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Coastal Inundation due to Storm Surges on a Mediterranean deltaic area under the effects of Climate Change

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Description of Research Theme

Storm Surge: Sea Level Elevation due to low SLP + high Winds

- Increase of **coastal inundation** and erosion **risk** on coastal low-land areas
- Intense impacts on: People – Properties – Habitats – Public spaces – Agriculture
- Focus area: **Mediterranean** basin
- Case study: **northern Aegean** → coastal zone of **Nestos river delta**
- Large scale outputs:
  - ➢ Maps of hazard areas of high coastal sea levels
  - ➢ Occurrence probabilities of storm surge levels
  - ➢ Magnitudes of storm surge levels
- Fine scale outputs:
  - ➢ Flooded areas of extreme storm surge
  - ➢ Probabilities of flood events by extreme storm surge
  - ➢ Coastal Flood Risk indexing

Aims & Objectives of Research

Climate Change impacts on Storm Surge Sea Levels

- Investigation through modelling of storm surge in the Mediterranean for 130 years (**1971-2100**)
- Estimation of **future magnitudes** and **occurrence frequencies** of **storm surge maxima** under several available (mediocre to pessimistic) **climatic scenarios** for GHG concentrations
- **Climate Change Impact** signal on the Mediterranean coastal zone

Climate Change impacts on Coastal Inundation levels

- Estimate coastal inundation **probabilities** and **extents**
- Introduce a **coupled system** of **surge-flood model**
- Estimate **Coastal Vulnerability Index** due to storm surge inundation
- Focus on a **Greek coastal zone** with **river delta**

Methodology Climatic Data **RCMs / RCPs / Study Periods**

Atmospheric forcing for MeCSS model:

Wind (velocity and direction) **S**ea **L**evel **P**ressure

3 Regional Climate Models (RCMs)

MED-CORDEX initiative https://www.medcordex.eu/

CMCC-CCLM **CNRM**-ALADIN **GUF**-CCLM-NEMO

2 Representative Concentration Pathways

IPCC 2014

RCP4.5 (mediocre) **RCP8.5** (pessimistic)

3 Study Periods

Control Run Reference Period (**1971-2005**)

Future Runs Short-term Future (**2021-2055**) Long-term Future (**2066-2100**) Periods

Climate data Validation

against **ECMWF** re-analyses **CERA-20C** https://www.ecmwf.int/en/research/projects/cera

check for extreme barometric systems **Deep Depressions** over the Mediterranean region

Methodology Storm Surge Model **MeCSS**

Numerical Model — 2-D Shallow Water Equations

Results: — Sea Surface Height **SSH**

Boundaries: — Closed basin

Simulation Period: — 1971-2100

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} UH + \frac{\partial}{\partial y} VH = 0$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV + g\frac{\partial \zeta}{\partial x} = -\frac{1}{\rho_o}\frac{\partial P_A}{\partial x} + E_h\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) + \frac{1}{\rho_o}C_s\frac{W_x\sqrt{W_x^2 + W_y^2}}{(h+\zeta)} - C_b\frac{U\sqrt{U^2+V^2}}{\rho_o(h+\zeta)}$$

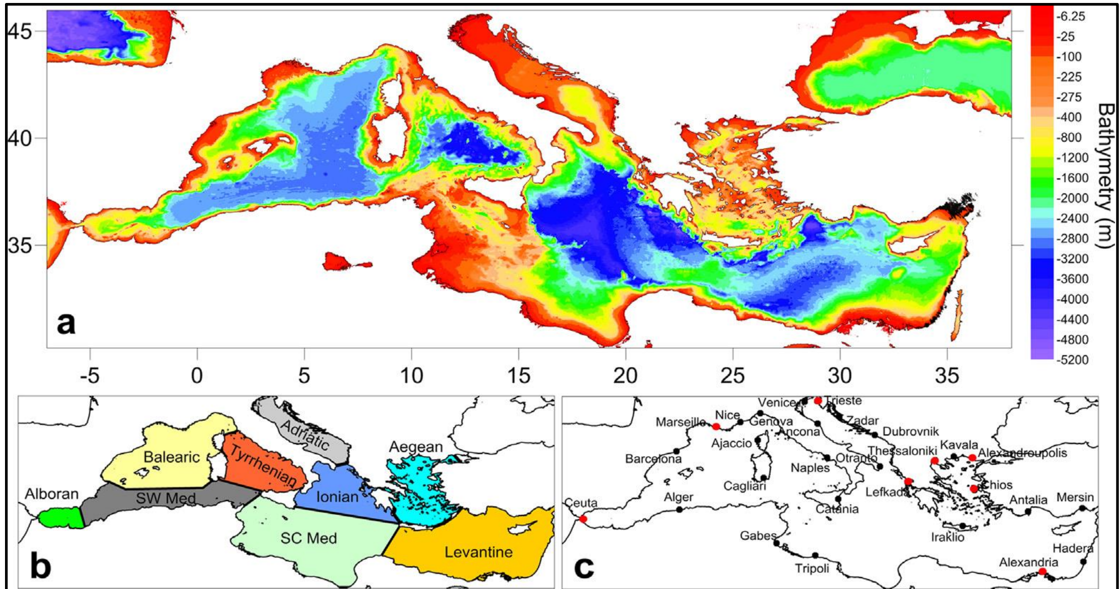
$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU + g\frac{\partial \zeta}{\partial y} = -\frac{1}{\rho_o}\frac{\partial P_A}{\partial y} + E_h\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + \frac{1}{\rho_o}C_s\frac{W_y\sqrt{W_x^2 + W_y^2}}{(h+\zeta)} - C_b\frac{V\sqrt{U^2+V^2}}{\rho_o(h+\zeta)}$$

Available Field Data	SSH	by HNHS + GLOSS tide-gauges	5+4 stations	1995-2005
Signal processing:	De-tiding	Removal of steric effects	High-pass filter	

a) Mediterranean Sea bathymetry - MeCSS model domain

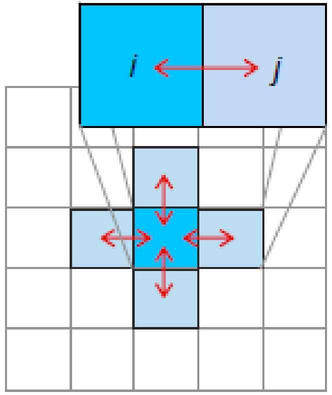
b) Regional Seas

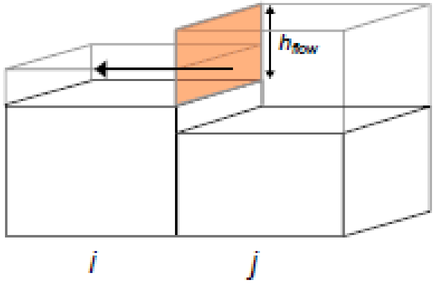
c) 8 tide-gauge stations (**red dots**) + 20 locations (**black dots**)



Methodology Coastal Inundation Module **CoastFLOOD**

Numerical Model	Floodplain Manning-type flow
Mechanics:	SSH difference between neighboring cells
Concept:	Raster-based storage cell LIFLOOD-FP
Boundaries:	SSH on the seafront by MeCSS
Simulation Period:	hours to days
Cases:	35-yr maxima of storm surge events
Scales:	Large inundation areas

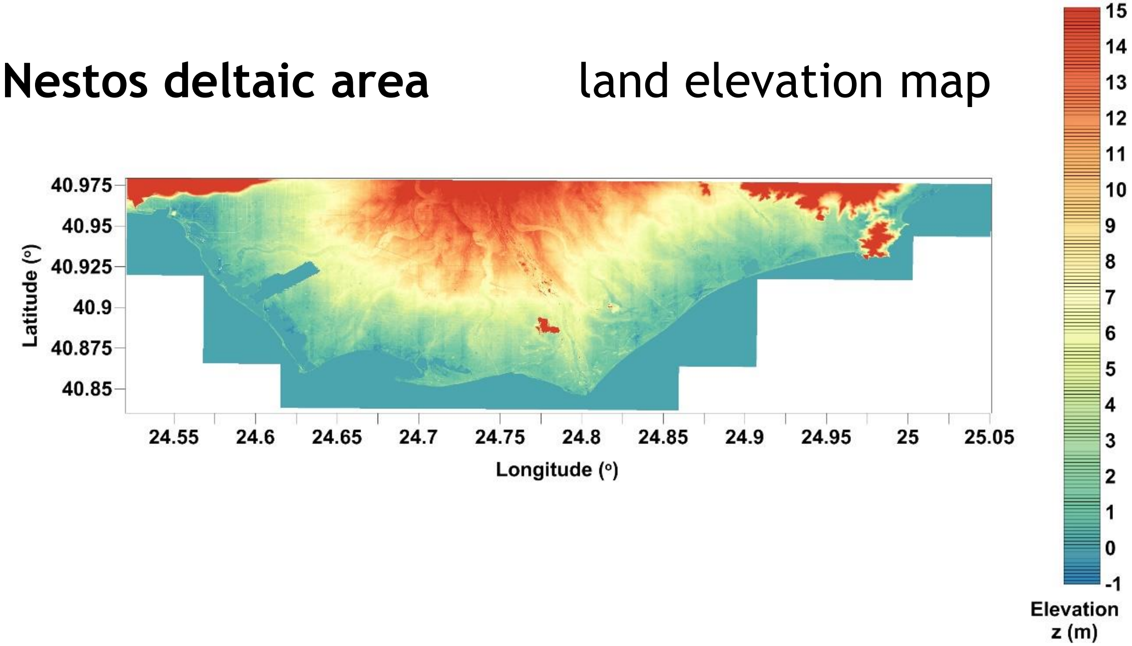




$$\frac{dh_{i,j}}{dt} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{dxdy}$$

$$Q_x^{i,j} = \frac{h_{flow}^{5/3}}{n} \cdot \left(\frac{h_{i-1,j} - h_{i,j}}{dx} \right)^{1/2} dy \qquad Q_y^{i,j} = \frac{h_{flow}^{5/3}}{n} \cdot \left(\frac{h_{i,j-1} - h_{i,j}}{dy} \right)^{1/2} dx$$

Nestos deltaic area land elevation map



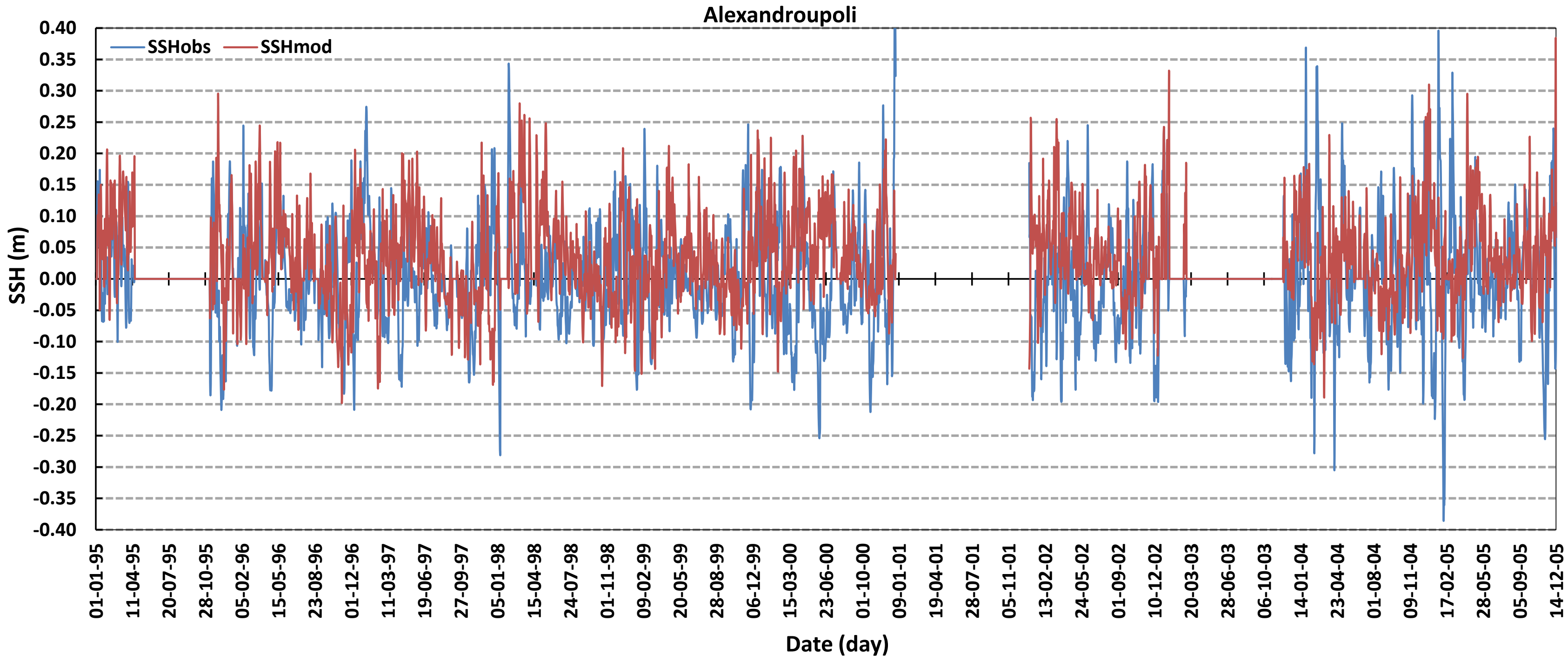
Coastal zone - Nestos deltaic area

CoastFLOOD module: **dx = 5m** **28 million cells !!**

Hellenic Cadastre https://www.ktimatologio.gr/

Model Validation MeCSS results: SSH timeseries

Qualitative validation



Comparison of the

10-yr timeseries

SSH (m) in Alexandroupoli

modelled output (**mod**)

vs.

field data (**obs**)

Quantitative validation

$$E(\%) = 100 \cdot \left(\overline{SSI_{\mathrm{mod}}} - \overline{SSI_{obs}}\right) \Big/ \left(\frac{\overline{SSI_{\mathrm{mod}}} + \overline{SSI_{obs}}}{2}\right)$$

Error Index

$$COR(SSI_i) = \left(\frac{\sum_{i=1,5} \left(SSI_{\mathrm{mod}} - \overline{SSI_{\mathrm{mod}}}\right) \cdot \left(SSI_{obs} - \overline{SSI_{obs}}\right)}{\sum_{i=1,5} \left(SSI_{\mathrm{mod}} - \overline{SSI_{\mathrm{mod}}}\right)^2 \cdot \sum_{i=1,5} \left(SSI_{obs} - \overline{SSI_{obs}}\right)^2} \right)$$

Pearson correlation

$$RMSE = \sqrt{\frac{\sum_{i=1}^{5} \left(SSI_{mod,i} - SSI_{obs,i}\right)^2}{5}}$$

RMS Error

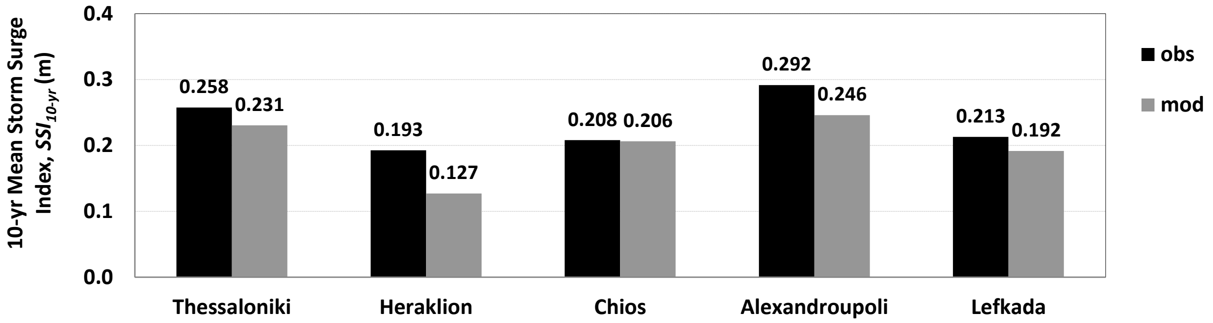
$$WSS_{SSI} = 1 - \frac{\sum_{i=1}^{5} \left|SSI_{\mathrm{mod}} - SSI_{obs}\right|^2}{\sum_{i=1}^{5} \left(\left|SSI_{\mathrm{mod}} - \overline{SSI_{\mathrm{mod}}}\right| + \left|SSI_{obs} - \overline{SSI_{obs}}\right| \right)^2}$$

Wilmmott Skill Score

Model Validation

MeCSS results: Inter-/Intra- Annual Maxima

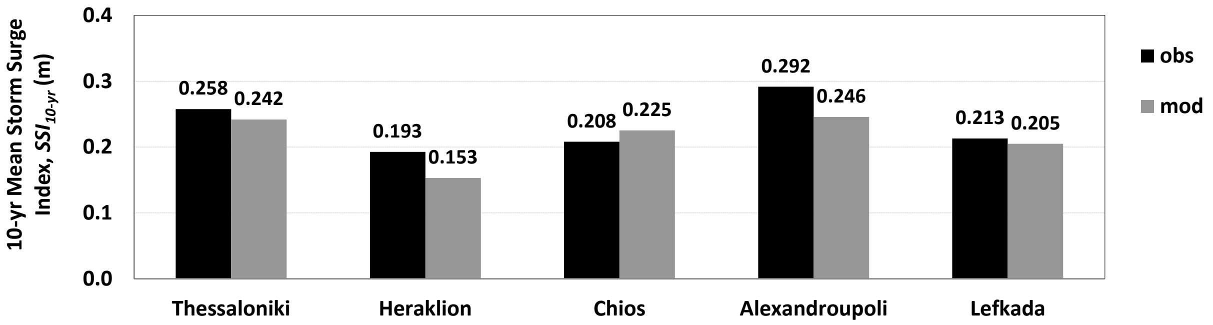
CMCC-forced MeCSS



Coastal Site	$SSI_{obs,10yr}$ (m)	$SSI_{mod,10yr}$ (m)	MEAN E_i (%)	MEAN EI_i
Thessaloniki	0.258	0.231	-10.54%	-0.342
Heraklion	0.193	0.127	-32.11%	-0.857
Chios	0.208	0.206	-0.18%	0.018
Alexandroupoli	0.292	0.246	-16.92%	-0.519
Lefkada	0.213	0.192	-10.30%	-0.322

Pearson Correlation	Willmot Skill Score
0.849	0.735
RMSE	$RMSE/SSI_{mean}$
0.039	18.0%

GUF-forced MeCSS



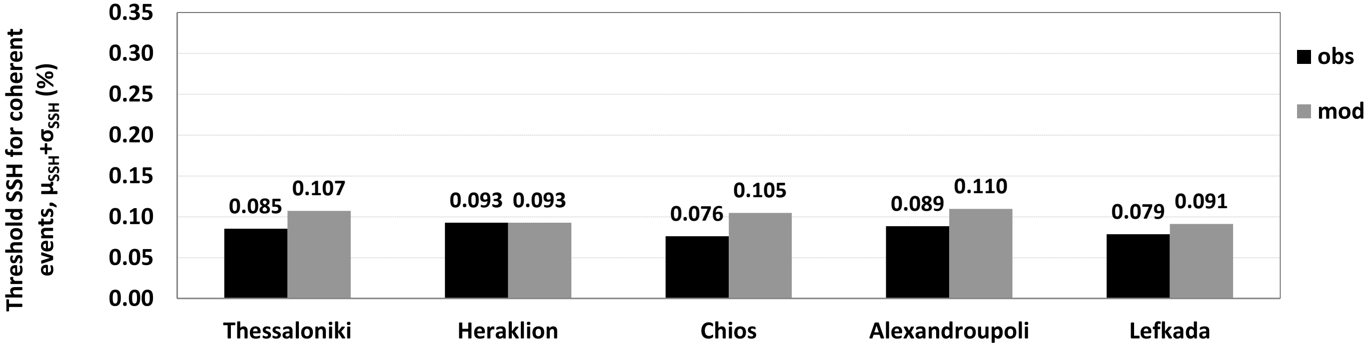
Coastal Site	$SSI_{obs,10yr}$ (m)	$SSI_{mod,10yr}$ (m)	MEAN E_i (%)	MEAN EI_i
Thessaloniki	0.258	0.242	-6.29%	-0.206
Heraklion	0.193	0.153	-16.82%	-0.486
Chios	0.208	0.225	8.28%	0.281
Alexandroupoli	0.292	0.246	-17.20%	-0.561
Lefkada	0.213	0.205	-4.17%	-0.133

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

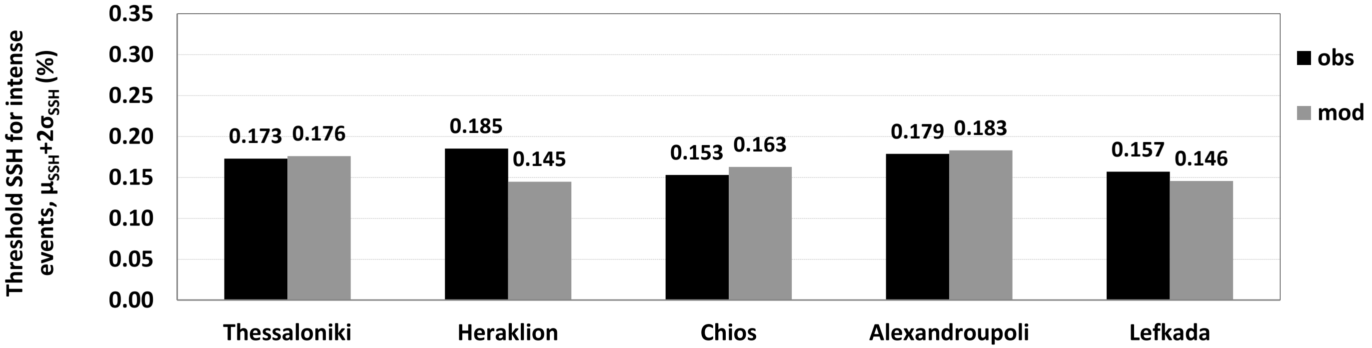
Model Validation Statistical Measures

CMCC-forced MeCSS

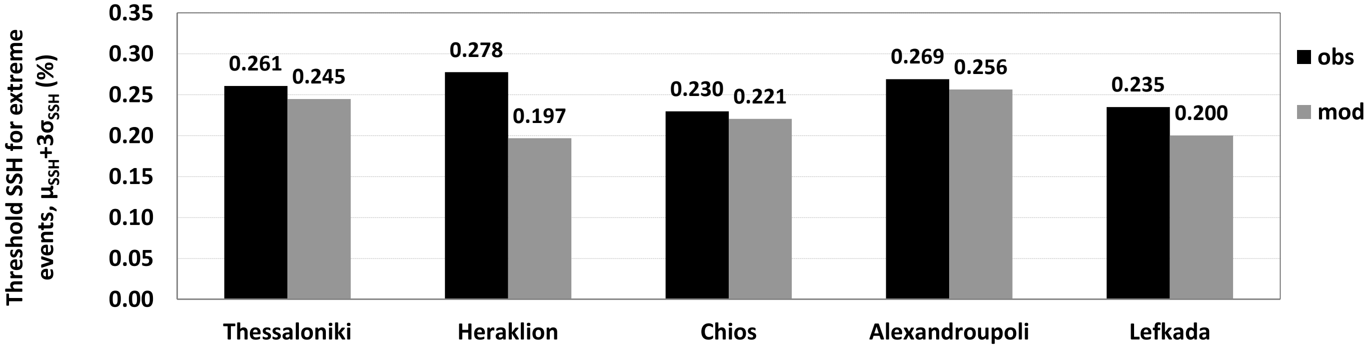
Comparison of 10-yr thresholds of SSH (m) in 5 Greek stations for **mod** and **obs** data



Coherent events



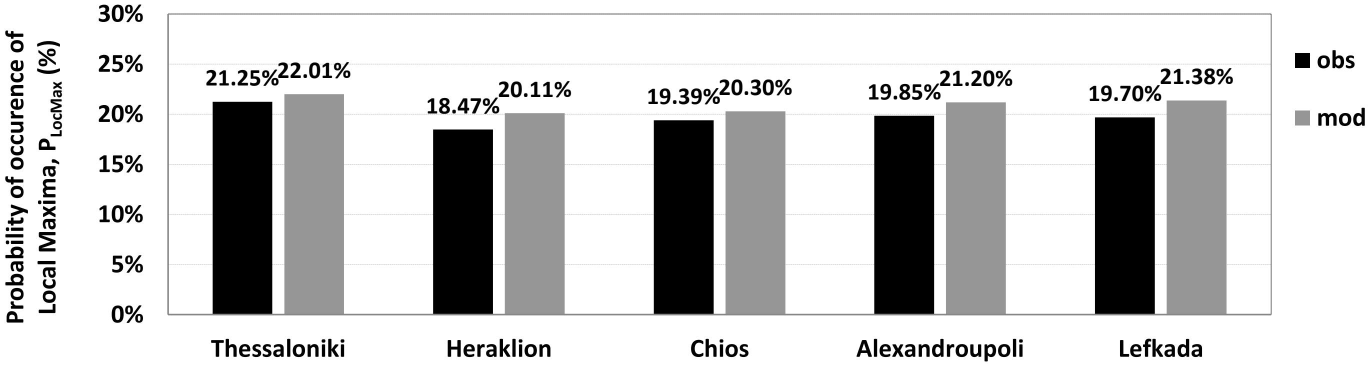
Intense events



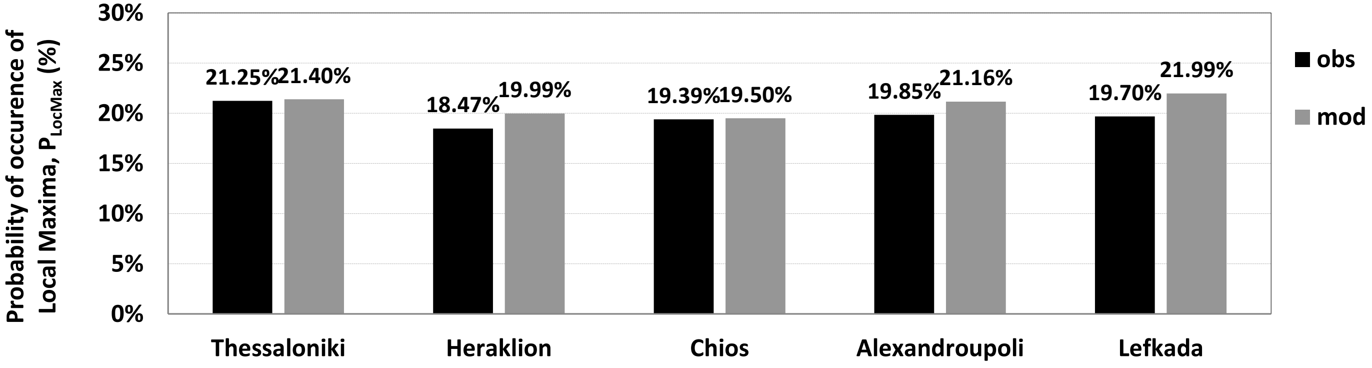
Extreme events

Probabilities of Occurrence

CMCC-forced MeCSS



CNRM-forced MeCSS



Comparison 10-yr probabilities of occurrence

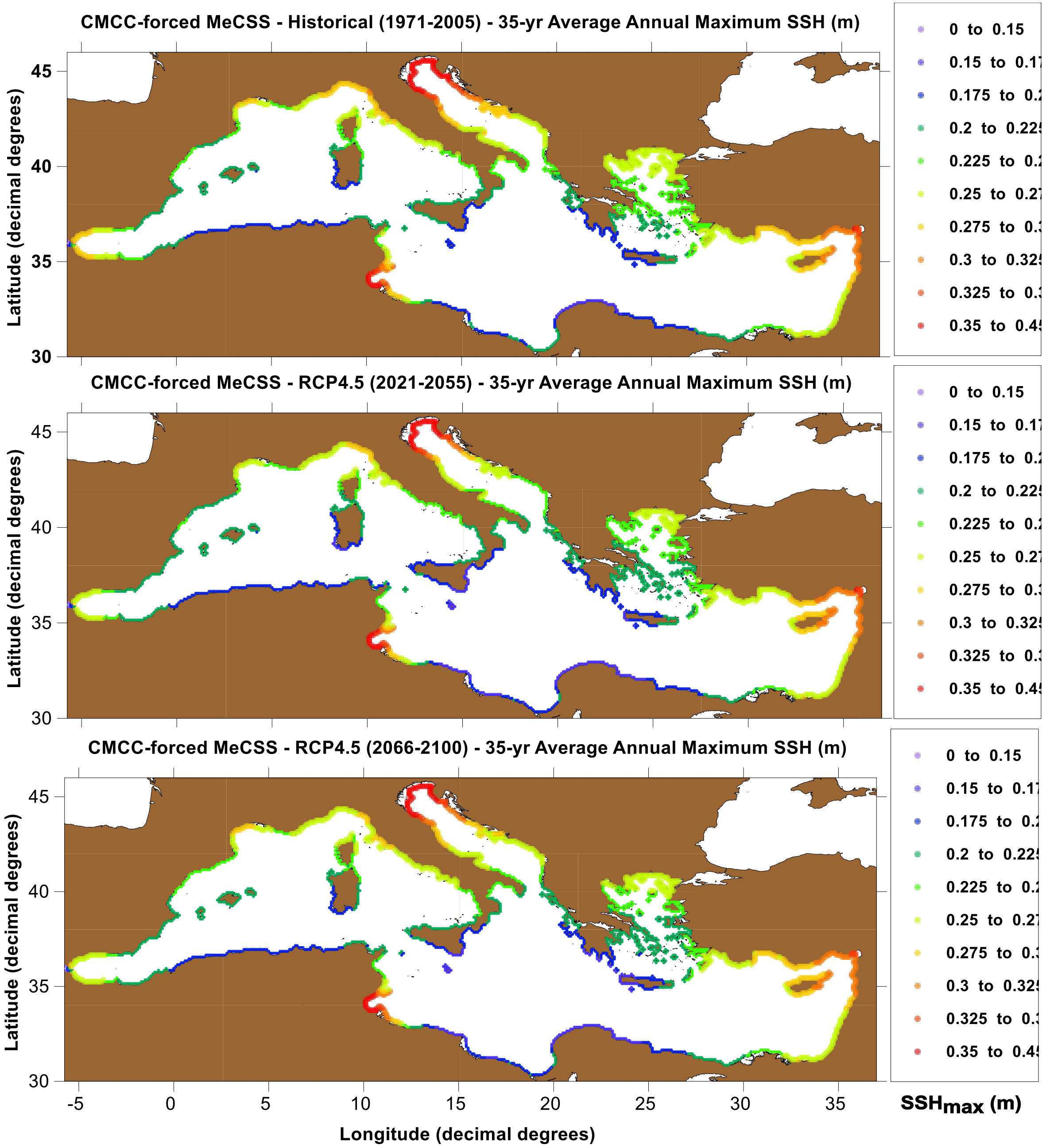
for local maxima in SSH timeseries (%)

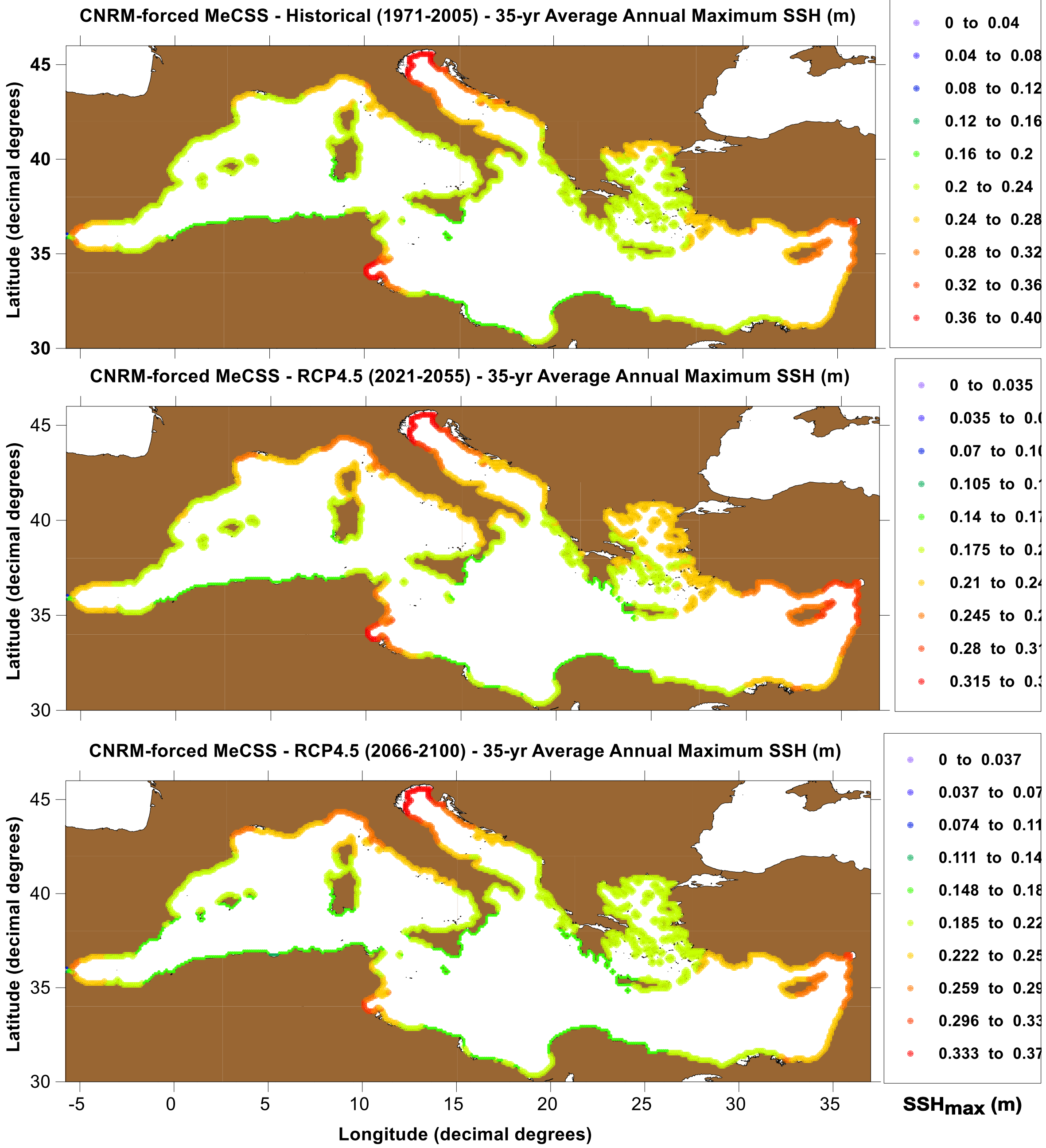
of 5 Greek stations for

modelled (mod) and field (obs) data

Results Storm Surge Levels in the Coastal Zone

RCP4.5





Results   Signals under Climate Change Effects

CMCC-forced MeCSS			AVERAGE of 28 stations	
SCENARIO	PERIOD	YEAR	$DSSH_{max}$ (m)	$DSSH_{max}$ (%)
RCP4.5	Near Future	**2021-2055**	0.008	2.54%
	Far Future	**2066-2100**	-0.012	-3.54%
RCP8.5	Near Future	**2021-2055**	-0.013	-3.41%
	Far Future	**2066-2100**	-0.024	-7.05%

CNRM-forced MeCSS			AVERAGE of 28 stations	
SCENARIO	PERIOD	YEAR	$DSSH_{max}$ (m)	$DSSH_{max}$ (%)
RCP4.5	Near Future	**2021-2055**	-0.042	-11.55%
	Far Future	**2066-2100**	-0.027	-7.63%
RCP8.5	Near Future	**2021-2055**	-0.025	-6.25%
	Far Future	**2066-2100**	-0.017	-4.35%

GUF-forced MeCSS			AVERAGE of 28 stations	
SCENARIO	PERIOD	YEAR	$DSSH_{max}$ (m)	$DSSH_{max}$ (%)
RCP4.5	Near Future	**2021-2055**	-0.013	-2.91%
	Far Future	**2066-2100**	-0.028	-7.42%
RCP8.5	Near Future	**2021-2055**	-0.031	-8.01%
	Far Future	**2066-2100**	-0.037	-9.56%

Differences of **future - past**

Storm surge maxima $DSSH_{max}$ (m) and (%)

in 28 Mediterranean stations

2 future study periods (2021-2055 and 2066-2100)

2 RCPs

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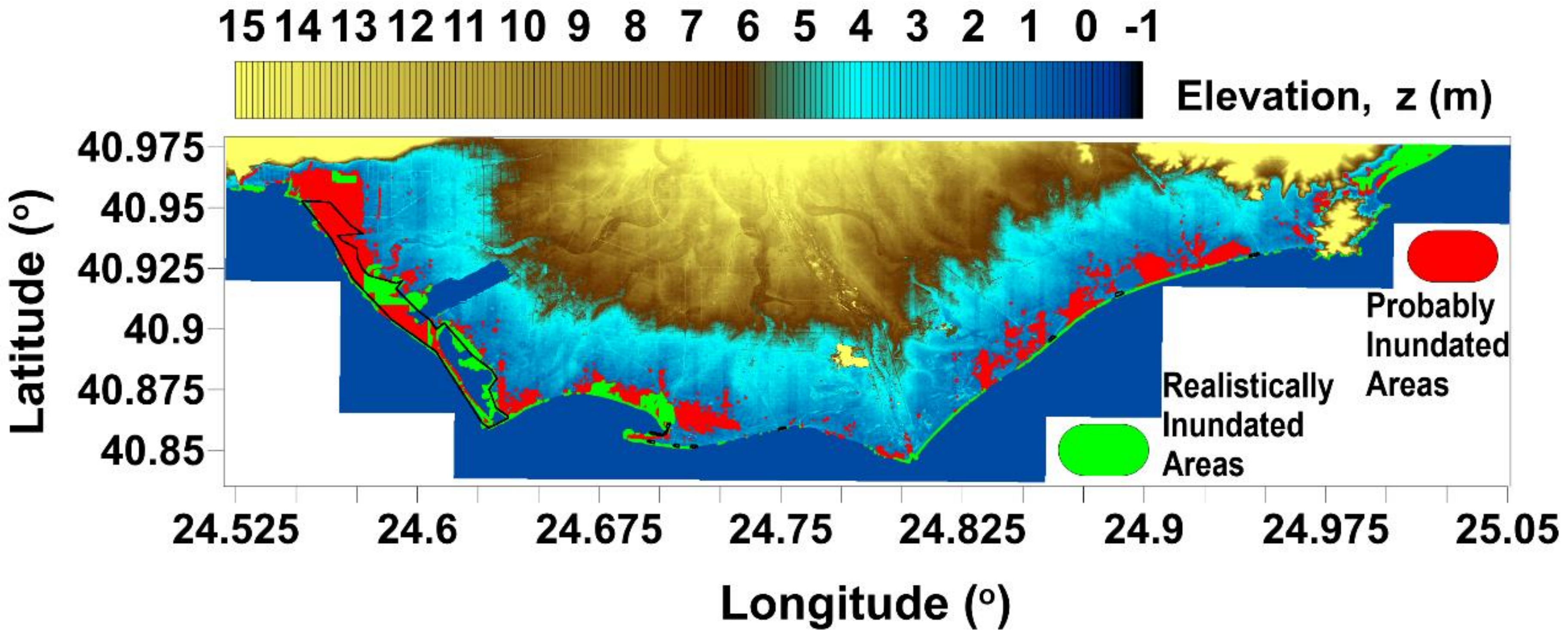


Illustration of the simulated results of storm surge inundation in low-land areas coastal for a theoretical extreme value of SSH > 0.5 m, in Nestos river delta. Red color refers to probably inundated low-land areas; green color refers to actually inundated areas by realistic CoastFLOOD simulations; black closed lines refer to possibly affected areas (lagoons; urban, port and touristic areas).

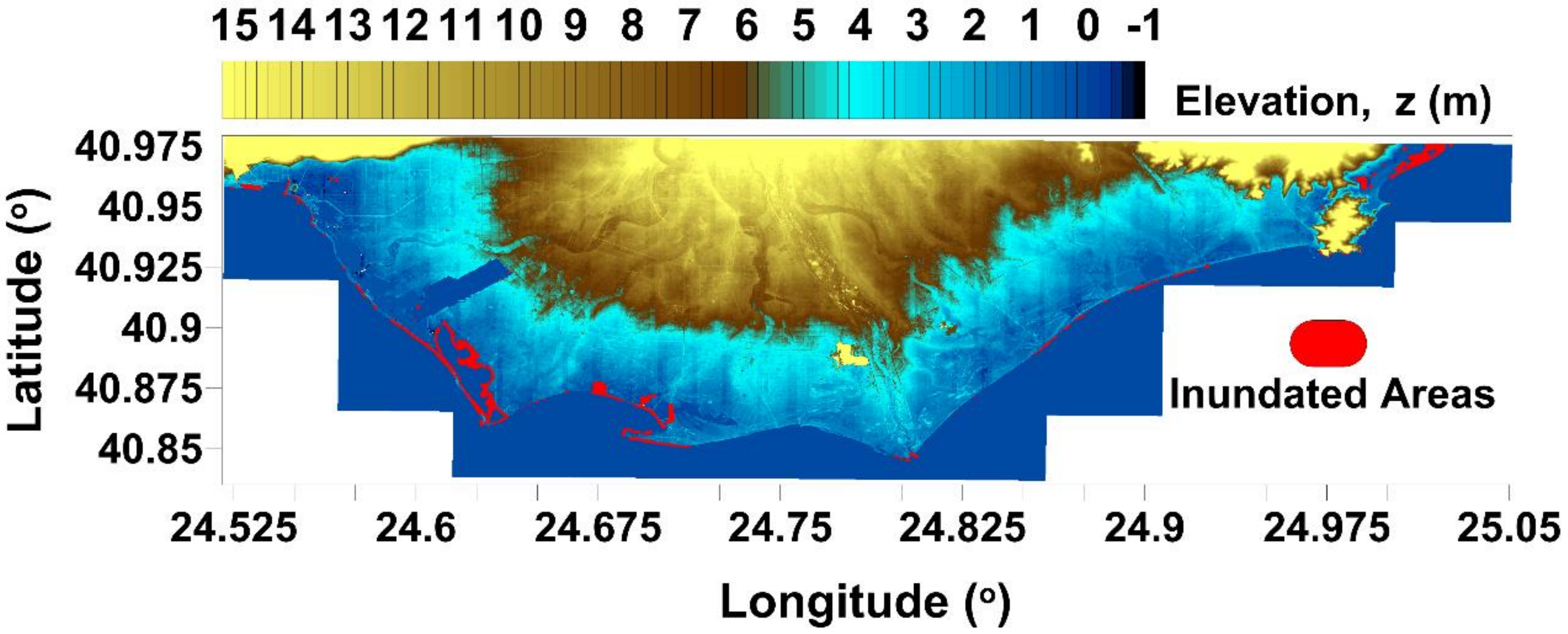
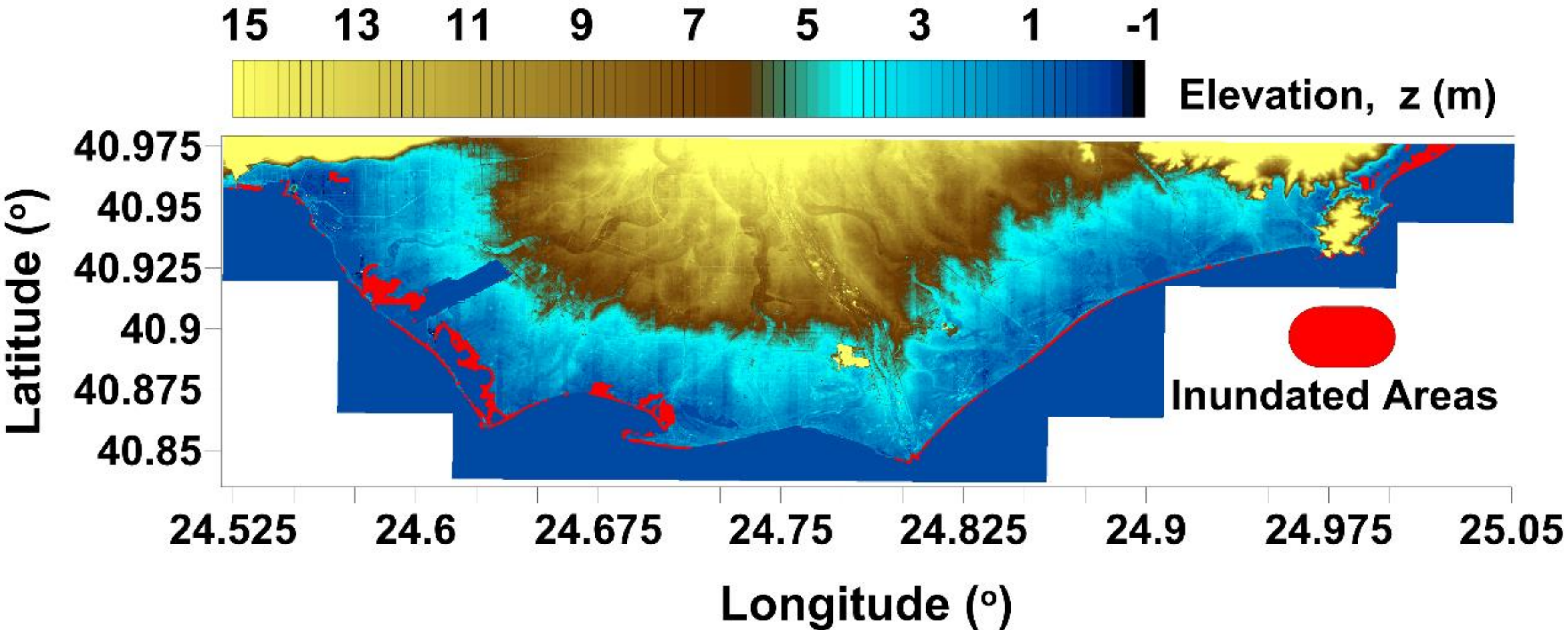
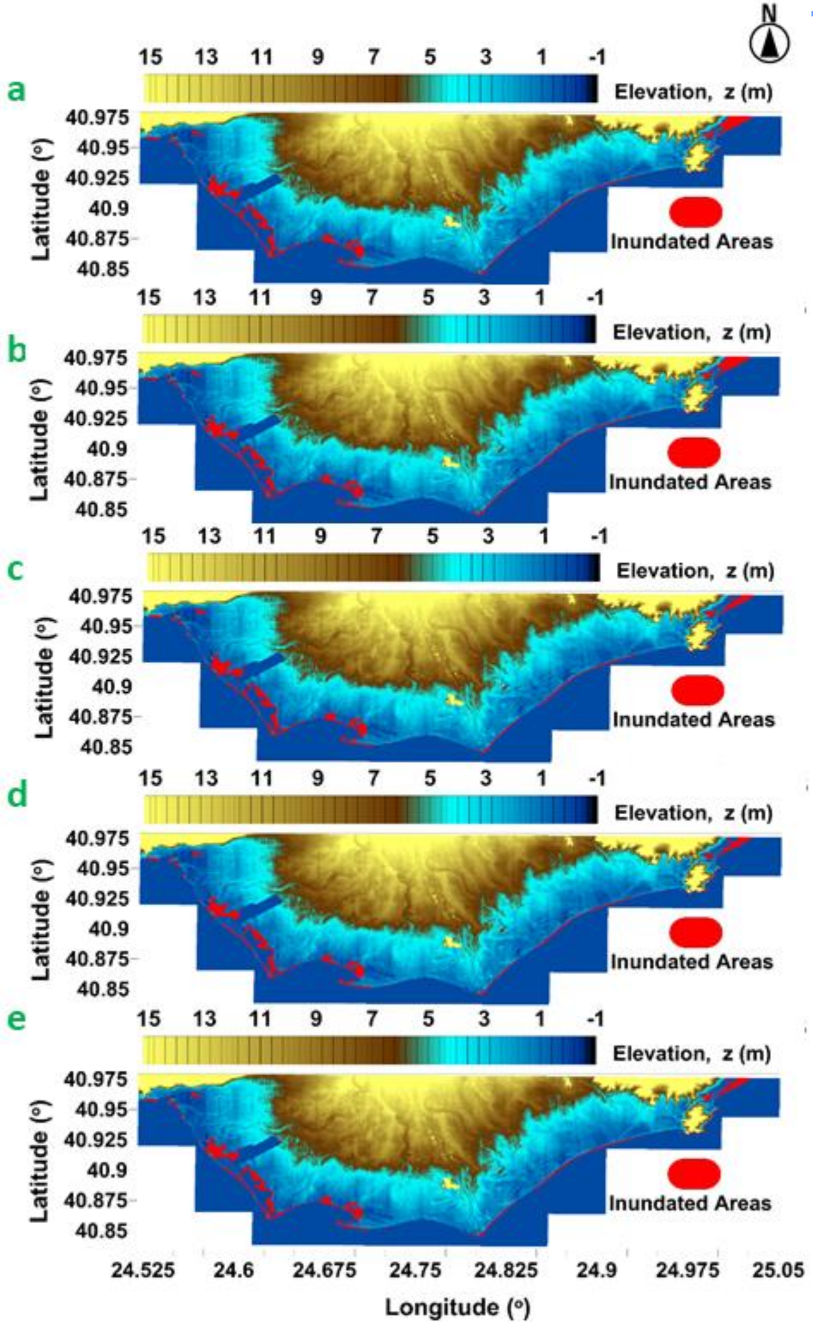


Illustration of the simulated results of storm surge inundation in low-land areas coastal for a mild event with value of SSH > 0.201 m, in Nestos river delta. Probably affected coastal areas of interest are portrayed with red color.



Estimated inundation areas due to 50-year storm surge maxima based on CMCC-forced MeCSS-driven CoastFLOOD simulations in the region of interest at the Nestos river delta; Scenario/Period: Historical (1971-2000).



Estimated inundation areas due to storm surge based on

GUF-forced MeCSS-driven CoastFLOOD simulations

In the region of interest at the Nestos river delta

<u>Scenarios/Periods</u>

a) Historical (1971-2000)

b) RCP4.5 (2021-2050)

c) RCP4.5 (2071-2100)

d) RCP8.5 (2021-2050)

e) RCP8.5 (2071-2100)

MeCSS-driven CoastFLOOD (M-CF) model results

A) Flooded Area FA (ha)

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	STF	381.420	358.847	447.705	0.14	1.13	-1.01	6.10	-22.03	15.99
RCP4.5	LTF	352.045	356.615	382.425	-7.57	0.50	-15.44	-1.29	-6.98	8.27
RCP8.5	STF	365.465	377.780	359.442	-4.05	6.47	-20.52	-3.31	4.97	-1.66
RCP8.5	LTF	359.477	365.055	383.352	-5.62	2.88	-15.24	-1.54	-4.89	6.43

A) Flooded Probability FP (%)

Study Case		A			B			C		
Scenario	Period	CMCC M-CF *FP* (%)	CNRM M-CF *FP* (%)	GUF M-CF *FP* (%)	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	0.15	0.09	0.35	0	0	0	44.90	-115.18	80.72
RCP4.5	STF	0.09	0.01	0.35	-38.66	-91.58	0.86	168.00	-191.21	117.86
RCP4.5	LTF	0.08	0.03	0.25	-42.34	-65.32	-27.67	89.66	-154.29	98.79
RCP8.5	STF	0.10	0.10	0.23	-33.99	8.43	-32.01	-3.96	-79.88	83.19
RCP8.5	LTF	0.04	0.05	0.15	-73.23	-46.90	-57.42	-22.72	-99.49	115.67

B) respective differences Diff (%)

between climatic scenario runs

C) Diff (%) by different forcing input

as CMCC-, CNRM-, GUF-forced MeCSS

Risk = Probability × Consequence

refers to large scale coastal inundation by extreme storm surge events, defined by the seawater flooded area and the corresponding flood probability derived with the coupled MeCSS-CoastFLOOD model

Risk matrix for **CFRI** (Coastal Flood Risk Index)

PERIOD	RP: 1971-2000
RCM \ WCS	REF
CMCC	2
CNRM	1
GUF	5

SCENARIO \ PERIOD		STF: 2021-2050			LTF: 2071-2100		
RCP	RCM \ WCS	REF	CC	EXT	REF	CC	EXT
4.5	CMCC	1	1	1	1	1	1
	CNRM	1	1	1	1	1	1
	GUF	5	5	5	3	3	3
8.5	CMCC	2	2	2	1	1	1
	CNRM	2	2	2	1	1	1
	GUF	3	3	3	2	2	2

CFRI COLOR SCALE		
RANK	VALUE	COLOR
VERY LOW	1	
LOW	2	
MODERATE	3	
HIGH	4	
VERY HIGH	5	

$$R = H \times V$$

R is risk

H is hazard

V is vulnerability

$$V = \frac{E \times S}{C}$$

E is exposure

S is sensitivity

C is adaptive capacity

Discussion of Results

- Projections of coastal sea level changes due to short and mid time-scale processes, such as waves and storm surges, respectively, should be superimposed to projections of long-term MSL. In the present study, only the effects of storm surge on coastal inundation is considered, excluding the short-term wave-induced runup and coastal flooding or the projected long-term land loss and permanent inundation caused by regional SLR in the Mediterranean Sea due to CC.

- CoastFLOOD module in its present form is specifically set up (boundary conditions, simulation times, time stepping, etc.) for mid-term sea level elevations induced by steady-state storm surge events with rather slow evolution of coastal SSH.

- ➢ Storage cell models with fixed time steps tend to be more sensitive to boundary conditions than hydraulic features in the floodplain domain, such as friction.
- ➢ Friction coefficient values usually cannot be determined *a priori*, and are used as a basic calibration factor, yet if the land use and terrain synthesis is known, then specified friction coefficients should be used.
- ➢ In general, the storage cell, raster-based, Manning-type, flood flow models are equally capable in floodplain flow prediction to more advanced diffusive wave models of 2-D SWEs.

Conclusions of Research MeCSS Storm Surge Model

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- Comparison of **model** vs **in situ** 10-year mean **SSI** for MeCSS → high correlation (COR>0.79 reaching up to 0.89)
- Lowest RMSE of SSI and SSH_{max} (<3 cm, 13% of SSI_{mean}) for GUF-MeCSS run → Very high WSS>0.80
- GUF-forced MeCSS model setup generally (yet not locally) most reliable performance of MeCSS for east-central MED
- MeCSS model also scores well in statistical thresholds
- It underestimates small values of SSH and performs better for large SSH for intense and extreme storm surge events
- MeCSS model perform well for the amount and occurrence frequency of surge events

Conclusions of Research   Mediterranean Storm Surges

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- Extreme magnitudes of SSH range between 0.35 - 0.50 m in the Mediterranean
- Higher values along parts of northern coasts and the Gulf of Gabes in its southern part
- The spatial distributions of surge level maxima are estimated to remain similar to past periods
- Largest SSHmax of the Mediterranean occur in the Adriatic Sea for both model and measurements mainly due to the reinforcement of the inverse barometer effect with intense wind forcing mechanisms

- In general, only the **near future period** under **RCP4.5** shows a small increase of 2.5% compared to the reference period for the CMCC-forced MeCSS model run.
- Assumption: RCP scenarios estimate in general a storminess attenuation in the Mediterranean during the 21st century

Conclusions of Research CoastFLOOD module

- The coastal inundation model simulations refer to the study area of the entire Nestos delta coastal zone with several floodplains on the local beaches and around the lagoons.
- CoastFLOOD model is a rather simplistic approach of horizontally decoupled Manning-type flow with terrain friction driven by the seawater elevation on the coastal floodplains. Nevertheless, it is a robust module capable of simulating coastal flooding on a raster-based, storage cell mapping that can represent probable inundation extents induced by storm surges in a reasonable time with the available computational resources.
- There is a rather consistent pattern of model output, i.e. that GUF-forced MeCSS and CoastFLOOD implementations overestimate SSH_{max}, FA and FP compared to the CMCC- and CNRM-forced setups for the Reference Period.
- GUF-forced CoastFLOOD overestimates by 80-200% the flood probability compared to the CMCC- and CNRM-forced setups.
- The most affected areas are the banks of the lagoons, the lower parts of coastal agricultural lands westernmost of the Keramoti town, a small part of the Keramoti port infrastructure, the coastal touristic sites on their shorefront, and the sandy beaches in the eastern part of the study region.

The proposed modelling approach of coastal inundation for deltaic areas focuses on the detailed representation of the inland terrain as a computational domain to achieve good estimative accuracy of arbitrary coastal flood events.

- The sum of the potentially flooded low-land areas, corresponding to values of land elevation $z \leq 0.5$ m, in the study region of Nestos river delta was calculated to be 1,803.758 ha.

- The values of Flooded Areas (FA) refer to probably inundated areas due to 30-years maxima of SSH on the sea-front. Initially, the maximum reference level of possibly inundated coastal areas was determined as FA = 541.69 ha, which is equal to a 30.03% of the determined low-land areas.

- The GUF-forced CoastFLOOD overestimates the flood extents compared to the CMCC- and CNRM-forced setups for almost all study periods.

- The CMCC- and GUF-forced CoastFLOOD results show a tendency towards attenuation of coastal floods, i.e. with rather low values < -8% for the first one and down to higher negative scores of -20% for the latter (under any future RCP scenario).

Acknowledgements

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Integrated Quantitative Assessment of Climate Change Impacts on Mediterranean Coastal Water Resources and Socioeconomic Vulnerability Mapping

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