidence, water supply contamination, vegetation destruction) impacts on the coastal zone (White, 1974). The existence of numerous cities, river deltas, islands, low-land areas and topographically versatile regions (e.g. Greek coastal zone and the Aegean Archipelago) over the Mediterranean coastal zone supports the need to consider possible Climate Change impacts on near-shore sea level elevation in terms of coastal planning (Nicholls and Hoozemans, 1996). Although the tidal signal is an important factor in assessing the mid-term sea surface elevation, in the long run the Mediterranean basin's sea level extremes are mainly related to storm surges rather than to the combination of tides and surges (Marcos et al., 2009). The goal of the present study is to investigate the interannual evolution of storm surges, together with the seasonal and spatial variability of extreme sea level anomalies in the Mediterranean (with a special focus on the Greek seas) for the 21st century under specific climatic conditions. Collateral objectives are the assessment of occurrence frequency for extreme storm surge events in the future and the identification of the main driving mechanisms above different coastal sub-regions of the Mediterranean. Based on the above we focus also on the derivation of indices regarding specifically the impact of Climate Change on the evolution of storm surge extremes for the current century. A basic byproduct of the investigation is the good qualitative and quantitative evaluation of our numerical hydrodynamic models, which simulate the sea level anomalies induced by meteorological conditions in the changing climate of the future.

Storm surges may have significant differences between the various Mediterranean regions, due to the topography of each area and the storm characteristics. There is a high correlation between the surges over the western and central Mediterranean and the North Atlantic Oscillation (Marcos et al., 2009), while its relation with surges in the eastern Mediterranean is also significant but weaker due to the distance from the atmospheric (pressure) action centers. Storm surge events in the Aegean Sea generally exhibit low magnitude and occurrence frequencies of extreme events (Krestenitis et al., 2011). Satellite altimetry data for the 1993-2000 period (Tsimplis et al., 2009) and mathematical simulations for the 2000-2004 period (Krestenitis et al., 2011) showed that the gradient of the increasing sea level trend is steeper over the eastern than the western Mediterranean coasts. Regarding the North Adriatic basin, its shape determines unique sea surface dynamics with seiches, surges, astronomical tides, and the long fetch of strong southeasterly winds

(Sirocco) that may favour intense storm surge conditions (Lionello et al., 2012). A region with intense atmospheric cyclogenesis in the Mediterranean is the Levantine basin (Campins et al., 2011). The seasonal distribution of sea storms over the Mediterranean region has presented significant changes in the last centuries. Changes in sea storm frequency were strongly associated with tremendous floods in the Spanish coastal zone of the Mediterranean in the late 16th, late 17th, and mid 19th centuries. Mediterranean surges have a clear seasonal distribution with high positive surges occurring mostly in winter, however a reduction in the number of severe storm events is predicted by Marcos et al. (2011) in the 21st century over southern Europe, which might lead to a decrease in the number of storm surges there. Nevertheless, the Mediterranean is a 'hot spot' for Climate Change, according to Giorgi (2006). Based on a Climate Change study for the period of 1951-2050, Conte and Lionello (2013) confirmed that storminess attenuation is probable above the Mediterranean Sea. However, the mean sea level rise and land subsidence might increase the hazards of coastal flooding.

In the present work, we seek to explore the trends of sea level extremes due to atmospheric conditions for a period of 150 years, under a future climate scenario with highly increasing concentrations of atmospheric greenhouse gases. The Climate Change scenario used in the study is A1B, one of the 35 presented in the Special Report on Emission Scenarios given by the Intergovernmental Panel on Climate Change (IPCC, 2001). A1B emission scenario is applied on the 3rd version of the Regional Climate Model (RegCM3; Pal et al., 2007), which in turn forces the high resolution Aristotle University of Thessaloniki Storm Surge Model (AUTSSM; De Vries et al., 1995; Krestenitis et al., 2011; Trifonova et al., 2012; Villatoro et al., 2014), for the period of 1951 to 2100. Evaluation of AUTSSM's implementations on the Mediterranean and the Greek seas against available *in situ* measurements showed that the simulation from 1951 until today can efficiently reproduce spatial and temporal distribution of the Sea Level Height (SLH) extremes. The evolution of seasonal variability and the contribution of atmospheric factors on the general trend of SLH distribution were also investigated along the Mediterranean coastline and over the Mediterranean sub-basins (e.g. Aegean Sea, Adriatic Sea). We divided the study period into two main time-spans: the *Past Period* (1951-2000) and the *Future Period* (2001-2100); the latter with two equal Sub-Periods (2001-2050; 2050-2100). We compared alterations of SLH maxima and their occurrence frequencies over various Mediterranean sub-regions during those Periods, which are parts of the continuous 150-year climatic simulation, forced by the RegCM3 implementation in the Mediterranean Sea. Moreover, specific regions of significant probable coastal vulnerability were detected, based on high frequencies and magnitudes of sea level extremes, and proper indices for storm surges and Climate Change impact on them.

2. METHODOLOGY

2.1 Climate model

The Regional Climate Model (RegCM) was developed by the International Centre for Theoretical Physics in Trieste, based on the Mesoscale Model version 4 from the National Center for Atmospheric Research-Pennsylvania State University. RegCM is an atmospheric model of finite differences, with hydrostatic balance and vertical Σ-coordinates, which accounts for the sub-grid scale variability of clouds (Giorgi et al., 1993; Pal et al., 2000), extensively used for climate simulations to investigate past and/or future evolution of atmospheric parameters. Future changes on the climatology of cyclones in the Mediterranean Sea, under A2 and B2 climate scenarios, have also been investigated with RegCM simulations (Lionello and Giorgi, 2007), eventually coupled with a wave model to study the changes of wind-wave interactions in the Mediterranean Sea towards the end of the 21st century (Lionello et al., 2008). The numerical climate simulations in this study were developed by the Department of Meteorology and Climatology of Aristotle University of Thessaloniki, in the framework of a research project whose partial goal is to assess the impacts of Climate Change on the marine climate, the waves and the storm surges of the Mediterranean Sea, focusing especially on the Greek seas (see also Acknowledgements Section). The implemented emission scenario (A1B) is based on the assessment that all the energy sources will be equally used, and is characterized as pessimistic, with the CO_2 concentrations reaching up to 815 ppm until the end of 21st century (IPCC, 2001). A1B belongs to the A1 scenario category, which describe a future of very rapid economic growth, with new and more efficient technologies and high earth population. Wind and Sea Level Pressure (SLP) fields were simulated for the entire Mediterranean and the Greek seas, with spatial horizontal resolutions of 25×25 Km and 10×10 Km, respectively. The rest calibration parameters are mentioned in Table 1. Tegoulias et al. (2013), Velikou et al. (2014) and Vagenas et al. (2014) presented extensive information and validation with *in situ* data, regarding the effectiveness of the RegCM3 implementation to investigate climate changes over Europe. RegCM3 simulations provided the atmospheric forcing input of the AUTSSM hydrodynamic storm surge model (see Section 2.2).

Table 1. Basic parameterizations of RegCM3 implementation in the Mediterranean and the Greek seas.

Parameterization	**Reference / Values for RegCM3-Med and RegCM3-Gre**
Number of Grid Points; Vertical Levels	192×108 and 128×160; 18 and 18
Integration Time; Time Step	January 1st, 1950 – December 31st, 2100; 60 sec and 30 sec
Driving Field; Terrain and Land Use Resolution	ECHAM5 and RegCM3-Med; 10 min and 3 min
Schemes: Cumulus; Convective Closure; Planetary Boundary Layer	Grell (1993); Fritsch & Chappell (1980); Holtslag et al. (1991)

2.2 Storm surge model

AUTSSM is a two-dimensional hydrodynamic model that solves the depth-averaged shallow water equations and is used to predict the SLH induced by atmospheric conditions. The Mediterranean/Greek Climate Surge Models (MeCSM/GreCSM) are the implementations for the entire Mediterranean basin on a 1/10˚×1/10˚ horizontal grid and for an extended basin including the Greek seas on a 1/20˚×1/20˚ horizontal grid, respectively. The 6-hourly atmospheric forcing, namely the winds at 10 m elevation from mean sea level and the SLP fields, are provided by the RegCM3 simulations (see

Section 2.1) for the entire study period (1951-2100). The calculation of the horizontal shear stresses on the sea-air interface, used in the momentum equations, is based on the following:

$$\tau_{sx} = \rho_A C_s |\mathbf{W}| W_x \quad \& \quad \tau_{sy} = \rho_A C_s |\mathbf{W}| W_y \quad \& \quad C_D = \left(0.63 + 0.066|\mathbf{W}|\right) / 10^3 \qquad [1]$$

where ρ_A is the air density, $\mathbf{W}=(W_x, W_y)$ is the wind velocity horizontal vector with its norm given by $|\mathbf{W}|=(W_x^2+W_y^2)^{1/2}$, and C_D is the friction coefficient given by the approach of Smith and Banke (1975). The atmospheric pressure contribution is included in the momentum equations in terms of a pressure gradient $dp_a/(\rho \cdot dl)$, where p_a is the atmospheric pressure, ρ is the density of the water, l is the longitudinal (x) or latitudinal (y) spatial coordinate of the Cartesian model grid. The study areas (model domains), sub-regions and stations are shown in Figure 1 (the Black Sea and Atlantic Ocean excluded in simulations). The General Bathymetric Chart of the Oceans (GEBCO; http://www.gebco.net/) was used to build the model bathymetries with bilinear interpolation into the models' computational grids.

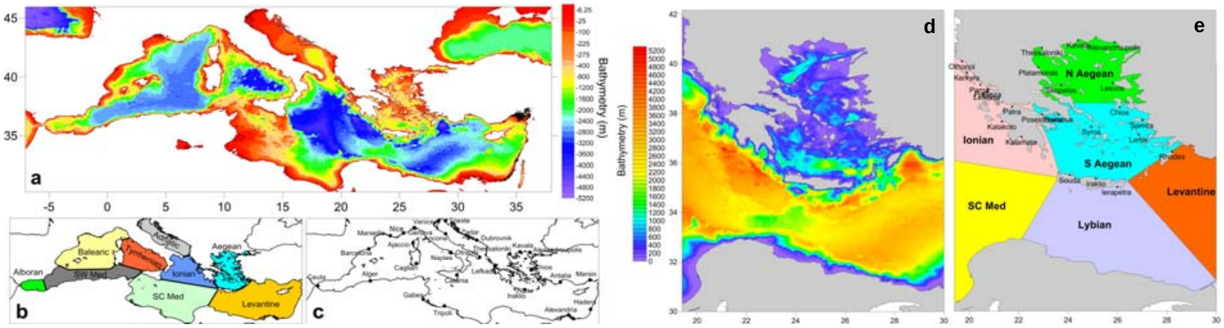

Figure 1. *Left panel*: a) Bathymetry (m) of MeCSM domain (Atlantic and Black sea excluded). b) 9 regional seas of MeCSM domain. c) Locations of the 28 stations of MeCSM domain. *Right panel*: d) Bathymetry (m) of GreCSM domain. e) Locations of 25 stations and 6 sub-regions for GreCSM domain. Please note that the Aegean is split in northern and southern part and MeCSM's Levantine region is divided to Lybian and Levantine Seas. (SC: South-Central, N: North, S: South, and SW: South-Western)

2.3 *In situ* observations

In order to evaluate the validity of MeCSM and GreCSM simulations during the *Past Period* of the investigation, *in situ* sea level measurements were collected from two sources. Data from the Global Sea Level Observing System (GLOSS; http://www.gloss-sealevel.org/) were used for the broader Mediterranean region (4 stations) and data from the Hellenic Navy Hydrographic Service (HNHS; http://www.hnhs.gr/portal/page/portal/HNHS) were used for the topographically diverse Greek seas (5 stations). The GLOSS data were obtained by the University of Hawaii Sea Level Center (UHSLC; http://uhslc.soest.hawaii.edu/home). High-quality (one record per 10 minutes) measurements were collected from four GLOSS stations, namely Marseille, Ceuta, Trieste and Alexandria (Figure 1c). The recording periods correspond to 1998-2007 and 1951-2008 for Marseille and Ceuta, respectively, while the available data for Alexandria and Trieste cover only a small time-span from 2009 to 2012. In addition, data from four stations in the Aegean Sea (Thessaloniki, Alexandroupolis, Iraklio and Chios) and one in the Ionian Sea (Lefkada) were collected from the HNHS tide-gauge network, covering an 11-year period (2002 to 2012). No observations were available for the remaining stations, presented in Figure 1; these are used only as characteristic locations around the Mediterranean and Greek coastlines, where simulated time-series are derived and analyzed in the current study. In the cases of both GLOSS and HNHS stations, the daily-averaged SLH values, used in the study, were derived from the measured data after subtraction of the mean sea level, which was determined using a moving average technique. Thus all observed SLH time-series were processed using a heuristic technique, which consisted of a high-pass filter operator with a cut-off frequency of 1/30 days, in order to exclude long term oscillations of the sea level (Conte and Lionello, 2013). The latter can be primarily induced by the steric effects, due to the large-scale, low-frequency, thermohaline fluctuations and/or total mass variations of the enclosed basin under investigation (Carillo et al., 2012). This type of effects is not simulated by MeCSM or GreCSM, and thus needed to be excluded from the observations as well. Conclusively, in all following comparisons of model output against available gauge data, only daily-averaged values are used for both the simulated and the recorded data of SLH. Moreover, it is noted that MeCSM and GreCSM do not include modelling of the tides. However, given that in most of the considered stations (in the Mediterranean) the tidal cycle is of the semi-diurnal type, i.e. records have two high and two low tidal values of approximately equal size every lunar day, thus a daily-averaged value of the recorded time-series removes implicitly almost all of the tidal effects in the signal. This is not the case of course for stations where mixed semi-diurnal tides prevail, yet discrepancies due to explicit daily averaging are very small compared to the increase of SLH due to storm surges.

3. MODEL EVALUATION

Comparisons of available *in situ* data against numerical simulations' output are presented, in order to validate the storm surge model (MeCSM and GreCSM) results. The simulated time-series cover the exact same periods with the respective observations and refer to model grid points closest to each one of the actual gauge stations.

3.1 Local maxima of sea level anomalies

We calculated the "local" SLH maxima for four stations (Ceuta, Marseille, Trieste and Alexandria) representing the Mediterranean Sea from West to East. During the "local peak" computation we compare all daily-averaged SLH with its adjacent values; if a daily value is larger than both of its "neighbours", then this SLH value is defined as a local peak. The local peak frequency of occurrence, presented in Figure 2, is derived from the number of days that local maxima appeared in the SLH time-series, divided by the total number of days of each study period. For each station, all local peaks that exceed 20 and 30 cm were computed, in order to evaluate the model during extreme surge periods. The comparison of local peaks frequency, between model and *in situ* data, shows that the agreement is satisfactory in all stations. The 10-year period comparison at Marseille shows local peak frequencies around 20% for both model (22.3%) and *in situ* (18%) time-series (Figure 2a). Local peaks that exceed the elevation of 20 cm also present similar occurrence frequencies between model output and observations (1~2%). We calculated contiguous but slightly smaller frequencies of occurrence for a station in the western Mediterranean (Ceuta; Figure 2b), while the extreme local peaks (>20 cm) are almost negligible, indicating the predominance of low SLHs in the western Mediterranean. In the N. Adriatic Sea, we derived higher values (Trieste; Figure 2c) for both model (23.8%) and measurements (19.6%), while the frequencies of local peaks over 20 cm are in very good agreement (~2.65%) for both time-series. Significant local peak frequencies for SLH over 20 cm were observed only in Trieste. This observation is in agreement with previous studies that found the highest SLH values of the Mediterranean over the northern Adriatic area (e.g. Marcos et al., 2009). Based on observations and simulations, Conte and Lionello (2013) showed that the largest SLHs of the entire Mediterranean coastal region occur in Trieste, with generally smaller surges outside the Adriatic. The northern Adriatic Sea reveals the highest sea level values for both model and measurements, mainly due to wind forcing mechanisms. The calculated occurrence frequency of SLH local peaks is very low for the southeastern station of Alexandria (<4%; Figure 2d), while the frequency of local peaks exceeding 20 cm, derived from both MeCSM and *in situ* time-series, is almost zero.

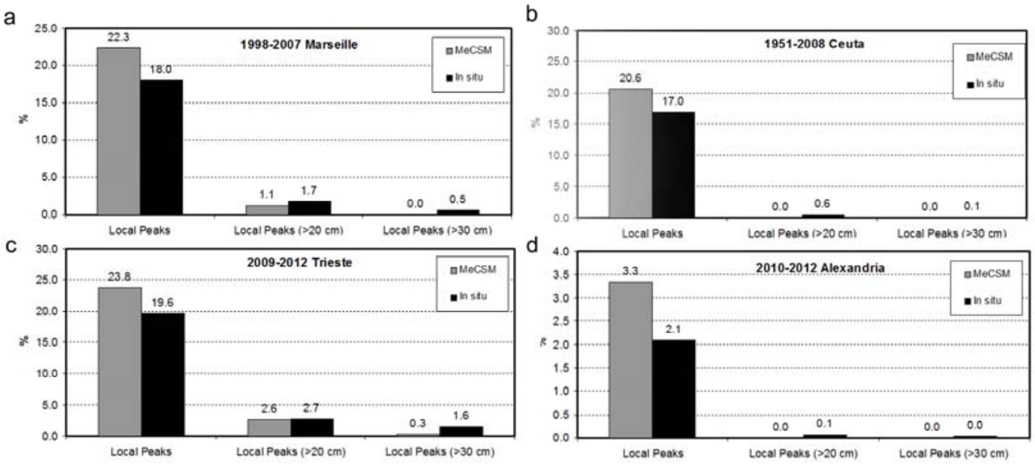

Figure 2. Occurrence frequency (%) of SLH local peaks, from daily-averaged *in situ* (black) and respective MeCSM (grey) data; for all recorded maxima and for maxima exceeding the thresholds of 20 and 30 cm; a) in Marseille (1998-2007), b) in Ceuta (1951-2008), c) in Trieste (2009-2012), and d) in Alexandria (2010-2012).

3.2 Storm Surge Index

The statistically significant values of the largest annual sea level anomalies can be investigated using the Storm Surge Index (*SSI*). *SSI* is defined as the average of the three highest independent storm surge maxima (derived from SLH time-series) per year (Conte and Lionello, 2013); only the storm events separated by at least 120 hours (estimated maximum duration of a storm) are considered as independent. The *SSI* for both simulated and observed time-series was calculated for each of the eight stations, along with the corresponding Percent Error (*E*) and Error Index (*EI*):

$$E(\%) = 100 \cdot \left(\overline{SSI_{mod}} - \overline{SSI_{obs}}\right) \Big/ \left(\frac{\overline{SSI_{mod}} + \overline{SSI_{obs}}}{2}\right) \ \& \ EI = \left(\overline{SSI_{mod}} - \overline{SSI_{insitu}}\right) \Big/ \sqrt{\left(\sigma^2_{SSI_{mod}} + \sigma^2_{SSI_{insitu}}\right) \Big/ 2} \qquad [2]$$

where SSI_{mod} and SSI_{obs} are the respective *SSI* derived from modeled and observed data, σ is the standard deviation of the *SSI* time-series for each station, and the overbar denotes time-averaged values. It is noted that *E* and *EI* are positive when the model overestimates the amplitude of the sea level against observed data. High *SSI* values occur over the northern Adriatic coastal region (Trieste), where both modeled and observed *SSIs* are around 30 cm (Figure 3a). The low Percent Error (~6.8%; Figure 3b) supports the good performance of MeCSM during this period. Small overestimation of the simulated SLHs in comparison with the *in situ* data (*EI*=0.29; Figure 3b) is detected in agreement with Conte and Lionello (2013). Even though MeCSM underestimates the *SSI* at all other stations (negative *EI* values), the error is generally small and SSI_{mod} and SSI_{obs} values are very close. The Ceuta station is an exception with higher errors (|*E*|>50%; *EI*=-3.65), probably due to discrepancies of the old time-series of measured SLH (starting in 1951). However, both model results and observations show low *SSI* values (<20 cm), supporting the low presence of SLH extremes in the area due to meteorological conditions; it is also noted that, even though the model underestimates the magnitude of surges, it performs well in terms of predicting the frequency of local maxima over this western-most region (Figure 2b). Conte and Lionello (2013) also showed results of climate storm surge simulations with significantly high *E* (>40%) and similar underestimations of the simulated SLHs over coastal regions of the western Mediterranean. Lower errors (in absolute values) are derived at the stations of both Marseille (*E*=-16.7%; *EI*=-0.66) and Alexandria (*E*=-10.33%; *EI*=-0.30), where the modeled *SSIs* are around 22 cm and 14 cm, respectively.

With regard to the diverse Greek coastal zone, the lowest *SSI* values were calculated at the Ionian Sea (Lefkada) (Figure 3a), as derived from both MeCSM and observed time-series. GreCSM simulations seem to overestimate the SLH extremes in the Ionian Sea station. The highest values (27 cm) were observed at the northern Aegean stations. Although MeCSM underestimates the respective extremes, it produces the highest values (~22 cm) over the same region, in agreement with observations. The GreCSM results are far better than MeCSM's for the latter stations and also very good for the Iraklio station (Figure 3c). The largest (absolute) *EI* for the Greek stations was calculated for MeCSM in Thessaloniki (*EI*=-1.23; Figure 3b). The remaining Greek stations display smaller |*E*| (<20%) and |*EI*| (<1), indicating that the MeCSM simulation errors, as derived from the comparison with the observed data, are not significant. Overall, the comparison of measured and simulated *SSIs* shows that, apart from the western-most area near the Gibraltar strait, the model performs adequately. It is noted that the impact of the error in the vicinity of the strait is strongly local and does not affect the other areas of the basin. In general MeCSM underestimates *SSI* in all stations compared to the high spatial resolution GreCSM implementation. The latter proves more appropriate for the simulation of extreme storm surges, as it is clear that the improvement of the model's performance (Alexandroupolis and Thessaloniki), based on absolute *EI* is larger than its downgrading (Lefkada and Chios; Figures 3b and 3d).

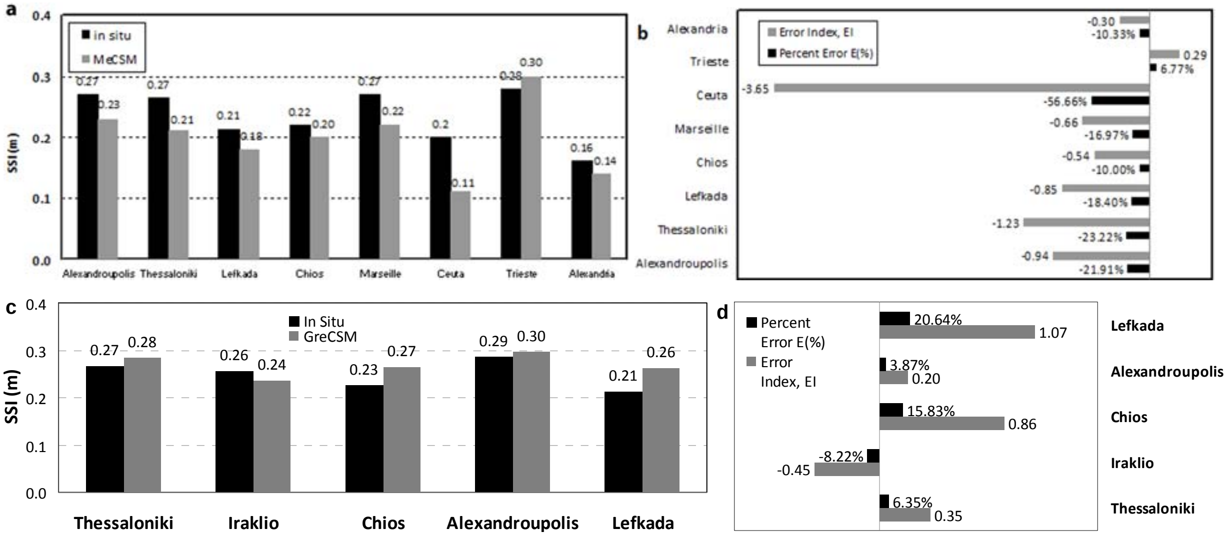

Figure 3. Comparison between MeCSM/GreCSM [upper/lower graphs] (grey) and *in situ* time-series (black), for the 2002-2012 period, concerning a,c) Storm Surge Index (*SSI*) values; b,d) Percent Error *E* (%) (black) and/or Error Index *EI* (grey) values at Mediterranean (upper graphs) and Greek (lower graphs) stations.

3.3 Statistical measures (exceedance probabilities and percentiles) of extreme storm surge events

In a study about intermittency of coastal sediment transport in the surf zone, Jaffe and Sallenger (1992) heuristically defined the events that exceed a critical value, as 'coherent extreme events'. A similar probabilistic approach is used in the present study, due to the climatological nature of the presented analysis, which does not allow ; a "coherent" event is defined as having values of $SLH_{coh} \geq (m+\sigma)$, and an "intense" event as $SLH_{int} \geq (m+2\sigma)$, where *m* is the mean of the SLH time-series over the entire study period (11 years in the case of the Greek stations), and *σ* is the corresponding standard deviation. The exceedance probabilities (P_{coh} and P_{int}) of critical values ($SLH_{cr}=m+\sigma$ *and* $m+2\sigma$ respectively) for all Greek stations is presented in Figure 4, as derived from both simulated and observed time-series. P_{coh} describes the occurrence frequency of rather common extreme events, and P_{int} of significantly extreme and rare events. Simulated values are correlated well with the measured ones in all stations, with lower frequencies of coherent events at the central Aegean (Chios) and higher values over the Ionian Sea (Lefkada); the inverse is valid for intense events probabilities. In general, both model implementations reveal very good performance against *in situ* data for all areas.

The performance of MeCSM was also evaluated by the use of statistical dispersion measures, namely high order percentiles (80th, 90th, and 95th) *Per*, presented in Table 2. The highest values were derived for the N. Adriatic (Trieste) from both simulated and observed data ($Per_{mod,95}$=18 cm and $Per_{obs,95}$=24.9 cm), in agreement with the occurrence frequencies of high local peaks (Figure 2) and the respective *SSI* (Figure 3a). Ceuta showed poor agreement between simulated and observed data, yet both time-series revealed the lowest percentiles among all stations. At the French coast, the relevant comparisons in Marseille show fairly good agreement, namely for the 80th (Per_{mod}=6.8 cm and Per_{obs}=7.2 cm), 90th (Per_{mod}=12.3 cm and Per_{obs}=13.4 cm), and 95th (Per_{mod}=16.3 cm and Per_{obs}=18.7 cm) percentiles. In general, the percentiles distribution over all stations showed similar behaviour for both model and observations, indicating that the simulation of the *Past Period* follows the regional surge characteristics of the Mediterranean Sea, as derived from the available gauges. Figure 5 presents indicatively a comparison between MeCSM and GreCSM (left and right graphs respectively) against *in situ* data, concerning the high-order 90th percentile Per_{90} at the Greek stations for the 2002-2012 period. The lower *SSI* values for the Ionian Sea and the Central Aegean (Lefkada and Chios; Figure 3a) are also confirmed by the percentile levels. The major discrepancy concerns the Iraklio station, yet the nested GreCSM output is far better than the coarser domain MeCSM there. Similarly, the high-order 90th percentile, describing extreme storm surge magnitudes, is improved by finer simulations when compared to observations for the southern and northern Aegean Sea.

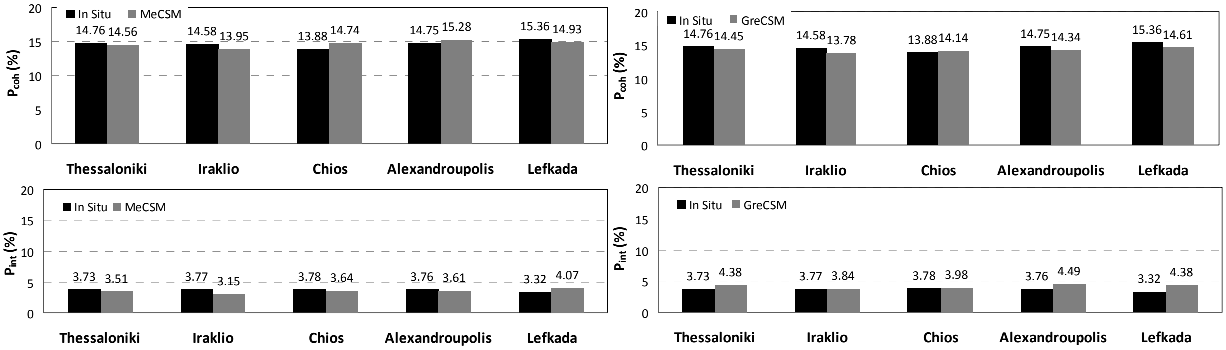

Figure 4. Comparison between MeCSM/GreCSM [left/right graphs] (grey) and *in situ* time-series (black), for the 2002-2012 period, concerning the exceedance probabilities of coherent [upper graphs] and intense [lower graphs] events, P_{coh} and P_{int} respectively, at the Greek stations of Iraklio (S. Aegean), Chios (Central Aegean), Lefkada (Ionian Sea), Thessaloniki and Alexandroupolis (N. Aegean).

Table 2. High order (80th, 90th, 95th) percentiles of SLH (m) at several stations, derived from MeCSM (Per_{mod}) and *in situ* (Per_{obs}) data.

Per	**80th**		**90th**		**95th**	
Station	Per_{mod}	Per_{obs}	Per_{mod}	Per_{obs}	Per_{mod}	Per_{obs}
Marseille	6.8	7.2	12.3	13.4	16.3	18.7
Ceuta	2.2	5.5	4.1	9.4	5.9	13.1
Trieste	8.0	9.8	13.2	17.9	18.0	24.9
Alexandria	7.1	10.7	9.1	13.7	11.5	15.9

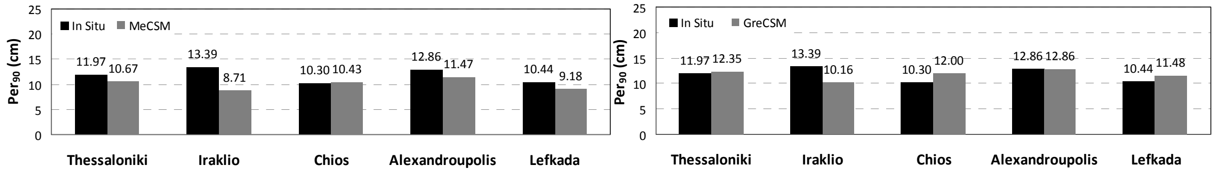

Figure 5. Comparison between MeCSM/GreCSM [left/right graphs] (grey) and *in situ* time-series (black), for the 2002-2012 period, concerning the high-order 90th percentile Per_{90} at the Greek stations.

4. RESULTS

We produced results with MeCSM and GreCSM for the 1951-2100 climate simulations, in order to investigate the contribution of SLP on the SLH regional variability, depending on topographic and morphological features. Moreover the seasonal variability of SLH along the Mediterranean and Greek coastlines and over the osculate seas and sub-basins was studied. Furthermore, the general spatial (at sub-basins) and temporal (on specific stations) trends of SLH were calculated until the end of the 21st century. Last but not least, we derived the magnitudes of future significant events of storm surges along the Mediterranean coastline, also assessed the possible impacts of extreme storm surges on the coastal zone, and finally we derived an index of Climate Change influence on the possible future evolution of storm surge severity.

4.1 Atmospheric contribution on extreme storm surge events

The evolution of the annual maximum SLH (SLH_{max}) for all study stations, under Climate Change, derived from the 150-year simulation, covering the greater part of the Mediterranean coastal zone. Specifically, the Adriatic and Aegean Seas are two major Mediterranean basins with special morphological features that have been affected by significant storm surges in the past. In an older study of ours (Krestenitis et al., 2014a), we investigated the contributions of winds and pressure fields to the SLH for various regions of the Mediterranean, and we deduced that surge maxima are predicted to be mainly induced by low-pressure systems and severe winds in the northern Aegean and Adriatic Seas, respectively. To elaborate further on the storm surge characteristics and the related driving mechanisms for the *Past* and *Future* study *Periods*, we investigate the storm surge extremes' evolution using one coastal station from each area (Trieste and Iraklio; Figure 6 left panel). The MeCSM simulation reproduced SLH maxima that exceed 0.80 m in Trieste (Figure 6c). Focusing on the peak SLHs at Trieste in the *Future Period*, we detect 3 strong events (SLH>0.60 m), corresponding to 2016, 2036 and 2094. The prevailing strong southerly winds (≥20 m/sec) over the Adriatic Sea during these storms (red vectors in Figure 6a) are responsible for these peak SLH events. Although the SLP trend is increasing, the interannual evolution of maximum SLH is essentially stable during the *Future Period*, in agreement with low correlation between the annual SLH_{max} and the corresponding SLP values. The *Past Period* is characterized by lower SLH maxima, which is in agreement with the observations of Raicich et al. (2003), showing that in the 1940–2001 period, the frequency of strong positive surges exhibited a likely negative trend, whereas trends of lower surges were stable. The MeCSM simulation also shows relatively stable trend for the frequency of local peaks (~27.4%; Figure 6d) during the *Past Period*. At the same time, the annual frequency of local peaks strongly decreases during the entire 21st century (*Future Period*), indicating that even though a few greater extremes may occur in the future, the number of local peaks may decrease, most likely due to the general increase of SLP (Figure 6b). This increase of SLP is probably related to the increasing anticyclonic atmospheric circulation over the Mediterranean, which may cause a northward shift of the mid-latitude storm tracks (Giorgi and Lionello, 2008). The relation between atmospheric conditions and extreme surge events in the Aegean coastal region is different. The SLH maxima present a decreasing trend that is inversely correlated with the increasing trend of the SLPs; annual maximum SLHs in Iraklio continue to drop in the entire *Future Period* (Figure 6c), while the respective SLPs show a continuous increase (Figure 6b). Moreover, the local peak frequency also shows a respective decreasing trend during the entire study period (Figure 6d). The prevailing southwesterly winds, during extreme events in Iraklio (Figure 6a), is unfavorable for accumulating waters near the shore. The highest extreme SLHs exceed 0.3 m (e.g. 2013, 2037 and 2091) and coincide with very low pressures (~990 hPa; Figure 6b) and unfavorable weak winds (red vectors in Figure 6a), indicating the direct effect of low pressure systems on the sea level variability of this coastal area. Analogous findings for other Aegean stations (not shown here), based on the GreCSM simulations, suggest that pressure is predicted as the main factor controlling extreme storm surge events over the entire region except from the Rhodes station (south-central Aegean). In Rhodes a high impact of the intense wind regime is predicted on the evolution of SLH maxima (Figure 6; right graphs of right panel).

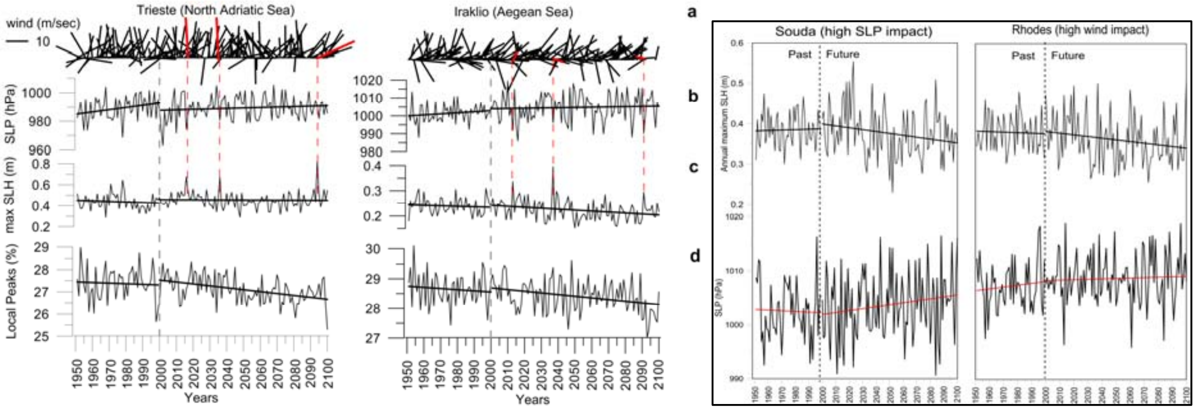

Fig. 6. *Left panel*: Climatic evolution of a) directional winds (m/sec), b) SLP (hPa) from the RegCM3 simulation, c) annual maximum SLH (m), and d) occurrence frequency (%) of SLH local peaks from the MeCSM simulation in Trieste (North Adriatic; left panel) and Iraklio (Aegean Sea; right panel). The linear trends for the *Past* and *Future Periods* are indicated with a thick solid black line and the highest annual maxima of each station are indicated with vertical red colour dash lines. *Right panel*: Climatic evolution of annual maximum SLH (m) [upper right panel] and SLP (hPa) [lower right panel], from the GreCSM simulation in Souda (South Aegean; left graph of right panel) and Rhodes (Southeastern Aegean; right graph of right panel). The linear trends for the *Past* and *Future Periods* are indicated with a straight black (for maximum SLH) and red (for SLP) line.

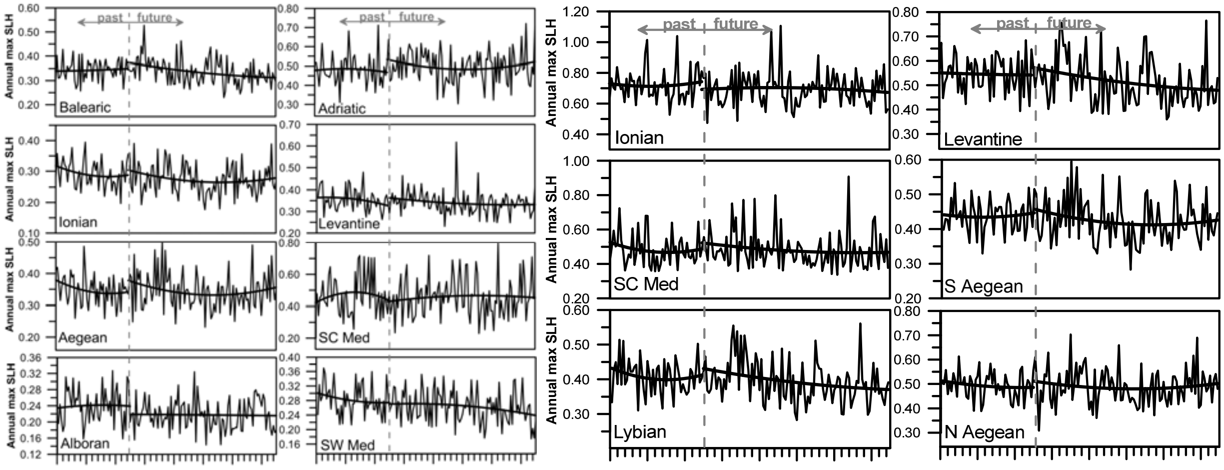

Figure 7. Temporal evolution of annual maximum SLH (m) from MeCSM simulations for the 8 regional seas of the Mediterranean (see Figure 1b) [left panel graphs]; the same feature from GreCSM simulations for the Greek seas (see Figure 1e) [right panel graphs]; 2nd degree polynomial trends of *Past* and *Future Periods* are indicated with a thick solid black line.

4.2 Climatic evolution of extreme storm surge events

Figure 7 presents the annual SLH maxima from MeCSM and GreCSM simulations, for the Mediterranean (left panel graphs) and the Greek Seas (right panel graphs) sub-basins, respectively. Although the SC Med shows significantly low annual surge duration and coverage values (Krestenitis et al., 2014b), it also presents very high SLH maxima (>60 cm) due to storm passages, for both *Past* and *Future Periods.* It is the only region that does not show decreasing trends of annual maximum values during the entire 21st century. Contrastingly, a strong decreasing trend during both periods is identified for the SW Med; the storminess attenuation is supported by a decrease in storm maxima, duration and coverage (Krestenitis et al., 2014b). Very low maxima may also occur over the western-most Mediterranean, in the Alboran region (<30 cm), but with a future trend of lower slope, compared to the SW Med. In all the other regional seas, the annual sea level maxima range between 30 cm and 40 cm, without a distinguishable trend. The annual extreme maxima do not show significant changes during the *Future Period* for most of the Mediterranean sub-basins. However, the frequency of local peaks may show significant reduction, even in areas, where SLH maxima may increase in the future (e.g. Adriatic Sea). All coastal stations of the Adriatic Sea showed decreasing trends in local peak frequencies for the entire study period (e.g. Trieste; Figure 6d), but, at the same time, higher annual sea level maxima may appear in the *Future Period* (Figure 6c and Figure 7; left panel). The north-central Mediterranean Sea (Adriatic and Aegean Sea) shows a decreasing trend of annual maxima over the first half of the *Future Period*, but with a small increase during the last 30 years of the century. It follows that the predicted attenuation of storminess refers more to the frequency of local peaks, duration and coverage of the storm surges (Krestenitis et al., 2014b) and not to the magnitude of localized surge maxima, which may be higher than the peak values of the *Past Period*.

Analysis of the GreCSM simulations differs. The temporal evolution of annual SLH maxima for the Greek Seas' sub-basins is presented in Figure 7 (right panel graphs). The finer resolution simulations reveal that in the Ionian Sea the severity of storm surge extremes may be larger than the one predicted by MeCSM. The SLH maxima are generally double in magnitude compared to MeCSM values, yet with a decreasing trend towards the end of the 21st century, nevertheless showing extremely high values (>1 m) from 2030 to 2040. The Aegean Sea is predicted to show the same rising trend towards 2100 with slightly more pronounced values than the ones by MeCSM simulations. For the south-central Mediterranean part of the basin that coincide in both simulated sets, the magnitudes and limit values of SLH are the same. The values of SLH extremes are also larger in the Levantine Sea for the finer resolution model, though the general trends are similar.

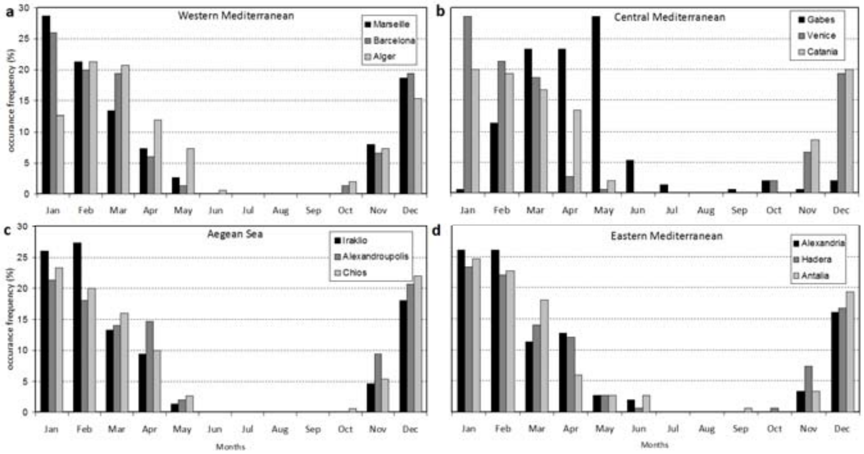

Figure 8. Monthly occurrence frequency (%) of annual maximum SLH appearance from the MECSM simulation (150-year period) at selected stations of the a) Western Mediterranean, b) Central Mediterranean, c) Aegean Sea, and d) Eastern Mediterranean.

4.3 Seasonal variability of extreme storm surge events

To investigate changes in the seasonal variability of storm surges in the Mediterranean, we defined the monthly occurrence frequencies at selected stations (Figure 8); these stations cover the western (Barcelona, Alger and Marseille; Figure 8a), central (Venice, Catania and Gabes; Figure 8b) and eastern (Antalia, Habera and Alexandria; Figure 8d) Mediterranean, with the addition of three locations (Alexandroupolis, Chios and Iraklio; Figure 8c) from the topographically diverse Aegean Sea. As expected, the majority of extreme events occur during winter and spring seasons for all stations. The western region is characterised by high occurrence frequencies of SLH$_{max}$ during winter months. Especially for the Spanish and French coasts, the highest values (10~27%) are observed from December to March (Figure 8a). This tendency is slightly stronger in the *Future Period* for Barcelona, Nice, and Marseille (not shown here), with an increase of winter and autumn frequencies and a corresponding reduction of spring values. North African stations (i.e. Gabes) present higher storm occurrence during spring. A striking feature is the monthly variability in Gabes (Figure 8b), with the storm maxima concentrated in the period between February and May; the peak occurrence frequency in the station (29%) appears in May and is by far the highest spring value observed. These observations are in agreement with the findings of Trigo et al. (1999) climatology study of atmospheric cyclones in the Mediterranean region. They have found a pronounced increase of cyclone routes over northern Africa in spring, with major eastward and north-eastward paths. In the eastern Mediterranean, storm events are expected to be most frequent from December to April (Figure 8d), while relatively notable summer frequencies may also occur, mainly in the Levantine Sea; contrastingly, zero summer frequencies are derived for the majority of the stations, especially along the European coasts. High occurrence of annual SLH maxima is predicted over the Adriatic coastal zone during winter and early spring, while relatively high autumn frequencies are also present, especially in the northern part (e.g. Trieste). The stations of the Ionian Sea show similar temporal variability of extreme surges, with most events occurring during winter and early spring (e.g. Catania; Figure 8b). Differences are also observed between the North and South Aegean Sea (Figure 8c). At the southern station of Iraklio, wintry annual SLH maxima are common (>25%) and, at the same time, the spring extreme surges are few, compared to the northern stations of Chios and Alexandroupolis. Nevertheless, the majority of incidents occur during November and the following winter season.

4.4 General trends of extreme sea level heights

The study period is divided in three 50-year time spans, in order to investigate the general trends of the maximum and average SLH, from both MeCSM and GreCSM simulations under the A1B climate scenario. Generally, the average SLH over the entire Mediterranean Sea slightly decrease along the three 50-year periods (Figure 9; right graphs of left panel), following the mildly increasing trend of minimum SLPs (not shown here), probably related to the poleward shift of storm tracks and the reduction of cyclonic activity in an increasing CO_2 climate (Lionello et al., 2002). However, distinctive deviations from this general trend occur at several regions. In the open Balearic Sea we can observe an increasing trend of extreme SLH values along all 50-year periods, varying inversely with the corresponding SLP trends; the stronger low pressure systems in 2001-2050 cause a respective increase of maximum SLH values. Contrastingly, in the N. Adriatic Sea, the increasing trend of SLH maxima does not follow the respective variation of the annual SLP minima. Although minimum pressure values are low in the first (50-year) *Future Period* and increase during the following years, the maximum SLHs increase continuously, as also described in Section 4.2. The wind effect actually determines the general trend of this topographically unique area. It is noted that in the central and southern Adriatic region, SLH maxima seem to follow the long-term variation of pressure, with rise during the first 50 years and drop during the last 50 years of the 21st century. In the Ionian Sea (Lefkada), the influence of winds is weaker and the SLP appears as the main factor controlling peak SLHs. Based on GreCSM simulations, the Aegean Sea shows lower SLH maxima during the *Past Period* and a pronounced increase in the entire region during 2001-2050; this increase, moderates in the second 50-year *Future Period* (Figure 9; upper graphs of right panel). Similarly, over the northeastern Levantine coastal zone, SLH maxima increase in the area. On the other hand, the mean SLH trends follow a decrease in both areas, supporting the long-term prediction of a general attenuation of storminess over the eastern Mediterranean basin.

The distribution of the 95th percentile for the entire study period (1951-2100) over the Mediterranean confirms the high simulated SLH levels over the N. Adriatic Sea, where 5% of the values may noticeably exceed the level of 17 cm (Figure 10). On the contrary, the central southern region reveal the lowest high-order percentiles (<8 cm) of SLH, with an exception over the gulf of Gabes (>10 cm). The central N. Aegean and the northeastern Levantine appear to give high-order percentiles of SLH over 15 cm. A rather obvious borderline that coincides with the 10 cm contour line travels along the Balearic Islands, Sicily, Crete and crosses transversely the Egyptian coastline. This can be seen as an implicit boundary, which divides the region into two separate areas with low (south) and high (north) 95th percentile levels for SLH.

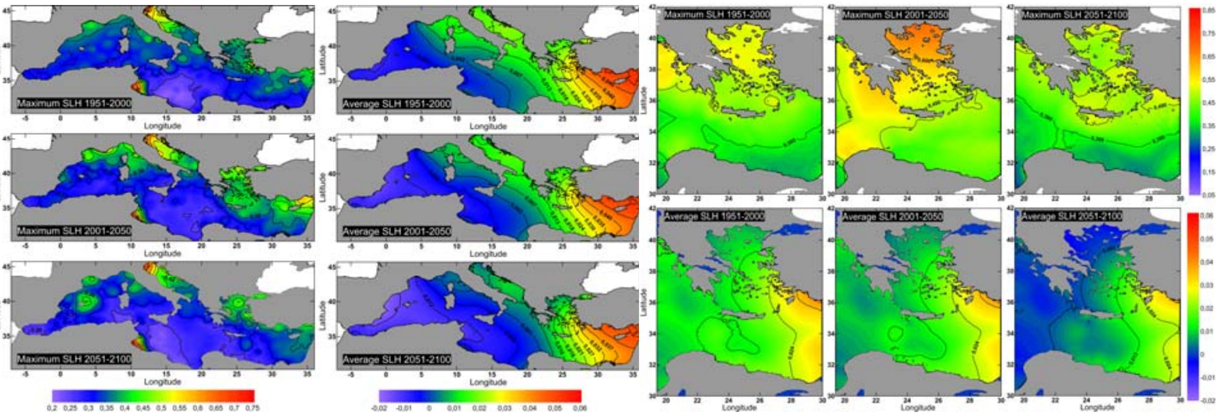

Figure 9. *Left panel*: Horizontal distribution of maximum (left graphs) and average (right graphs) SLH (m) for the periods of 1951-2000, 2001-2050, and 2051-2100 (descending series of graphs), as derived from the MeCSM simulation. *Right panel*: Horizontal distribution of maximum (upper graphs) and average (lower graphs) SLH (m) for the periods of 1951-2000, 2001-2050, and 2051-2100 (left to right series of graphs), as derived from the GreCSM simulation.

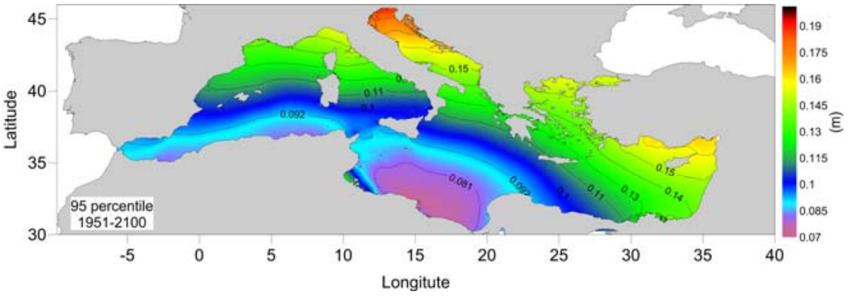

Figure 10. Horizontal distribution of the 95th percentile of SLH (m) over the Mediterranean Sea by MeCSM simulations during 1951-2100.

4.5 Significant storm surge extremes along the coastline

The statistically significant maximum SLH that may occur for the period of 1951 to 2100 under the specific climate conditions can be described by *SSI* (Section 3.2). The average *SSI* values along all coastal grid cells are calculated for the entire study period (1951-2100) and presented in Figure 11, showing the distribution of the potential annual maximum SLH with a 150-year return period along the Mediterranean (left graph) and the Greek seas (right graph) coastline. Significantly high *SSIs* are detected along the N. Adriatic coastline, especially over the Venice Lagoon (~38 cm). This observation is in agreement with the simulated and observed *SSI* (~30 cm) values during past periods (Figure 3a; Trieste). The *SSI* levels along the southern Adriatic and Ionian coastal zones may fluctuate around 20 cm. Extreme *SSI* values (>35 cm) could also occur at the Gulf of Gabes; the maximum values over this area might occur during summer storms, as described in Section 4.3 (see also Figure 8b). In the rest of the N. African coasts *SSI* values are less than 20 cm, and may range around 15 cm along the Libyan coast. The potential annual SLH maxima are also significantly high along the N. Aegean and Minor Asia coasts, with values that may exceed the level of 25 cm and might reach up to 45 cm based on the GreCSM simulations (Figure 11; right graph). Similarly, the entire Cyprus coastline is predicted to have high *SSI* values that exceed the mean Mediterranean level (SSI_{mean}=22 cm) for the 150-year period of MeCSM simulation. Generally, it is noted that for most of the central and eastern European coasts, the *SSIs* range above the mean level; only the areas of South Italy and the southern Ionian Sea present lower values. Nonetheless, GreCSM forecasts show that *SSI* might approach the value of 35 cm on the Ionian coastal zone. The French and western Italian coasts display possible values around 25 cm, while the *SSIs* range at lower levels for the Balearic Islands, western Corsica and western Sardinia. In the areas of Malta and southern Crete even smaller risks of extreme SLH appear due to meteorological conditions, while the potential hazard from storm surges is high in the islands of the eastern and northern Aegean for a 150-year return period.

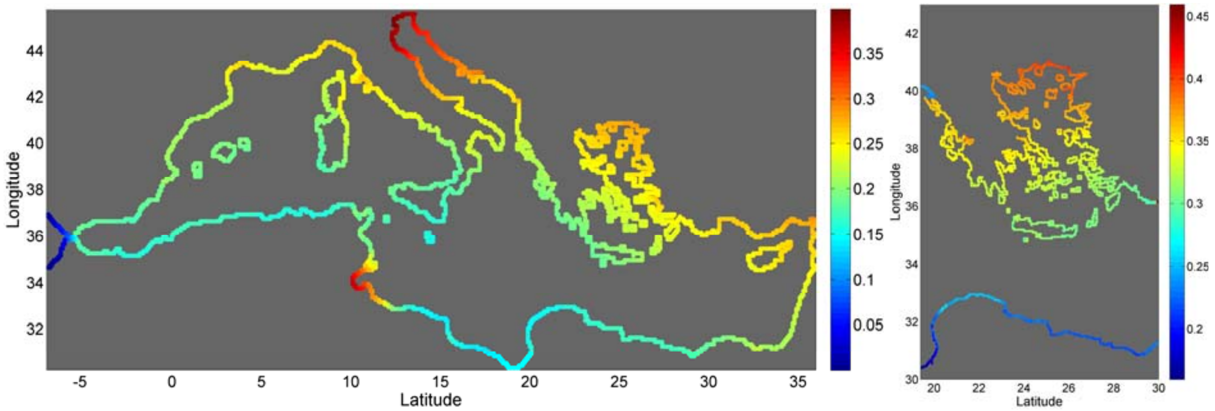

Figure 11. Storm Surge Index (*SSI*, in m) along the entire Mediterranean (left graph) and the Greek seas' (right graph) coastline as derived from the 150-year MeCSM and GreCSM simulation, respectively. (Atlantic Sea cells are not simulated, thus the zero values)

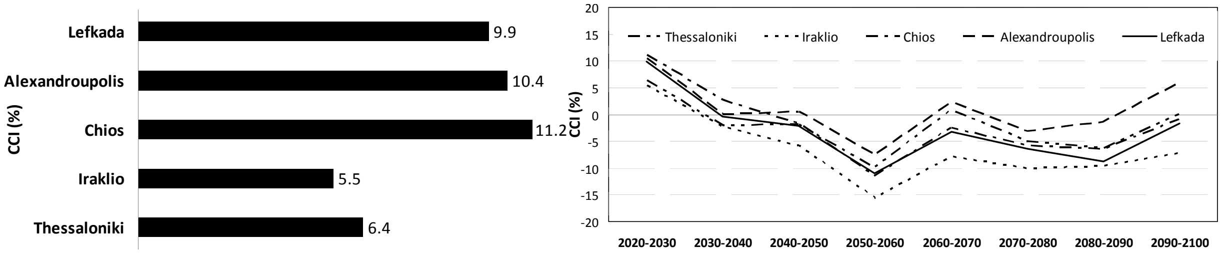

Figure 12. Climate Change Index *CCI* (%) based on averaged *SSI* (m) for two characteristic 11-year periods in the past (2002-2012) and the future (2020-2030) from GreCSM simulations [left graph], together with the evolution of *CCI* in consequent 11-year periods until the end of the 21st century [right graph], at the Greek stations of Iraklio (South Aegean), Chios (Central Aegean), Lefkada (Ionian Sea), Thessaloniki and Alexandroupolis (North Aegean).

4.6 Climate Change Index

The short-term effects of Climate Change on the storm surge extremes were also calculated based on GreCSM simulations, by comparing the averaged *SSIs* of two 11-year periods, i.e. one in the past (validated against observations) and the other in the future. The Climate Change Index *CCI* (%) was defined as a percent difference of these two modeled *SSIs*, i.e. for 2002-2012 (validated) and e.g. 2020-2030 (near future) in all stations, based on Conte and Lionello (2013):

$$CCI(\%) = 100 \cdot \left(\overline{SSI_{mod}^{(2002-2012)}} - \overline{SSI_{mod}^{(2020-2030)}} \right) \Big/ \overline{SSI_{mod}^{(2002-2012)}} \qquad [3]$$

In Figure 12 the *CCIs* are given calculated by Eq. [3] (left graph), together with the evolution of *CCI* in consequent 11-year periods until the end of the 21st century at five Greek stations (right graph). It is predicted that the storm surge extremes, expressed by the *SSI*, might be increased (everywhere positive *CCI*) by 5.5~11.2% for the upcoming 11-year period of 2020-2030, at five characteristic stations of the Greek coastal zone. The largest rise of *SSIs* until 2030 is anticipated for the central Aegean and the Ionian Sea, while the biggest actual magnitude of *SSIs* is forecasted to appear in N. Aegean (e.g. 33 and 30.5 cm in Alexandroupolis and Thessaloniki) followed by the central Aegean region (e.g. 0.29 cm in Chios island). It is also depicted that the evolution of 11-yearly *CCIs* follow the same pattern for all Greek stations, namely a decrease until 2060 (negative values everywhere) and an increase towards the end of the 21st century. This is in agreement with the analysis of general trends for SLH maxima in Sections 4.2 and 4.4 (Figures 7 and 9; right panels). The evolution of alterations in storm surge extremes, induced by future Climate Change, is predicted to be more pronounced for the N. Aegean region (Alexandroupolis and Thessaloniki), giving the highest *CCIs* from 2020 to 2100 (Figure 12; right graph).

5. CONCLUSIONS

Numerical hydrodynamic simulations were used to investigate the evolution and characteristics of storm surge events in the Mediterranean Sea due to future atmospheric conditions under Climate Change. The study was based on the A1B climate scenario and covered the entire Mediterranean basin and specifically the Greek seas, for a period of 150 years (1951-2100). *In situ* observations confirmed the good performance of the storm surge climate simulations for several regions of the Mediterranean Sea. Specifically for the Greek seas, the nested finer spatial resolution model (GreCSM) performed better than the coarser one (MeCSM), which results were used as initial and boundary conditions' input for. This was the case for several regions in Greek seas, where storm surges are mostly induced by atmospheric pressure than driven by wind forces.

We found that the surge extremes over the entire Mediterranean region may decrease following the increasing trend of the minimum sea level pressures. Areas with medium storm surge magnitudes (e.g. the Ionian Sea) may also reveal high exceedance probabilities of statistically critical SLH values. These areas can be characterized as risky areas as far as coastal inundation (flooding and/or erosion) is concerned, even if the danger to coastal structures might reduce in the future, e.g. due to the predominance of low surge extremes during the 21st century. High frequencies of strong local peaks in sea surface elevation may appear over both the N. Adriatic and the N. Aegean Sea, while lower frequencies are predicted for the western Mediterranean. The potential annual extremes may range between 20-40 cm in the Adriatic, and around 35 cm over the central African Coast. The Storm Surge Index (*SSI*), which is a statistical measure of extremes for sea level height, may exceed the value of 25 cm at the N. Aegean, Cyprus and Minor Asia coasts, based on a temporal average for 1951-2100. In the eastern and central Mediterranean regions, *SSI*s generally lie over the entire region's mean level anomaly (~22 cm), caused by alterations in climatic conditions. The Balearic, Levantine, S. Adriatic and Aegean seas might show high extremes during the first half of the 21st century, following a decrease during the second half under the A1B climatic scenario. Our results showed that a generalized increase of the pressure-driven storm surge maxima can be expected until 2050. Other wind influenced areas, such as the N. Adriatic coasts, may not follow the aforementioned variability and is possible to reveal increasing trends of sea level anomalies during the entire 21st century.

In agreement with Tsimplis and Shaw (2010) and Marcos and Tsimplis (2007), we confirmed that the majority of extreme events may appear primarily in winter and secondarily in spring. However, we showed that there is an increase of summer extremes, especially over southern areas due to the increase of cyclogenesis (Trigo et al., 1999). Similarly, the autumn extremes may be more common under the A1B future scenario over the N. Adriatic region, probably due to the higher occurrence frequencies of southerly winds during autumn. A clear attenuation of the occurrence frequency for spring extreme events is predicted based on simulations over the central Aegean Sea. The levels are predicted to be lower over southern areas, Ionian and Alboran Seas. Although duration and coverage of the storms is decreasing, unique stronger extreme events, with higher sea level heights, may occur in the future in all regions. The storminess attenuation is more related to a decrease in coverage and frequency of storm surges and not to the actual magnitude of extreme events. The statistically significant extreme storm surge events are large in magnitude fro the N. Adriatic, the N. Aegean and the Gulf o Gabes. A heuristic index on Climate Change, compared to near past sea level extremes validated against observations, reveals that the short-term future risk of coastal inundation is higher on the decade of 2020-2030 for the Greek Seas. A following decrease is predicted during the 2060s and an obvious comeback of larger sea level anomalies towards the end of the 21st century.

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