Impact of sea level variability on coastal inundation in the Aegean, Ionian and Cretan Seas

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Abstract

Sea level is a key element of global scale climatic changes with potentially significant coastal impacts especially on the low-lying areas of the Mediterranean Sea, which is one of the most vulnerable regions to sea level rise worldwide. The sea level variability controls the inundation levels of the coastal zone, depending on the local topographic characteristics and the occurrence of severe meteorological events (e.g., storm surges). The scope of this study is to evaluate the interannual and spatial variability of the Sea Level Anomaly (SLA) in the Aegean, Ionian, and Cretan (AIC) Seas and evaluate its impact on the coastal inundation characteristics along the topographically complex Greek coastline. The analysis refers to a 29-years period from 1993 to 2021.

Keywords Water level, Remote sensing, Storm surge, Coastal flooding.

1 INTRODUCTION

Sea level is a key element of global scale climatic changes with potentially significant coastal impacts (Cazenave et al., 2014), especially on the low-lying areas of the Mediterranean Sea, which is one of the most vulnerable regions to Sea Level Rise (SLR) worldwide. The sea level variability controls i) the inundation levels of the coastal zone, depending on the local topographic characteristics (Ferrarin et al., 2021), ii) the shoreline retreat, coastal erosion, and land loss, and iii) the salinity levels in estuaries and freshwater aquifers. The main motivation of the current study is to assess the state and severity of coastal hazards, related to sea level increases and coastal inundation, over the Aegean, Ionian, and Cretan Seas (AIC; Figure 1a), located in the northeastern Mediterranean Sea. The investigation spans over a long recent period from 1993 to 2021 (29 years). We focus on 20 identified low-lying coastal areas (Figure 1b) that have been impacted by intense flooding events in the past and expand the analysis with the use of finer land elevation data (5 m spatial resolution model grids).

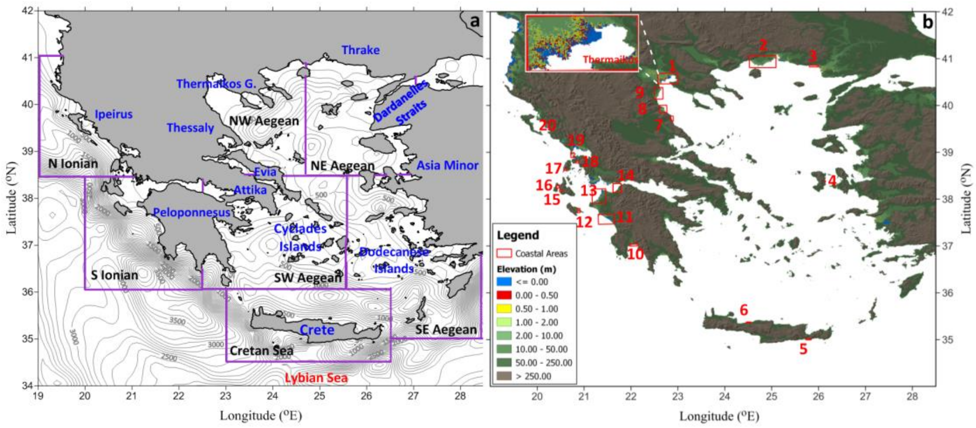

Figure 1 (a) Bathymetry of the study area divided into 7 sub-regions (b) Land elevation (m) map, derived from the 25 m Copernicus (https://land.copernicus.eu/) Digital Elevation Model (DEM) showing the study's 20 coastal areas

2 METHODS AND DATA

2.1 Sea level observations & Digital Elevation Model data

The altimeter satellite SLA data (sea surface height above mean sea level), computed with respect to a twenty-year (1993-2012) mean, has been collected from the Copernicus Marine Service (CMEMS; https://data.marine.copernicus.eu/product/SEALEVEL_EUR_PHY_L4_MY_008_068/description; accessed in January 2023; Pujol and Larnicol, 2005) to investigate the sea level variability over the 7 AIC sub-regions (Figure 1a) and provide the boundary conditions of the coastal flooding simulations at 20 study coastal areas (Figure 1b), covering the 29-year period (1/1/1993-31/12/2021). The dataset of coastal land elevation is of spatial high resolution (5 m) and was derived by the available geospatial data from the DEM of the official Greek service for comprehensive recording of real estate and property's metes-and-bounds, i.e., the Hellenic Cadastre (https://www.ktimatologio.gr/en). This high resolution dataset was used to investigate the variability of the inundation levels over the 20 coastal areas that have been impacted by recorded intense flooding events in the past (Figure 1b). The geometric accuracy of the DEM is less than 0.70 m, while its absolute accuracy is less than 1.37 m with a 95% confidence level (Chrisafinos and Kavvadas, 2016). The 20 selected case study areas (and the aquatic basins they belong to) are well-known lowland coastal areas, based on the Hellenic Cadastre's official DEM and the fact that they are prone to flooding events.

2.2 Numerical simulations of coastal inundation

We implement modeling of coastal inundation induced by slowly varying sea level on the coast due to storm surges with CoastFLOOD model (Makris et al., 2023a). CoastFLOOD is an Aristotle University of Thessaloniki (AUTh) in-house numerical model, applied in littoral inundation hydrodynamic studies focused on local scales over the selected areas of the coastal zone in Greece (Androulidakis et al., 2023). CoastFLOOD is a depth-averaged, 2-D horizontal, mass balance, flood flow model, especially indicated for coastal areas (Makris et al., 2020, 2022). It follows the concept of reduced complexity Manning-type flows for 2-D floodplains (Bates et al., 2005). Two types (realistic and idealized) of numerical simulations were developed to derive i) daily realistic estimations of coastal inundation covering the 29-year period, based on the satellite-derived SLA levels along each study area (jobs: 20 areas × 10,592 days), and ii) estimations of the extreme floods, based on four idealized extreme scenarios of SLA (0.5, 1, 1.5 and 2 m; jobs: 4 scenarios × 20 areas) along the coastline boundary of each study area.

3 RESULTS

The interannual evolution of the mean annual SLA, averaged over 7 AIC sub-regions, revealed clear positive trends during the 1993-2021 period (Figure 2a). The general trend over the entire area was 3.6 mm/year, higher than the overall Mediterranean (2.44 mm/year; Bonaduce et al., 2016). The highest Sen's slopes were derived for the Aegean Sea with strongest trends for the SW Aegean (4.1 mm/year). The northern Aegean revealed the highest 99th percentiles in 2010 (>0.25 m; Figure 1b), when the maximum SLA values of the entire study period occurred.

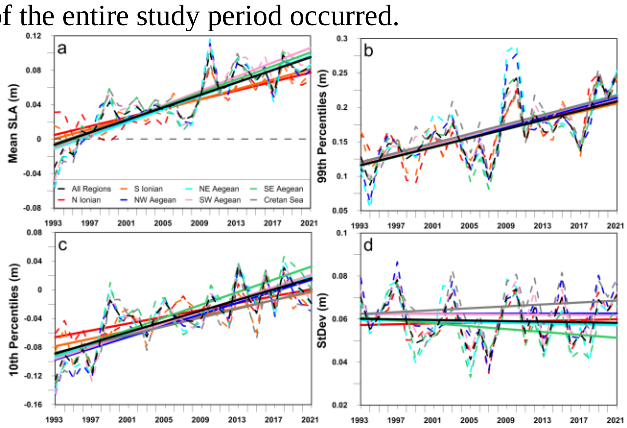

Figure 2 a) Annual variability and trends of: (a) the mean SLA; (b) the 99th percentile; (c) the 10th percentile, and (d) the standard deviation (StDev), averaged over 7 AIC regions for the period 1993–2021

To allow the comparison between different coastal areas, for which the amount of low-land cells significantly varies, and to further produce a more objective index for the estimation of coastal flooding impact for each area, the daily Flood Coverage Percentages ($FCP_{i,j}$, %) was computed as:

$$FCP_{i,j} = {FA_{i,j}}\Big/{FA_{ext,j}} \tag{1}$$

where $FA_{i,j}$ is the flooded area for each study case j and i day based on the respective satellite-derived $SLA_{i,j}$, and $FA_{ext,j}$ is derived for each study area j based on an extreme case scenario of SLA=1 m. The FCP levels are related to two main factors (Figure 3): the sea level high peaks (e.g., 99th percentile of SLA) and the land elevation characteristics of each coastal area (e.g., distribution of low-lying areas). The FCP levels for all study areas, averaged over the 29-year period, shows strong spatial variability with very low percentages (<4%) at Alexandroupolis, Agiokampos, and 15-20% at the central and northern Ionian Sea. The very high FCPs computed for the southern Ionian areas (Areas 11 and 12) were related to both high SLA levels (>0.20 m) and the extended low-lying land (e.g., >40% of Area 11's land elevation z lays below the mean sea level: z<0 m), allowing extended flooding, especially during strong storm surge events (>16% mean FCP).

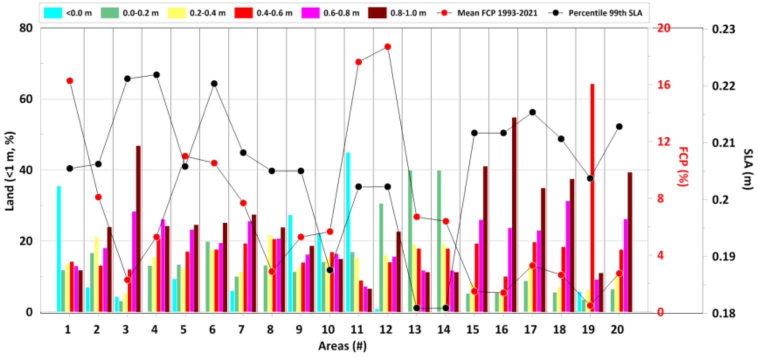

Figure 3 Frequency (%) of land elevation categories derived from all land cells (below 1 m) of each study area; the FCP averaged from daily values (zero values excluded) and the 99th Percentile of SLA are shown

The variability and trends of the annual SLA and the respective annual frequency of flooding at 20 selected low-lying areas of the AIC domain are presented in Figure 2. Strong positive trends of flooding annual frequency were computed in coastal regions of the northern Aegean (>8%/decade), associated to the increasing SLA levels and the low-land characteristics of these areas.

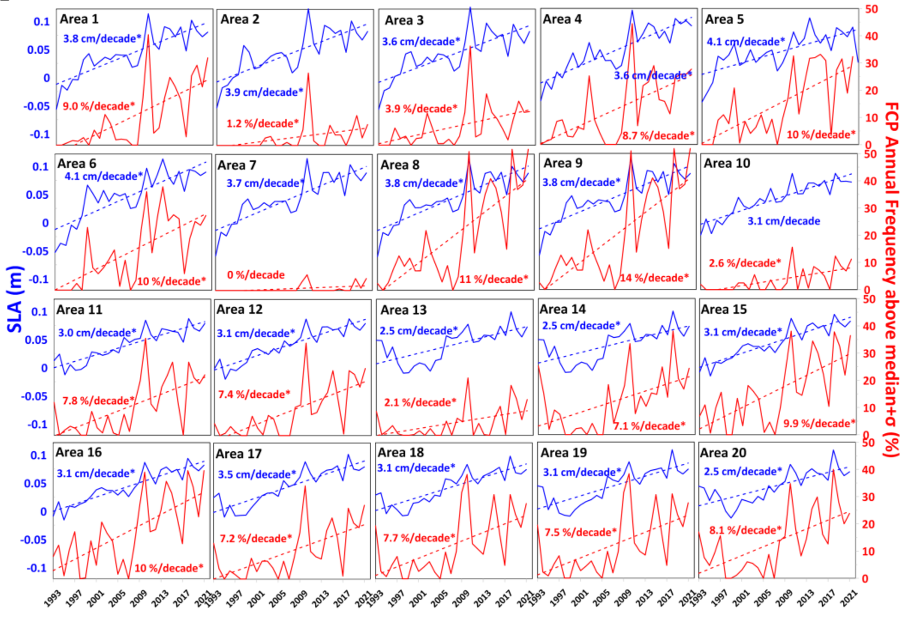

Figure 4 Annual evolution of mean SLA and annual frequency of FCP above median+σ level for 20 coastal areas during 1993-2021; the linear regressions and the respective Sen's slopes for each case are also shown

The Coastal Inundation Hazard Index (CIHI) is defined as the product of the Frequency of Occurrence (FO, %) of the days with extreme FCP_{ext} (>median+σ, %) multiplied with the temporal mean of the FCP_{ext} (derived from daily values i of the 1993-2021 period), and calculated for each study area (j) as:

$$CIHI_j = FO_j \times \overline{FCP_{ext,i,j}} \tag{2}$$

The CIHI values were normalized over their min–max range, to make individual index results for each of the 20 study areas directly comparable to each other, by following a Likert scale classification ranging from very low to very high corresponding to a 1–5 ranking system. Five areas (Areas 1, 5, 6, 11, 12) with CIHI larger than 3 were detected, characterized of high hazard to coastal inundation, as derived for the 1993-2021 period. Thermaikos Gulf (Area 1) and especially its western coastal area revealed high FO (10.4%) of extended flooding (FCP_{ext}: FCP>mean+σ), while the mean FCP_{ext} was around 19% resulting to CIHI=4. More hazardous flooding conditions (CIHI=5) were detected for the two areas in Cretan Sea (Ierapetra and Rethymno) showing FO>14% and mean FCP_{ext}>16%.

Table 1. Means and ranking (1-5) of FO, mean FCP and CIHI derived for the 20 coastal areas and the 1993-2021 period. Ranking: 1 (very low), 2 (low), 3 (medium), 4 (high), 5 (very high). CIHI values larger than 3 (high and very high) are highlighted with red color.

Area	Area	FO	MEAN FCP	CIHI (product)	CIHI (Ranked)
1	**Thermaikos**	0.104	0.188	0.019	4
2	**Nestos**	0.028	0.144	0.004	1
3	**Alexandroupoli**	0.028	0.050	0.001	1
4	**Chios**	0.130	0.103	0.013	3
5	**Ierapetra**	0.146	0.168	0.025	5
6	**Rethymno**	0.140	0.196	0.027	5
7	**Pineios**	0.006	0.092	0.001	1
8	**Agiokampos**	0.142	0.083	0.012	2
9	**Katerini**	0.197	0.074	0.015	3
10	**Kalamata**	0.035	0.065	0.002	1
11	**Katakolo**	0.106	0.264	0.028	5
12	**Laganas**	0.090	0.321	0.029	5
13	**Manolada**	0.044	0.098	0.004	1
14	**Patra**	0.068	0.097	0.007	2
15	**Argostoli**	0.160	0.029	0.005	1
16	**Livadi**	0.174	0.029	0.005	1
17	**Vassiliki**	0.100	0.075	0.008	2
18	**Palairos**	0.123	0.045	0.006	1
19	**Preveza**	0.122	0.009	0.001	1
20	**Igoumenitsa**	0.132	0.059	0.008	2

4 DISCUSSION AND CONCLUSIONS

The variability of the Sea Level Anomaly (SLA) over the Aegean, Ionian and Cretan Seas has been evaluated with the use of satellite-derived observations during a 29-year period from 1993 to 2021. The SLA observations along the coastal zone of the AIC domain were used to force numerical simulations of coastal inundation with CoastFLOOD model (Makris et al., 2023a, 3023b) at 20 selected low-lying areas to estimate their hazard levels due to episodic increases of sea level, as derived during the 29-year period. The general SLA trend over the entire AIC domain was 3.6 mm/year, which is higher than the overall Mediterranean (2.44 mm/year; Bonaduce et al., 2016) and the eastern Mediterranean (3.1 mm/year; Mohamed and Skliris, 2022) trends. The highest Sen's slopes were derived for the Aegean Sea with strongest trends for the SW Aegean (4.1 mm/year). Moreover, the Cretan Sea revealed the strongest interannual trend of the maximum SLA values (99th percentiles; 3.5 mm/year). The highest SLA levels were detected primarily in autumn and secondarily in winter, while the lowest seasonal means occurred in spring.

The Sen's slopes of the inundation levels computed for all 20 study areas were positive (increasing trends) and statistically significant (0.07%/year for the mean levels and 0.15%/year for the maximum levels). In all cases, a clear upward shift took place after 2009, ranging around 1.39% for the mean and 2.86% for the maximum levels. The highest SLA for all areas occurred in the years of 2010, 2013, 2014, 2016, 2018, 2019, 2020, and 2021, all during the last 12-year period, confirming the strong inter-decadal increase that enhanced the flooding levels after 2009. Very strong trends of extreme flooding were computed for the Cretan Sea, where the strongest trends of maximum SLA occurred. More hazardous flooding conditions (CIHI=5) were detected for the two areas of the Cretan Sea (Ierapetra and Rethymno) compared to the other study cases, showing both high frequency (>14%) and large inundation areas (>16%). High CIHI values were computed for the coastal zone of the southern Ionian Sea (Katakolo and Laganas). To extend the findings of the study, the next step is to develop climatic projections of coastal inundation under different climate change scenarios to test if the current increasing trends in the AIC domain may be probable in the 21st century under different Representative Concentration Pathways (RCP) scenarios. Moreover, for the complete assessment of flood probability at coastal sites of the AIC domain susceptible to inundation risk, the next step is to include wave observations for the integrated estimation of the combined impact of wave action and rising water levels, especially in the wave runup zone of the low-lying inland coastal areas.

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