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Future Projections of Extreme Storm Tides and Related Coastal Flooding along the Greek Coastal Zone under Climate Change Scenarios

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Abstract. The intensifying threat of coastal flooding due to climate change calls for robust modelling and site-specific projections of extreme storm surge events combined with estimations of Sea Level Rise (SLR) and astronomical tides. Greece, with over 15,000 km of coastline and several low-lying littoral zones, is particularly vulnerable to such hazards. This study aims to assess the projected impact of climate change on the magnitude and frequency of extreme storm surges across key coastal areas in Greece, through the integration of a) large-scale modelled coastal sea level dynamics and historical tide-gauge records, and b) high-resolution Digital Terrain Models (DTM) and fine-scale hydraulic flood modelling simulations. A hybrid methodology combining Extreme Value Analysis (EVA) for storm-induced sea levels with physics-based hydrodynamic inundation modelling (CoastFLOOD) was applied across several exposed areas along the Greek coasts. The case studies refer to both natural beaches in low-lying rural coastal environments and engineered waterfronts in urban areas. Coastal sea-level input for flood-hazard scenario simulations was constructed using GEV-based return levels (e.g., 50-, 100-year), including future SLR contributions and local characteristics of astronomical tides, based on Representative Concentration Pathways (RCP) 4.5 and 8.5. Graphical outputs include maps of flood extents, characteristic floodwater depths and

velocities, inundation hazard indices, and climate change signals. Our simulations reveal substantial increases in flood extent and intensity under future scenarios, mainly affected by potentially increasing SLR towards the end of the 21st century (2066-2100) compared to a reference historical period (1971-2005), especially in low-land urbanised zones. For the standard 100-year return level of storm tides, combined with SLR, floodwater inundation is projected to reach critical infrastructure, residential zones, and transport pathways. Furthermore, a preliminary exposure assessment indicates that coastal properties in certain areas may be affected under worst-case scenarios, underscoring the need for updated zoning and adaptive planning. These findings emphasise the need for integrating future storm surge extremes into locally implemented flood risk management, real estate and insurance valuation, socioeconomic impact assessment, and protection schemes in Greek coastal areas. The proposed methodological framework provides a reproducible approach for similar evaluations in other Mediterranean coastal regions facing flood threats.

Keywords: Coastal Inundation, Storm Surge, Sea Level Rise, Extreme Value Analysis, Greece.

1 Introduction

Coastal zones worldwide are increasingly exposed to the combined effects of mean sea-level rise (MSLR), changes in storminess, and anthropogenic pressures. In semi-enclosed basins such as the Mediterranean Sea, storm surges and wave storms, superimposed on rising mean sea level (MSL), can generate a total water level (TWL) that may threaten coastal communities, critical infrastructure, and ecosystems. Greece, with over 15,000 km of coastline and many densely populated, low-lying littoral areas, is particularly vulnerable to episodic coastal flooding driven by extreme storm-tide events.

Recent studies have shown that storm surge maxima in the Mediterranean exhibit substantial regional variability due to complex basin geometry, variable bathymetry, shifts in cyclogenesis centres, the distribution of cyclonic tracks, and the influence of deep depressions [1]. At the same time, long-term changes in storminess under climate change are not spatially uniform; several studies report a general attenuation of surge extremes over large parts of the basin, but with local increases at specific gulfs, bights, and coastal inlets [2]. Such nuanced patterns underscore the need for regional-to-local-scale assessments that translate large-scale climate signals into site-specific coastal flood-hazard projections [3,4].

For the design of engineering flood protection and coastal risk management, extreme total water levels with specified return periods are typically estimated using Extreme Value Analysis (EVA) applied to historical or modelled sea-level records. The Generalised Extreme Value (GEV) distribution and the Peaks-Over-Threshold approach have been widely used in coastal applications to estimate return levels of storm surge and wave heights [5,6]. In a changing climate, however, the uncertainty is prevalent; thus, modelling chains must integrate ensemble climate projections with hydrodynamic and statistical methods to derive future design conditions at the shoreline.

In parallel, numerical modelling of overland flooding has advanced significantly. While several complete shallow-water equation solvers provide full hydrodynamic simulations, reduced-complexity approaches (e.g., LISFLOOD and SFINCS) based on rasterised, mass-balance, Manning-type formulations have become very popular for large-scale applications, owing to their computational efficiency and ability to handle very high spatial-resolution digital elevation models (DEMs) [7,8]. The CoastFLOOD model [9] belongs to this category and has been applied to a range of coastal inundation problems in Greece and the US.

This contribution presents a hybrid framework designed to quantify future changes in extreme storm tides and associated coastal flooding along the Greek coastal zone under selected climate change scenarios. The specific objectives are to: (i) use atmospheric input from MED-CORDEX climate simulations [10,11] as input to feed MeCSS model runs for storm surges/tides [1]; (ii) derive ensemble projections of extreme sea levels at the shoreline based site-specific EVA [12]; (iii) transform these drivers into high-resolution flood hazard maps (extent, height, velocity, intensity) for several representative Greek coastal sites using high-resolution CoastFLOOD model simulations [9]; (iv) synthesise the results in terms of a Coastal Inundation Hazard Index (CIHI) ranking [13]; and (v) discuss implications for climate-resilient coastal management.

2 Methods and Data

The proposed methodology integrates regional climate projections, storm surge modelling, extreme value statistics, and reduced-complexity coastal flooding simulations applied along the entire coastline of Greece, with a focus on 20 characteristic littoral regions across the Aegean, Ionian, and Cretan Seas. It proceeds in four main steps: (1) storm-surge simulations for the Mediterranean Sea using the MeCSS model driven by Regional Climate Model (RCM) outputs; (2) extraction of annual maxima for storm-induced Sea Surface Heights (SSH) and EVA at littoral grid points along the Greek coasts; (3) construction of location-specific total water-level scenarios by adding maximum astronomical tidal ranges and projected MSLR; and (4) CoastFLOOD inundation simulations for

a set of representative Greek coastal sites under present and future extreme forcing.

Storm surges are simulated using the Mediterranean Climate Storm Surge (MeCSS) model, a depth-averaged barotropic hydrodynamic model based on the shallow-water equations. MeCSS solves for water levels and depth-averaged currents on a curvilinear grid covering the entire Mediterranean basin, with open boundaries prescribed at the Strait of Gibraltar and Marmara [1]. Atmospheric forcing consists of 10 m wind components and sea-level pressure fields from three high-resolution Mediterranean Coordinated Regional Downscaling Experiment (MED-CORDEX) RCMs:

- CMCC-CCLM: Euro-Mediterranean Centre on Climate Change (CMCC), Climate Model COSMO-Climate Limited-area Modelling (CCLM)
- CNRM-ALADIN52: National Center for Meteorological Research (CNRM) Aire Limitée Adaptation dynamique Développement InterNational (ALADIN)
- GUF-CCLM-NEMO: Goethe University of Frankfurt (GUF) CCLM – Nucleus for European Modelling of the Ocean (NEMO)

Simulations are conducted for a historical reference period (1971–2005) and two 35-year future periods (STF: 2021–2055; LTF: 2066–2100) under RCP4.5 and RCP8.5 [1, 10, 11]. For each coastal grid cell, the storm-induced SSH time series is extracted and high-pass filtered to remove low-frequency signals not related to meteorological forcing.

EVA is applied to the annual maximum storm-induced SSH series at each littoral grid cell. The GEV distribution is selected because it represents the limiting distribution of block maxima under general conditions [14]. The cumulative distribution function is defined by the location parameter μ, the scale parameter σ, and the shape parameter ξ, which controls the tail behaviour. Parameter estimation is performed using the L-moments method, which has proven robust for relatively short samples (here, 35 years of annual maxima per period) [12]. For each cell, 50- and 100-year return levels of storm-induced SSH are estimated. Confidence intervals are constructed using a parametric bootstrap procedure in which synthetic samples are generated from the fitted GEV, refitted, and return levels re-computed to obtain empirical percentiles.

To combine storm surges with long-term MSLR, the derived storm-induced SSH extremes are superimposed on projected MSL changes for the corresponding RCP scenarios and periods. This yields location-specific TWLs that represent the combined effect of surges, tides, and MSL change. These TWLs are used as offshore boundary conditions for local inundation simulations.

Coastal flooding is simulated using CoastFLOOD [9], a reduced-complexity two-dimensional model that solves the mass conservation equation on a regular raster grid. Water depths in each cell evolve according to the balance between incoming and outgoing discharges to neighbouring cells and local storage. Hydraulic fluxes are computed using a decomposed Manning-type formulation driven by water-level gradients between adjacent cells. The wetting–drying

algorithm activates or deactivates cells based on local water-depth thresholds. The computational domain covers coastal stretches of 1–20 km length and similar cross-shore extent, discretised at 2–5 m resolution, yielding simulation grids of up to about 16×10^6 cells.

The necessary DEMs are derived from the Hellenic Cadastre, which provides detailed topographic data for the coastal floodplains. Land-cover information is taken from CORINE Land Cover (CLC) datasets, which classify Europe into 44 land-use categories. These categories are mapped to Manning roughness coefficients through look-up tables, and the resulting spatially variable friction fields are used to parameterise floodplain resistance to water flow. For each coastal site, scenarios of extreme storm-tide events are translated into time-varying boundary conditions applied along the seaward edge of the domain, and simulations are run for several hours to a few days to capture the potential maximum inundation buildup.

Twenty representative coastal sites distributed across seven Greek regional seas are selected (Fig. 1): the northwestern, northeastern, southwestern, and southeastern Aegean Sea, the Cretan Sea, and the northern and southern Ionian Sea. Sites include both urbanised settings, such as Thessaloniki and the broader Thermaikos Gulf, Alexandroupolis, and Kalamata, and more rural or touristic locations, such as Laganas (Zakynthos), Vassiliki (Lefkada), and Ierapetra (Crete).

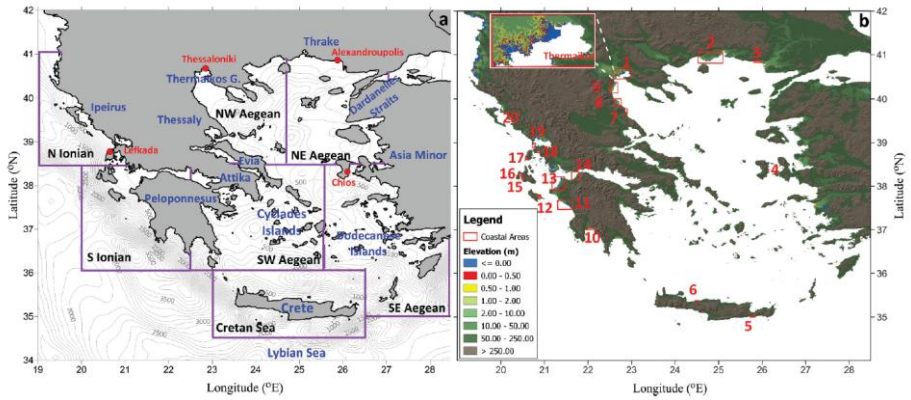

Fig. 1. Bathymetry of the study area with 7 subregions and 20 locations at the NW Aegean, NE Aegean, SW Aegean, SE Aegean, Cretan Sea, N Ionian, and S Ionian Sea: Thermaikos Gulf (1), Nestos (2), Alexandroupolis (3), Chios (4), Ierapetra (Crete; 5), Rethymno (Crete; 6), Pineios (7), Agiokampos (8), Katerini (9), Kalamata (10), Katakolo (11), Laganas (Zakynthos; 12), Manolada (13), Patra (14), Argostoli (Kefalonia; 15), Livadi (Kefalonia; 16), Vassiliki (Lefkada; 17), Palairos (18), Preveza (19), Igoumenitsa (20).

For each site and scenario, the spatial extent of flooding is extracted and normalised to a reference area (the global upper threshold of inundation area),

which serves as input to our coastal hazard analysis. The CIHI is defined as a composite metric combining a ranked driver-intensity term (based on the magnitude of the extreme TWL) with a ranked normalised flood-area term (the ratio of flooded area to a predefined ceiling):

$$CIHI_j = FO_j \times \overline{FCP_{i,ext}}_j \quad (1)$$

where *FCP* is the daily Flood Coverage Percentage (%), *FO* is the Frequency of Occurrence (%) of the days with extreme $FCP_{i,j}$, overbar denotes the temporal mean, and *i*, *j* are indices of the number of days and the study area, respectively. CIHI values are used to categorise sites into low-, moderate-, and high-hazard classes under present and future conditions, and to quantify relative changes attributable to climate forcing.

3 Results

3.1 Extreme Storm Surges on the Coast

The GEV-based EVA of MeCSS storm-surge simulations confirms the substantial spatial variability of extreme storm-induced SSH along the study area's coastline and, in particular, around Greece. For the historical reference period, the highest 50- and 100-year return levels in the wider Mediterranean are found in the northern Aegean. Along the Greek coasts, 50-year storm-surge return levels generally range from 0.25 to 0.55 m, with the highest values occurring at exposed gulfs with long fetches and favourable orientations relative to dominant winds (Fig. 2).

When comparing future periods with the reference baseline, a basin-wide attenuation of storminess is evident under both RCP4.5 and RCP8.5, particularly in the 2nd half of the 21st century (Fig. 3). Percentage differences in 50-year storm surges across the study area typically range from −30% to −2% by 2100. Nonetheless, this overall decrease may mask a substantial positive local deviation in the central and northern Aegean and Ionian Seas; storm-surge extremes may increase by up to 20–30%, depending on the RCM and scenario.

For Greece, the ensemble of MeCSS–RCM simulations reveals a mixed pattern. In several regions, particularly in the southern Aegean and parts of the Ionian Sea, the projected reduction in storminess is expected to slightly lower future surge extremes. In contrast, the northern Aegean, the entrance of Thermaikos Gulf, and some Ionian sites display modest but statistically meaningful increases in extreme storm tides under at least one scenario–RCM combination. When combined with MSLR, even modest changes in surge extremes can translate into appreciable differences in TWLs at the coast.

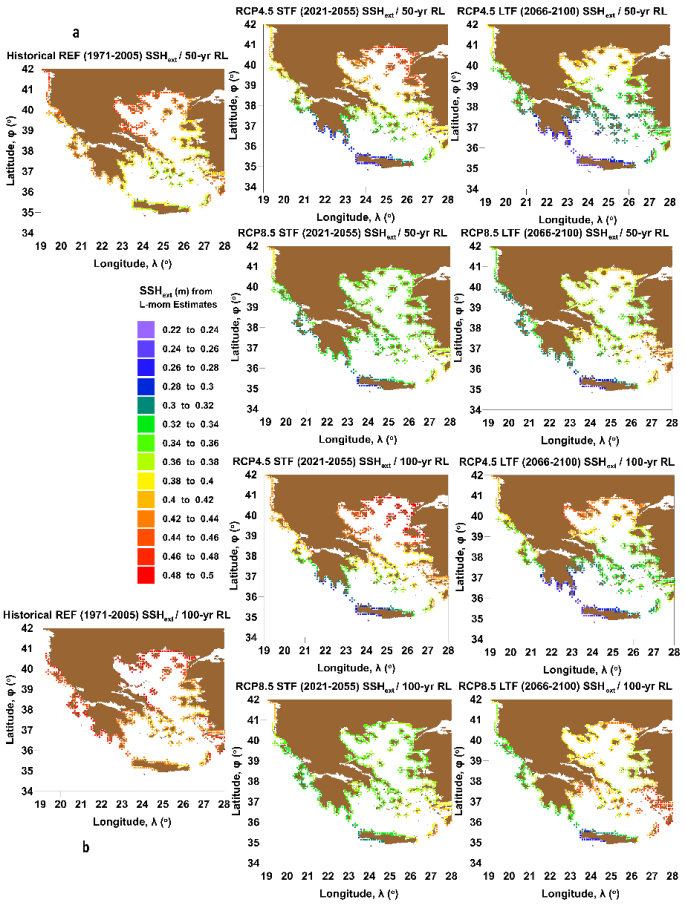

Fig. 2. Maps of 50- & 100-year RV of Extreme SSH by GUF-based MeCSS simulations during Reference, STF, LTF for RCP 4.5-8.5.

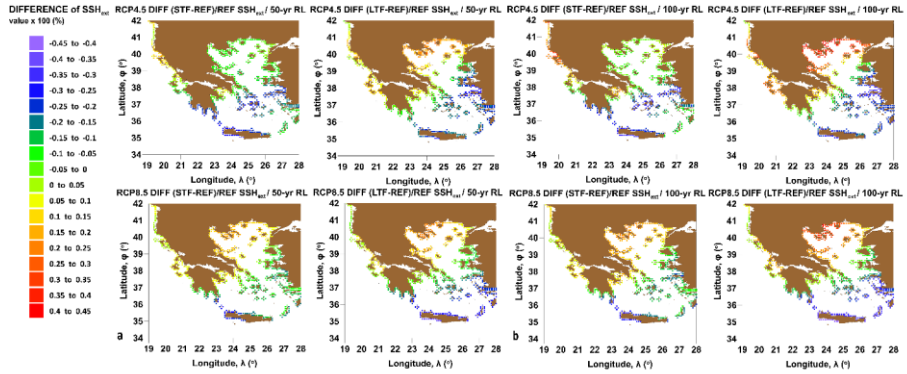

Fig. 3. Maps of Differences for 50- & 100-year RV of SSH$_{ext}$ by CNRM-based MeCSS simulations during Reference STF and LTF for RCP4.5-8.5.

3.2 Coastal Flooding Impacts due to several TWL Scenarios

CoastFLOOD simulations driven by the highest projected total water levels translate these offshore signals into spatially explicit flood maps (Fig. 4). For Alexandroupolis, located in the northern Aegean, future scenarios under the RCP8.5 project a clear expansion of flood extent across low-lying urban areas near the port and the airport access roads, with flooded areas increasing by more than 15% relative to present-day conditions in the long term. In Ierapetra, on the southern coast of Crete, steep topography restricts inland penetration, so flood extents remain relatively limited despite elevated water levels, highlighting the crucial role of local morphology. In western Greece, simulations for Kalamata and Plomari illustrate different hydrodynamic behaviours. In Plomari, a narrow coastal lowland is easily over-topped under combined surge and MSLR, and floodwaters can propagate along the coastal plain, threatening transport corridors and built-up areas. Kalamata, by contrast, exhibits hydraulic connectivity between the shoreline and more inland depressions, so storm tides can activate complex flow pathways that inundate areas not directly adjacent to the sea.

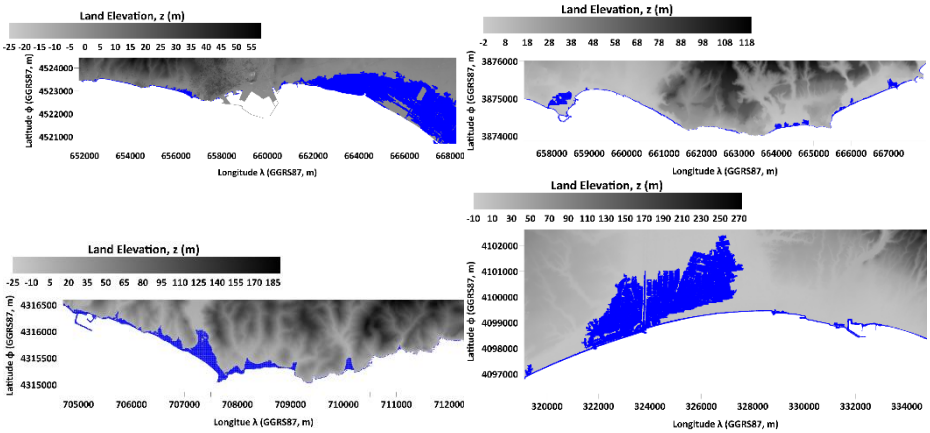

Fig. 4. Flood Extents (FA) with CoastFLOOD simulations driven by the highest extreme TWL in Alexandroupoli (N Greece), Plomari (W Greece), Kalamata (SE Greece), Ierapetra (S Greece) from left to right and top to bottom.

At several sites, projected changes in the area affected by flooding under RCP8.5 by 2100 fall within the range of 10–20%, whereas in other locations they remain within a few per cent, consistent with local attenuation of storminess.

3.3 Results on Flood Hazard Management

CIHI provides a synthetic view of these results by ranking all 20 sites based on combined driver intensity and flood response. Under historical conditions, the highest CIHI values occur in low-lying deltas, embayments, and back-

barrier plains with extensive urbanisation or critical assets. In the long-term future under RCP8.5, several of these sites experience an upward shift in hazard class, while a few locations with currently moderate hazard move into the high-hazard category. Conversely, a limited number of sites with favourable topography and reduced storminess exhibit stable or slightly reduced CIHI values.

Overall, the analysis reveals that the combined effect of changing storm surges and sea-level rise is highly site-specific (Table 1). The spatially coherent patterns associated with atmospheric deep depressions and Mediterranean cyclone tracks interact with local coastal morphology and land-use to produce a rich spectrum of future flood responses along the Greek coastline.

Table 1. Characteristic CIHI values for hazard severity by combining ranked driver (storm tide) intensity with a ranked Normalised Inundation Index (Flooded Fraction), $FA_{ext}/FA_{ceiling}$.

A/A	Ierapetra	Rethymno	Kalamata	Katakolo	Argostoli	Livadi
MAX	1.061	0.902	1.273	1.105	1.057	1.059
RANK	12	22	3	10	14	13
CIHI	5	5	1	5	1	1
A/A	Patra	Chios	Vasiliki	Palairos	Plomari	Kyparissia
MAX	1.105	0.974	1.042	1.055	1.222	1.138
RANK	11	18	16	15	5	7
CIHI	2	3	2	1	-	-

4 Discussion

The results confirm that climate change affects storm surges and coastal flooding in the Mediterranean in ways that simple monotonic trends cannot summarise. Instead, they emerge from a combination of (i) large-scale modifications in the frequency, intensity, and tracks of deep depressions and cyclones [15], (ii) regional sea-level rise [16], and (iii) local coastal morphology and human occupation [17,18]. The projected basin-wide attenuation of storm surges in many regions reflects a likely northward shift and reorganisation of atmospheric circulation patterns [1]. Yet, local hotspots of intensification persist, where topographic and bathymetric configurations favour surge amplification [13]. Specifically, a comparison of positive vs negative differences DIFF (%) in extreme Flood Extents (FA_{ext}) at selected Greek coastal sites is presented in Table 2, based on combinations of climatic scenarios, RCPs, RCMs, and Return-Periods (RPs), e.g.:

$$DIFF(FA_{ext}) = \left(FA_{ext,RCP45-STF} - FA_{ext,Reference}\right)/FA_{ext,Reference} \quad (2)$$

Positive changes are few but, conditionally, exceed the 5% significance threshold. For infrastructure designers and coastal planners, this implies that relying solely on basin-average or global sea-level rise projections is insufficient for robust risk assessments [18]. Instead, detailed regional modelling of storm surges, combined with extreme-value statistics and high-resolution inundation simulations, is required to identify the most critical sites and quantify the range of possible future outcomes. The hybrid framework presented here offers such a pathway by linking MED-CORDEX RCM outputs, MeCSS surge simulations, EVA, and CoastFLOOD at representative Greek sites. The used FA_{ext} values are classified in Section 3.2's analysis of coastal inundation impacts due to several TWL, prioritised based on outputs similar to Fig. 4 for all case study areas, where positive changes in DIFF(FA_{ext}) prevail.

Table 2. Positive vs negative differences DIFF (%) of extreme Flood Extents (FA_{ext}) from Eq. 2 at selected Greek coastal sites based on combinations of RCPs, RCMs, and RPs. Positive changes are marked in bold.

RCP/ Future	RCM	RP (years)	Ierapetra	Rethymno	Kalamata	Laganas	Thermaikos
RCP45-STF	CMCC	50	-2.03%	**1.51%**	-0.50%	**2.12%**	**2.70%**
		100	0.00%	**2.93%**	-0.39%	**2.13%**	**1.71%**
	CNRM	50	-6.26%	-11.64%	-5.74%	-2.88%	-0.98%
		100	-5.65%	-11.24%	-5.80%	-2.78%	**0.40%**
	GUF	50	-11.47%	-10.51%	-7.82%	-8.14%	-1.17%
		100	-11.55%	-13.97%	-9.13%	-12.45%	-2.15%
RCP45-LTF	CMCC	50	-4.15%	-5.42%	**0.77%**	**3.48%**	-1.41%
		100	-3.05%	-6.33%	**1.17%**	**5.01%**	-3.23%
	CNRM	50	-12.88%	-8.51%	**0.14%**	**3.21%**	**4.51%**
		100	-11.20%	-10.42%	**1.19%**	**5.40%**	**8.82%**
	GUF	50	-14.23%	-12.75%	-9.54%	-8.80%	-1.83%
		100	-15.25%	-14.39%	-10.30%	-12.09%	-2.28%

The proposed CIHI is a pragmatic tool for synthesising complex information into a form accessible to decision-makers. By combining ranked contributions from extreme total water levels and normalised flood extents, CIHI simplifies the communication of hazard severity and its evolution under climate change. However, CIHI should be interpreted alongside complementary indicators that capture exposure and vulnerability, such as population density, the economic value of assets, critical infrastructure, and ecosystem services, to derive comprehensive risk indices [19].

From the perspective of the United Nations Sustainable Development Goals (SDGs), the findings have direct implications for SDG 11 (Sustainable Cities

and Communities) and SDG 13 (Climate Action). Coastal municipalities with increasing CIHI values will need to integrate future storm-tide-driven flood hazards into spatial planning, building codes, emergency preparedness, and insurance schemes. Adaptation options may range from nature-based solutions, such as wetland restoration and beach nourishment, to engineered defences and managed retreat in the most exposed locations. The analysis also supports SDG 9 (Industry, Innovation and Infrastructure) by providing the quantitative basis for climate-resilient design of ports, transport links, and water-related infrastructure along the Greek coastline [20].

The study has several limitations that point to future research needs. First, while the GEV-based EVA assumes stationarity within each 35-year window, non-stationary approaches that explicitly incorporate time-varying covariates could provide additional insight, especially for mid- to long-term planning. Second, the analysis focuses on storm surges and mean sea-level rise, whereas wave setup, runup, and coincident river discharges are treated implicitly or neglected. Extending the framework to account for fully coupled flooding by integrating coastal surge and waves with fluvial and pluvial models would yield a more comprehensive representation of coastal compound flood hazards. Third, uncertainties associated with climate model ensembles, emission pathways, and local topographic data should be quantified more explicitly through systematic sensitivity and probabilistic analyses.

Despite these limitations, the present work demonstrates the feasibility and value of downscaling Mediterranean-scale climate information to the local scale of individual Greek coastal communities. The combination of physically based modelling and statistical analysis provides a consistent framework that can be updated as new climate scenarios, RCM simulations, and higher-quality topographic data become available.

5 Conclusions

A hybrid framework has been presented to assess future extreme storm tides and associated coastal flooding along the Greek coastal zone under climate change scenarios. The approach combines MED-CORDEX climate projections, MeCSS storm-surge simulations, GEV-based EVA, and reduced-complexity CoastFLOOD inundation modelling at high spatial resolution for twenty representative Greek coastal sites.

The results indicate that, while a general attenuation of storm surges is projected over large parts of the Mediterranean basin by the end of the twenty-first century, several Greek hotspots may experience local increases in extreme storm-tide levels and flood extents when storm surges are superimposed on mean sea-level rise. Projected changes in flood impacts range from negligible

to more than 20% under RCP8.5 in the long term (not shown here for brevity), depending on location, coastal morphology, and atmospheric forcing.

The Coastal Inundation Hazard Index (CIHI) introduced in this study provides a valuable synthesis of driver intensities and flood responses, offering a transparent means to compare hazard levels across sites and scenarios. The methodology and results can directly support coastal risk assessments, adaptation strategies, and investment planning aligned with the objectives of SDGs 9, 11, and 13.

Future work will focus on extending the framework to fully account for compound flooding, incorporating wave effects and river discharge, refining non-stationary statistical models of extremes, and integrating exposure and vulnerability data to derive comprehensive coastal risk indices for Greece and the wider eastern Mediterranean.

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