COASTAL INUNDATION DUE TO STORM SURGES ON A MEDITERRANEAN DELTAIC AREA UNDER THE EFFECTS OF CLIMATE CHANGE

Christos Makris[1], Vasilis Baltikas[1], Yannis Androulidakis[1], **Yannis N. Krestenitis**[1]
[1] *Lab of Maritime Engineering, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece*
(E-mail: cmakris@civil.auth.gr, vmpaltik@civil.auth.gr, iandroul@civil.auth.gr, ynkrest@civil.auth.gr)

ABSTRACT

This paper investigates the estimated climate change impacts on the future variations of coastal water inundation dynamics at a characteristic Mediterranean deltaic environment for the 21st century. Output by three Regional Climate Models (RCM) are used with Representative Concentration Pathways (RCP) 4.5 and 8.5, for a short-term (2021-2050) and a long-term (2071-2100) future period. The latter feed a coupled modelling system for the simulation of storm surges and consequent coastal inundation on the littoral floodplain of Nestos river delta (northern Aegean Sea, Greece). Thorough validation of storm-induced sea level elevation is presented and the differentiations of model outputs driven by various RCM/RCP combinations are investigated. Increased deltaic vulnerability due to coastal inundation is found under the RCP8.5 scenario especially for the 1st half of the 21st century.

Keywords: coastal inundation, storm surge, Nestos river delta, climate change, numerical modelling.

1. INTRODUCTION

The Mediterranean Sea basin is considered to be a hotspot in terms of Climate Change (CC) projections, associated with regional impacts on sea level variations of the coastal zone, *i.e.* affecting the intensity and frequency of occurrence of storm surges. Intense storm surge events threaten low-land coastal areas mainly by increasing the inundation risk of littoral floodplains that may provoke human casualties, land loss, onshore infrastructure and property damages, environmental degradation, etc. Therefore, in the present work, the storm surge patterns in the Mediterranean coastal zone are investigated for a 130-years period (1971-2100) incorporating the newest available climatic data. The impact of CC on an environmentally sesnitive Mediterranean deltaic area is also explored by examining the future variation trends of storm-induced coastal inundation, simulated with a coupled system of surge-flood models.

2. METHODOLOGY

Numerical simulations of coastal hydrodynamics cover three 35-years time-windows, *i.e.* the Reference Period (RP) from 1971 to 2005, the Short-term Future (2021-2055) and the Long-term Future (2066-2100) Periods (SFP and LFP).

2.1. Available Climatic Data

The atmospheric forcing of the storm surge model (wind and sea level pressure fields) is provided by three RCMs, namely the CMCC-CCLM, CNRM-ALADIN, GUF-CCLM-NEMO, of the MED-CORDEX database (https://www.medcordex.eu/). Historical climate data by all the RCMs have been validated against ECMWF's CERA-20C re-analysis dataseries (https://www.ecmwf.int/en/research/projects/cera), and estimations of future CC projections are based on RCP4.5 and RCP8.5 [1].

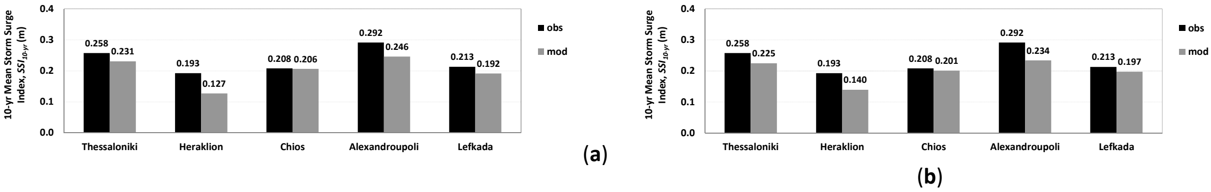
2.2. Numerical Modelling

2.2.1. Storm Surge Model - MeCSS

The surge-induced sea surface height (SSH) in coastal areas is numerically simulated with the Mediterranean Climatic Storm Surge (MeCSS) model [2, 3], which is a 2-DH barotropic model for hydrodynamic ocean circulation, based on the depth-averaged shallow water equations [4, 5]. MeCSS has been proven robust in reproducing the inverse barometer effect and wind setup in coastal areas, causing intense SSH rise due to extreme storm surges, either in forecast [6] or climatic mode [7, 8].

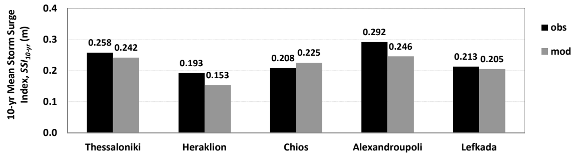
2.2.2. Coastal Inundation Module - CoastFLOOD

The flooded area (FA) due to storm surge in the coastal zone is numerically simulated with CoastFLOOD module [9], which is based on the raster-based, storage cell concept, similarly to the structure and numerical approach of the well-established LISFLOOD-FP model [10]. This way, SSH on the shoreline drives the seawater flow on the coastal floodplain via Manning-type equations in decoupled 2-D formulation. Inundation extents on the floodplain terrain are simulated on a super high-resolution (*dx*=5m) regular Cartesian grid of available data in raster GIS format (https://www.ktimatologio.gr/).



(a)

(b)



(c)

Pearson Correlation	Willmot Skill Score
0.793	0.816
RMSE (m)	RMSE/SSI_{mean}
0.029	13.1%

(d)

Figure 1. Comparison of 10-yr average *SSI* (m) in 5 Greek stations for: a) CMCC-forced, b) CNRM-forced, and c) GUF-forced MeCSS model (mod) and field (obs) data; d) Validation of the GUF-forced MeCSS model implementation by various scores: Pearson correlation, RMSE, RMSE/SSI_{mean} and Willmott Skill.

3. RESULTS AND DISCUSSION

3.1. Model Validation

In situ SSH observations from tide gauges by the HNHS (https://www.hnhs.gr/), during a part of the RP, are used to evaluate the performance skill of MeCSS model in several Greek coastal areas. Figure 1 illustrates comparisons between historical sea-level data and simulation outputs in the Greek coastal zone based on the Storm Surge Index (*SSI*) for all RCM-MeCSS implementations. The Root-Mean-Square-Error (RMSE), Pearson correlation, and Willmott Skill score for intra- and inter-annual *SSH* maxima reveal that the GUF-forced MeCSS setup occasionally produces the most reliable suimulations compared to the CMCC- and CNRM-forced MeCSS model runs. In general, MeCSS output is in acceptable to good agreement with field observations, thus considered credible for CoastFLOOD module forcing.

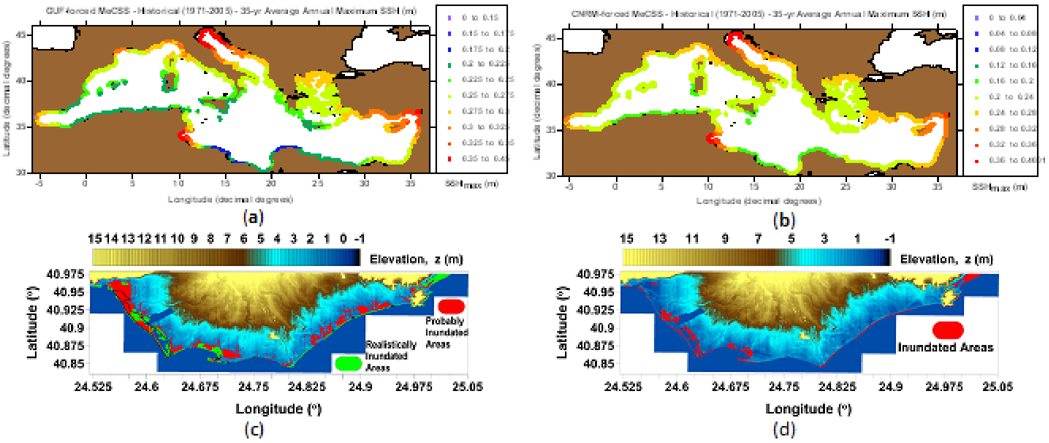


Figure 2. Illustrations of mapped MeCSS output of 35-yr average annual maxima SSH_{max} (m) during the RP for a) GUF-forced and b) CNRM-forced setups. CoastFLOOD results of storm surge inundation in low-land coastal areas of the Nestos river delta for c) a theoretical extreme value of SSH>0.5m and d) simulated MeCSS SSH_{max} in RP; c) red color refers to probably inundated low-land areas; green color refers to actually inundated areas by realistic CoastFLOOD simulations; black closed lines refer to possibly affected regions (lagoons, urban and touristic sites).

Table 2. MeCSS-driven CoastFLOOD (M-CF) model results of: a) Flooded Area, FA (ha); b) respective differences Diff (%) between climatic scenario runs; c) Diff (%) by different forcing input as CMCC-, CNRM-, GUF-forced storm surge implementations.

Study Case		a			b			c		
Scenario	Period	CMCC M-CF FA (ha)	CNRM M-CF FA (ha)	GUF M-CF FA (ha)	CMCC M-CF Diff (%)	CNRM M-CF Diff (%)	GUF M-CF Diff (%)	CMCC-CNRM M-CF Diff (%)	CNRM-GUF M-CF Diff (%)	GUF-CMCC M-CF Diff (%)
Historical	RP	380.897	354.832	452.257	0	0	0	7.09	-24.14	17.13
RCP4.5	SFP	381.420	358.847	447.705	0.14	1.13	-1.01	6.10	-22.03	15.99
	LFP	352.045	356.615	382.425	-7.57	0.50	-15.44	-1.29	-6.98	8.27
RCP8.5	SFP	365.465	377.780	359.442	-4.05	6.47	-20.52	-3.31	4.97	-1.66
	LFP	359.477	365.055	383.352	-5.62	2.88	-15.24	-1.54	-4.89	6.43

3.2. Coastal inundation by storm surges

Figure 2a and 2b present characteristic MeCSS simulation results of inter-annual SSH maxima for the 35-years RP, throughout the entire Mediterranean coastal zone. The largest storm surge levels are observed in the northern Adriatic Sea, the Gulf of Gabes and the northeastern part of the Levantine Sea (SSH_{max}=0.35-0.50m). In the Nestos river delta coastal zone storm surge maxima reach up to 0.33m. During the SFP SSH_{max} was estimated to slightly increase (<14%) compared to the RP (*not shown here*). GUF-forced MeCSS produces slightly higher estimations compared to CNRM- and CMCC-forced setups.
Figure 2c presents detailed maps of low-land areas susceptible to flooding (FA=1,803.76ha), overlayed by realistically inundated areas (FA=541.69ha) due to an extreme storm surge event in the coastal floodplain of the Nestos river delta. Figure 2d shows the flood extents simulated by GUF-forced CoastFLOOD during RP, revealing a FA=452.26ha, i.e. 25.1-83.5% of low-land or probably affected areas.

Table 2 presents CoastFLOOD results of *FA*, and their respective calculated percentage differences (*Diff*, %) between two RCPs for SFP/LFP and RP values; *Diff* due to various forcing input, is also examined in couples between CMCC-, CNRM-, GUF-forced coastal inundation implementations. The latter overestimates the flood extents compared to CMCC- and CNRM-forced setups for almost all study periods. A tendency for attenuation of coastal floods towards the end of the 21st century is estimated, i.e. reachnig down to -20% under any future RCP scenario. However, CNRM-forced CoastFLOOD results, show inundation patterns with a slight increase up to 6.5% under RCP8.5 for the 1st half of the 21st century.

4. CONCLUSIONS

Our results confirm the ability of MeCSS model to estimate the episodic sea surface elevation due to storm surges as a response to intense climatic conditions. We estimate a general decreasing trend in the averaged patterns of storminess under the considered climate scenarios. However, the magnitudes of *SSH* maxima may increase locally in certain regions of the Mediterranean during the 21st century. Nestos deltaic area is estimated to pertain probable hotspots affected by coastal inundation, such as lagoons, rural agricultures around the urban environment and some of the touristic sites on the coast.

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