



Coastal Hazards and Related Impacts in Greece

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Abstract

Greece has a coastline of about 16,000 km where most of its population, infrastructure, assets and socio-economic activity are concentrated. Most large urban and industrial conglomerates are located at the coast, as well as critical infrastructure such as its many seaports. Coastal areas also form the pillar of Greek tourism, a vital economic sector for Greece. At the same time, the Greek coasts face many climatic and geophysical hazards. This chapter provides a short review of some of these hazards and impacts, focusing mainly on those associated with Climate Variability and Change (CV&C). The analysis shows that the Greek coastal zone faces large threats, some of which are projected to be exacerbated by CV&C. Slow-onset relative sea level rise (RSLR) and extreme storm events will have very substantial and increasing impacts on the Greek low-lying coasts (e.g., beaches and deltaic coasts) and coastal infrastructure, assets and activities. Under both the slow-onset RSLR and the increasing magnitude and frequency of extreme sea levels, there will be very significant effects on the widths of the 7400 Greek beaches and, therefore, on their carrying capacity for tourism, recreational value and the value of associated assets from (at least) the 2050s. Impacts will further escalate by the end of the century,

when at least 40% (and up to 89%) of all Greek beaches will permanently retreat by a distance at least equal to their current beach maximum widths under the Representative Concentration Pathway – RCP8.5 and high ice-melt scenario; these retreats will have potentially devastating impacts on the ecosystems and infrastructure/assets they front. Future extreme sea levels will further exacerbate these impacts, with very severe flood damages and losses projected for the backshore ecosystems and assets, even if the fronting beaches recover after the storms. There will also be significant challenges for the critical infrastructure located at the coastal front, such as seaports, involving impacts from both flooding under extreme events and operational disruptions from, e.g., the increasing magnitude and frequency of extreme heat waves. It appears that detailed risk assessments and innovative adaptation measures are required to manage such impacts and build resilience in the Greek coastal zone. Effective integrated coastal management frameworks/plans should be developed and implemented, which will also require the adoption and effective implementation of appropriate regulation and governance structures.

Keywords

Hazards · Coastline · Climate variability · Sea level rise · Tourism · Storm · Infrastructure

Regina Asariotis: The views expressed are those of the author and do not necessarily reflect the views of the United Nations.

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Introduction

Coastal areas, by their exposure to many hazards, such as rising mean sea levels, storm surges and waves, fluvial/pluvial floods, increasing temperatures, cyclones, and tsunamis, are threatened by increasing land loss and flooding that can severely impact their ever-increasing populations, infrastructure, assets and economy. At the global level, large populations live in low-elevation coasts, with the majority of the

world's metropolitan areas located in the coastal zone, together with very significant infrastructure, such as seaports which facilitate over 80% of the volume of global trade (UNCTAD, 2020). Coastal areas are also, in many cases, major tourism destinations; tourism, which is increasingly associated with beach recreational activities according to the 'Sun-Sea-Sand-3S' model (Phillips & Jones, 2006), accounts for a large fraction of the Gross Domestic Product (*GDP*) of coastal and island States (UNWTO, 2017). At the same time, coasts face multiple hazards. In addition to the ever-present tsunami hazard for many coasts (Grezio et al., 2017), projections indicate increasing impacts under Climate Variability and Change (*CV&C*) from (a) slow-onset events, such as the mean sea level rise and increasing temperatures and (b) sudden-onset events, such as storm generated extreme sea levels (*ESLs*) and waves, heat waves, winds and heavy precipitation (IPCC, 2014; IPCC SROCC, 2019).

Greece (Fig. 21.1) has a coastline of about 16,000 km where most of its population, infrastructure, assets, and socio-economic activity are concentrated. Most large urban and industrial conglomerates are located on the coast, including the two largest metropolitan areas (Athens and Thessaloniki). Critical infrastructure assets, such as transport infrastructure and energy plants, are also located at the coast. There are many seaports in Greece, which not only facilitate international and national trade but also the transportation of a large number of passengers, making them and their resilience under *CV&C* critical for the sustainable development of the country. Tourism, which accounts for about 20.6% of the Greek *GDP* (SETE, 2018), is also focused on the coasts. The vast majority of annual international tourists (30.1 million arrivals, 19.03 billion USD receipts in 2018) vacation wholly, or partially, at coastal locations, choosing beach (*3S*) recreational activities (UNWTO, 2019). Therefore, beach aesthetics and adequate carrying capacity and infrastructure are crucial for the tourism sector and the economy as a whole (Tzoraki et al., 2018).

Against this background, the objective of the present contribution is to provide a short overview of the potential hazards and threats for the Greek coastal zone, focusing mostly on those induced by *CV&C*. The structure of the contribution is as follows. Section "Environmental Setting" provides a short overview of the geological, physiographic, climatic, and oceanographic characteristics of the Greek coastal zone with a special focus on those that could be associated with coastal hazards. Section "Coastal Zone Hazards and Impacts" focuses on the main coastal hazards/threats and, particularly, on sea level rise and extreme events that can force coastal flooding and erosion. Finally, Section "Discussion and Concluding Remarks" discusses the findings and provides some concluding remarks.

Environmental Setting

Geology and Physiography

Greece is located at the western margin of the Alpine-Himalayan orogenic belt, an area that has experienced major geotectonic events, such as the formation and subsequent degradation of the Tethys Sea, the development of subduction zones/trenches and orogeny (Le Pichon & Kreemer, 2010; Papanikolaou, 2013). Its tectonic complexity is demonstrated by the presence of major structures, such as the Hellenides orogenic belt, the western margin of the North Anatolian fault (North Aegean Trough), the Aegean volcanic arc and the Hellenic trench, the development of which is associated with the relative movement of the Aegean and Anatolian microplates, a major subduction zone in the south, and the collision between the Apulian platform and the Greek slabs in the northwest (e.g., Faccenna et al., 2014; Howell et al., 2017). This geotectonic setting has resulted in severe and diachronic seismicity (Papazachos & Papazachou, 1997) and volcanism (Vougioukalakis et al., 2019), as well as a complex physiography (Fig. 21.1).

A large portion of the Greek coastline forms on high-relief solid geological formations; low-elevation coasts form mostly as 'pocket' beaches, with linear and deltaic 'sandy' coasts having small extent (e.g., EUROSION, 2004). Excluding the deltaic coasts, there are about 7400 beaches in Greece with an overall length of about 2700 km; most of these beaches are narrow, with 67% of them recording a maximum width of less than 25 m (Karditsa et al., 2015). In terms of river fluxes, annual water and suspended sediment fluxes have been estimated as 44.3 km³ and 28.6 million tons, respectively (Poulos, 2019). There are few large rivers (Fig. 21.1) with moderate water and sediment fluxes to the coast (Poulos & Kotinas, 2020). There are also numerous ephemeral rivers contributing to the coastal sediment budgets during extreme precipitation events (Gamvroudis et al., 2015; Sauquet et al., 2019); for example, the small ephemeral river Krathis (Fig. 21.1) has been estimated to have annual sediment deposition fluxes of 3185 tons and sediment erosion fluxes of 43,545 tons (Tzoraki & Nikolaidis, 2007).

Climate and Oceanography

The Greek coastal zone generally has a temperate, dry, and hot climate. Mean temperatures ranged between 15.7 and 17.5 °C in the period 1979–2017 (Tzanis et al., 2019), whereas the mean annual precipitation for the marine/coastal regions has been estimated at 633 mm (Poulos, 2019). Physiography controls the wind regime in coastal areas, with

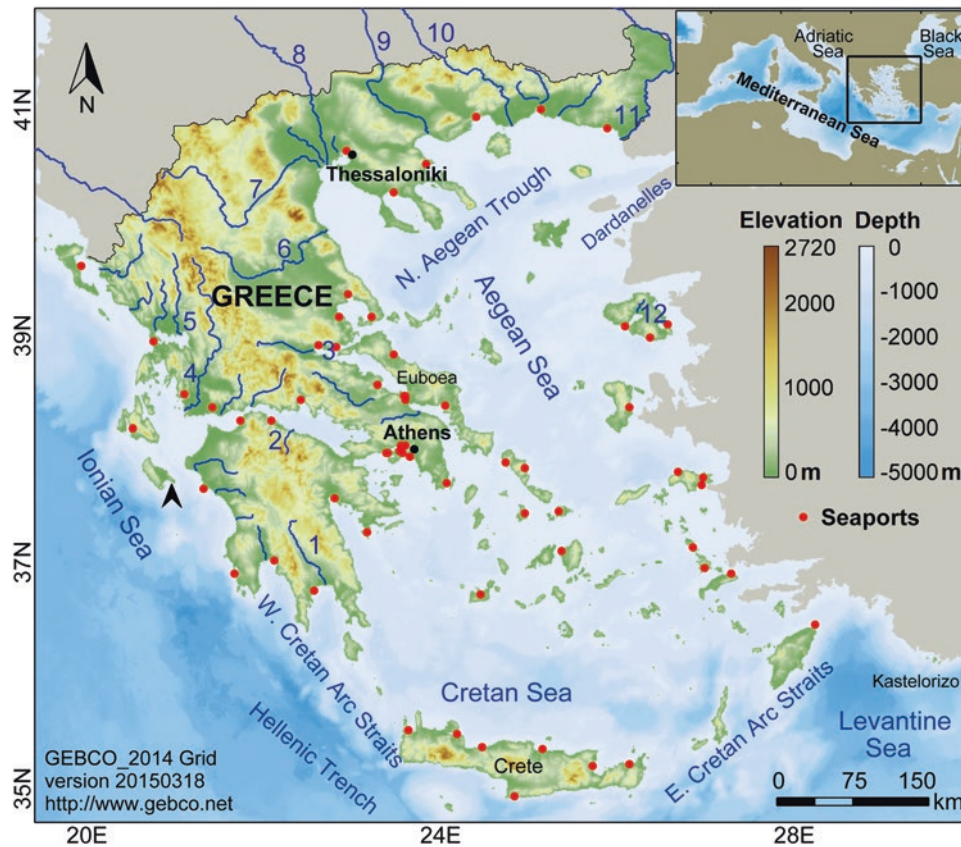


Fig. 21.1 Map showing the locations referred to in the text and the major (64) seaports listed in https://hub.arcgis.com/datasets/8be585162b814e1f89afa6a3de4e42cb_0/data?geometry=111.500%2C-27.047%2C113.500%2C31.665 (World Port Index)

Key: 1 Evrotas R., 2 Krathis R., 3 Maliakos Gulf, 4 Acheloos R., 5 Arachthos R. and Amvrakikos Gulf, 6 Pineios R., 7 Aliakmon R., 8 Axios R., 9 Strymonas R., 10 Nestos R., 11 Ebro R., and 12 Tsiknias R. and Kalloni Gulf. The arrow shows the location of Gerakas beach, Zakynthos (Fig. 21.4)

higher wind speeds recorded in winter, although there are also energetic summer events, forced mostly by the prevailing N–NE winds – ‘the etesians’ (Soukissian et al., 2007, 2017; Androulidakis et al., 2015).

The Hellenic peninsula divides the Eastern Mediterranean into the Aegean, Ionian, and Levantine Seas (Fig. 21.1). The freshwater deficit and the (generally) cyclonic circulation of the Mediterranean determine its hydrography and circulation (Wüst, 1961). Atlantic Water (AW), which enters through the Gibraltar Strait, flows eastwards along the African coast, with its salinity gradually rising to about 39 g kg^{-1} in the Levantine Sea, whereas a distinct surface/subsurface salinity minimum in the Ionian Sea identifies the Modified Atlantic Water (MAW). In the Levantine Sea, the combination of winter cooling and wind-stress curl forms the Mediterranean’s most voluminous water, the warm and highly saline Levantine Intermediate Water (LIW), found at water depths of 100–700 m (Lascaratos et al., 1993). The deep layers of the Ionian and Levantine Seas are filled by the so-called Eastern Mediterranean Deep Water (EMDW) that forms mostly in the

Adriatic Sea. A major change occurred in the early 1990s, when the Aegean Sea became, for a few years, the major EMDW source (Roether et al., 1996).

The Aegean Sea is connected to the Black Sea via the Dardanelles Strait, Marmara Sea, and the Bosphorus Strait and to the Ionian and Eastern Mediterranean basins through the Cretan Arc straits (Tsimplis et al., 1997, 1999). Black Sea water (BSW), of low salinity (about 18 g kg^{-1}) and relatively cool temperatures, flows into the NE Aegean Sea through the Dardanelles Strait at the surface (balanced by counter-flowing, subsurface warm and saline Aegean waters) and is advected southwards, commonly along the western Aegean coast (Olson et al., 2007). The Aegean Sea also imports surface/subsurface water from the Ionian and Levantine basins through the Cretan Arc straits, with MAW entering from the southwest and saline Levantine waters (Levantine Surface Water-LSW and LIW) from the southeast, which proceed toward the North Aegean, balancing the BSW southward flow. The deep layers of the North Aegean are occupied by the locally formed North Aegean Deep Water;

this water mass, after mixing with the incoming Levantine waters and overflowing the northern and central Aegean basins (Zervakis et al., 2000), forms the main source of the dense Cretan Deep Water (*CDW*) that may occasionally overflow toward the deep basins of the Eastern Mediterranean (Androulidakis et al., 2012). During periods of high *CDW* outflow, shallow water inflow from the Eastern Mediterranean is intensified, enhancing the formation of a distinct water mass in the Cretan Sea (the Transitional Mediterranean Water – *TMW*) found at depths of 700–1000 m; its overlying layer consists of modified Levantine waters (the Cretan Intermediate Water – *CIW*) (Theocharis et al., 1999).

Greek coasts are microtidal environments, with tidal ranges rarely exceeding 0.2 m (Tsimplis et al., 1995; Pugh & Woodworth, 2014). Interactions with the coastal morphology can locally enhance the tidal range and currents, as is the case in the narrow Euripus Strait between the mainland and the Euboea (Fig. 21.1), where a maximum tidal range of about 0.55 m and tidal currents of up to 3 m s⁻¹ are recorded (Tsimplis & Spencer, 1997). The complex physiography also controls its wave regime. In the Aegean Sea, northerly winds and waves prevail (Androulidakis et al., 2015), with highly energetic wave events of short duration occurring along island straits (Soukissian et al., 2007). Waves are generally higher in the south Ionian and south Cretan seas due to swell waves coming from the south and central Mediterranean, with the higher mean significant wave heights (about 1.6 m) recorded in winter (Emmanouil et al., 2016).

In recent decades, intensified warming has been recorded in the eastern Mediterranean, with the mean sea surface temperature (*SST*) in the Levantine and Aegean basins trending at $+0.048 \pm 0.006$ °C/year in the period 1982–2018 (Pisano et al., 2020). Mamoutos et al. (2014) examined the mean sea level rise (*SLR*) in the Aegean and Ionian Seas over the period 1992–2008 using altimetry information and found *SLR* rates of 4.6 and 4.3 mm/year in the northern and southern Aegean, respectively, and 2.4 and 2.8 mm/year in the north and south Ionian Sea, respectively. Such rates appear to be within the general Mediterranean trends (Mohamed et al., 2019), although the Aegean Sea seems to be rising at higher rates. In terms of projections, Hinkel et al. (2014) found that the future *SLRs* in the area will depend on the ice mass change (ice-melt) scenario.

In addition to *SLR*, changes in the intensity, frequency, and patterns of extreme storm surges and waves can, at least temporarily, induce coastal erosion and flooding. Generally, coastal extreme sea levels (*ESLs*) show a seasonal footprint, with extreme positives occurring in winter and under certain North Atlantic Oscillation modulations (Tsimplis & Shaw, 2010). Future *ESLs* are projected to show high spatial variability, being also sensitive to the evolution of the thermohaline circulation and the Black Sea buoyant inputs (Mamoutos et al., 2014). Recent studies have projected substantial

changes in the *ESL* return periods for the eastern Mediterranean, with the current 1-in-100-year event projected to occur several times annually in 2100 under the Representative Concentration Pathway – RCP8.5 (Vousdoukas et al., 2018). In terms of future waves, small changes in wave heights have been projected until the 2050s (Tsoukala et al., 2016).

Highly energetic events (Tropical-Like Cyclones – *TLCs* or *Medicanes*) are sometimes observed in the Mediterranean. These cyclones have characteristics similar to those of tropical cyclones, and although their development and evolution mechanisms are not yet fully understood (Miglietta & Rotunno, 2019), they can induce catastrophic winds and severe coastal (and inland) flooding, as was the case with the ‘*Ianos*’ storm that hit western Greece in September 2020 (Smart, 2020). Projections suggest that these extreme events may become less frequent in the future, but the intensity of the most energetic events may increase (Romera et al., 2017).

Coastal Zone Hazards and Impacts

In this section, some of the major coastal hazards/impacts that can increase risks for the Greek coastal zone are considered. This assessment is not exhaustive in terms of the many potential coastal hazards and impacts as it focuses mainly on those related to *CV&C*, particularly the mean sea level rise and extreme sea levels that can force coastal erosion and flooding.

Coastal Flooding and Erosion

Hazards

Observations of coastal change can provide estimates of the present threat of coastal flooding and erosion. High-resolution satellite and/or other airborne imaging and detailed Digital Elevation Models (*DEMs*) are required for accurate estimates at national/regional scales (UNFCCC, 2020), whereas other technologies can be utilized in smaller (local) scale studies, such as airborne *LiDAR* and/or *UAV* optical photogrammetric surveys, ground topographic surveys and/or continuous, high-frequency optical monitoring from ground video stations (e.g., Velegrakis et al., 2016; Hasiotis et al., 2017). Projections of future coastal change require estimates of the forcing hazards, such as the mean sea level rise and extreme sea levels and waves over different time periods and climatic scenarios.

The mean sea level rise along the Greek coast has been assessed using the Hinkel et al. (2014) projections for different climatic (*RCP4.5* and *RCP8.5*) and ice mass (ice-melt) change scenarios (low, medium, and high, see also Vousdoukas et al., 2017). *SLR* projections were combined

with projections of the land vertical movements (Peltier, 2004) to assess future relative sea level rise (*RSLR*) along the Greek coastline (Fig. 21.2). By 2050, the (slow-onset) *RSLR* along the Greek coastline has been projected as 0.18–0.23 m and 0.27–0.35 m under the *RCP4.5* and medium ice-melt scenario and *RCP8.5* and high ice-melt scenario, respec-

tively. *RSLR* is projected to accelerate in the later part of the century. By 2100 and under *RCP4.5*, it is projected to range along the Greek coast between 0.49 and 0.57 m and 0.68 and 0.78 m under the medium and high ice-melt scenarios, respectively. Under *RCP8.5*, even higher *RSLR*s are projected, i.e., 0.76–0.83 m and 1.04–1.16 m under the medium

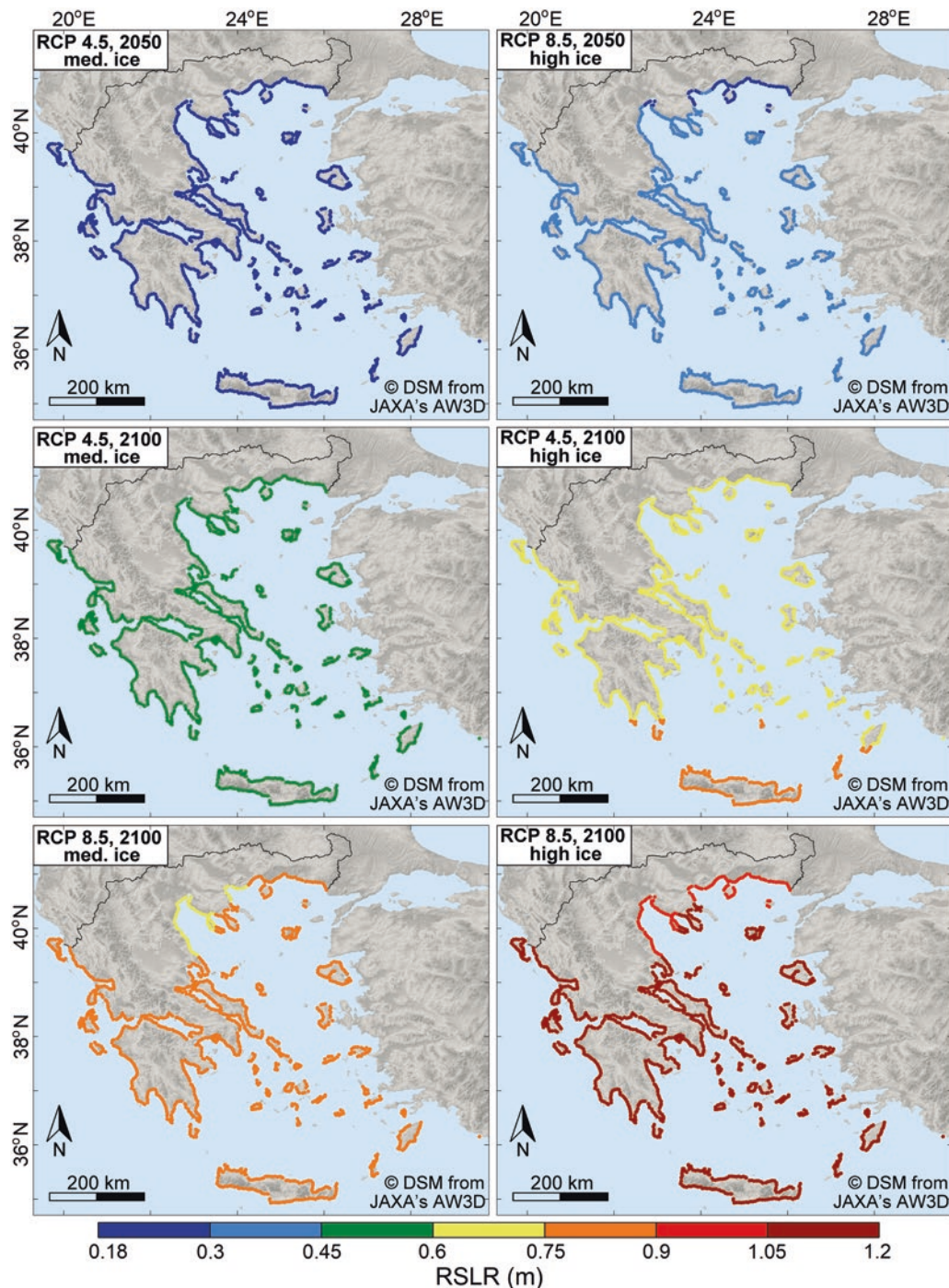


Fig. 21.2 Projections of the relative sea level rise (RSLR) along the Greek coastline in 2050 and 2100 under RCP4.5 and RCP8.5 and different ice-melt scenarios

Projections are relative to the mean of the 1986–2005 period. Original data from <https://www.pnas.org/content/113/47/13342>

and high ice-melt scenarios, respectively. Higher increases are projected for the South Aegean islands and Crete (Fig. 21.2). It should be noted, however, that local conditions, such as accelerated land subsidence, e.g., in the deltaic coasts, could modify the above projections upwards.

Extreme sea levels (*ESLs*) integrate the mean sea level, the astronomical tide, and the episodic coastal sea level rise due to storm surges and wave set-ups (Vousdoukas et al., 2018). *RSLR* projections (Hinkel et al. (2014) were combined with potential changes in tidal elevations due to sea level changes from their baseline (1995) values that were assessed on the basis of the TOPEX/POSEIDON Global Inverse Solution (Egbert & Erofeeva, 2002). Storm surge levels and waves (offshore significant wave heights (H_s), periods (T), and directions) were hindcasted for the period 1980–2014 through Delft3D-FLOW and WAVEWATCH III model simulations, respectively, and forced by ERA-INTERIM atmospheric conditions (Vousdoukas et al., 2017). Future storm surges and waves were projected using the same models and forced by a six-member GCM ensemble from the CMIP5 database (Vousdoukas et al., 2018). Finally, wave set-ups were estimated using a generic approximation ($0.2 \times$ the offshore H_s , CEM (2002)). Non-stationary extreme value analysis was used to obtain extreme values for the return periods of extreme events, such as the 1 in a 100-year event – ESL_{100} , a crucial design parameter for coastal infrastructure and protection schemes, and the *ESL* components and their uncertainties were combined in a probabilistic fashion through Monte Carlo simulations (Vousdoukas et al., 2018).

Following this approach, the ESL_{100} for 2050 and 2100 were projected along the Greek coastline (spatial resolution of about 25 km), with representative results shown in Fig. 21.3. Results show that the baseline ESL_{100} (mean of the period 1980–2014) varies along the Greek coastline, with the highest values found along the northern Aegean coast (up to 1.75 m above the mean sea level) and in the semi-enclosed Amvrakikos Gulf (up to 2.06 m). By 2050, ESL_{100} will increase by 0.12–0.65 m under the studied scenarios, with pronounced increases projected for some Aegean and Ionian coasts (Fig. 21.3). By 2100, ESL_{100} increases will be substantial, reaching up to 1.25 m above the baseline values under the high-end scenario (RCP8.5 and high ice-melt scenario).

Impacts

The assessment of the impacts of the increasing slow- and sudden-onset coastal hazards requires geospatial information (detailed DEMs and coastal ecosystem distribution) together with projections on future socio-economic trends (UNFCCC, 2020), which are not generally available with the necessary accuracy and resolution. Nevertheless, coastal erosion/flooding is likely to be severe under the projected hazards for both low-lying coasts (e.g., beaches and deltas) and critical coastal infrastructure, assets, and activities.

Concerning the assessment of coastal erosion, approaches depend on the scale and resolution of the application, the coastal type (i.e., ‘sandy’ or ‘cliffed’ coasts), the availability of topographic and hydrodynamic information and the hazard, i.e., slow-onset coastal erosion/drowning due to *RSLR* or rapid episodic retreat/inundation due to extreme events (Fig. 21.4).

The Greek geotectonic setting has resulted in a complex coastal physiography. A large portion of the coastline forms on cliffs consisting of ‘solid’ geological formations. Low-elevation coasts are mostly in the form of ‘pocket’ beaches, with the linear and deltaic beaches having small extents: beaches in Greece have an overall length of about 2700 km, cover an area of about 52 km² and are commonly backed by coastal infrastructure and assets, whereas deltaic coasts have an overall length of about 215 km and are usually backed by transitional coastal ecosystems and/or agricultural land (Alexandrakis et al., 2013; Karditsa et al., 2015).

To estimate the potential erosion of the most vulnerable sections of the Greek coastline, i.e., the beaches, the approach proposed by Monioudi et al. (2017) was followed. The approach involves two suites of cross-shore (1-D) morphodynamic models to assess potential ranges of erosion under *CV&C*: (a) a ‘long-term’ ensemble used to assess beach retreat/erosion due to *RSLR* that consists of 3 analytical models (Edelman, 1972; Bruun, 1988; Dean, 1991); and (b) a ‘short-term’ ensemble used to estimate the retreat caused by episodic sea level rise which includes four numerical models: SBEACH (Larson & Kraus, 1989), Leont’yev (1996), Xbeach (Roelvink et al., 2010), and a model that utilizes high-order Boussinesq equations for the hydrodynamic component (Karambas & Koutitas, 2002). Further details on these models and their comparison with experimental data can be found in Monioudi et al. (2017).

Due to the large scale and type of the application, model inputs were not based on in situ observations. Instead, the models were set up and forced using a range of plausible environmental conditions (bed slopes, sediment sizes, and wave forcing), resulting in a range of beach retreat projections, from which ‘low’ and ‘high’ ensemble estimates (the best fits of the lowest and highest projections) were calculated; these represent the most conservative and the most impacting projections for beach retreat/erosion, respectively. For the projection of the ESL_{100} impacts, model results were combined consecutively and under the premise that in these events, wave forcing is maximum. Finally, comparisons of the projections with the recorded beach maximum widths (*BMWs*) of Greek beaches (Karditsa et al., 2015; Monioudi et al., 2017), provided assessments of the minimum and maximum beach retreat/erosion for different date years and scenarios.

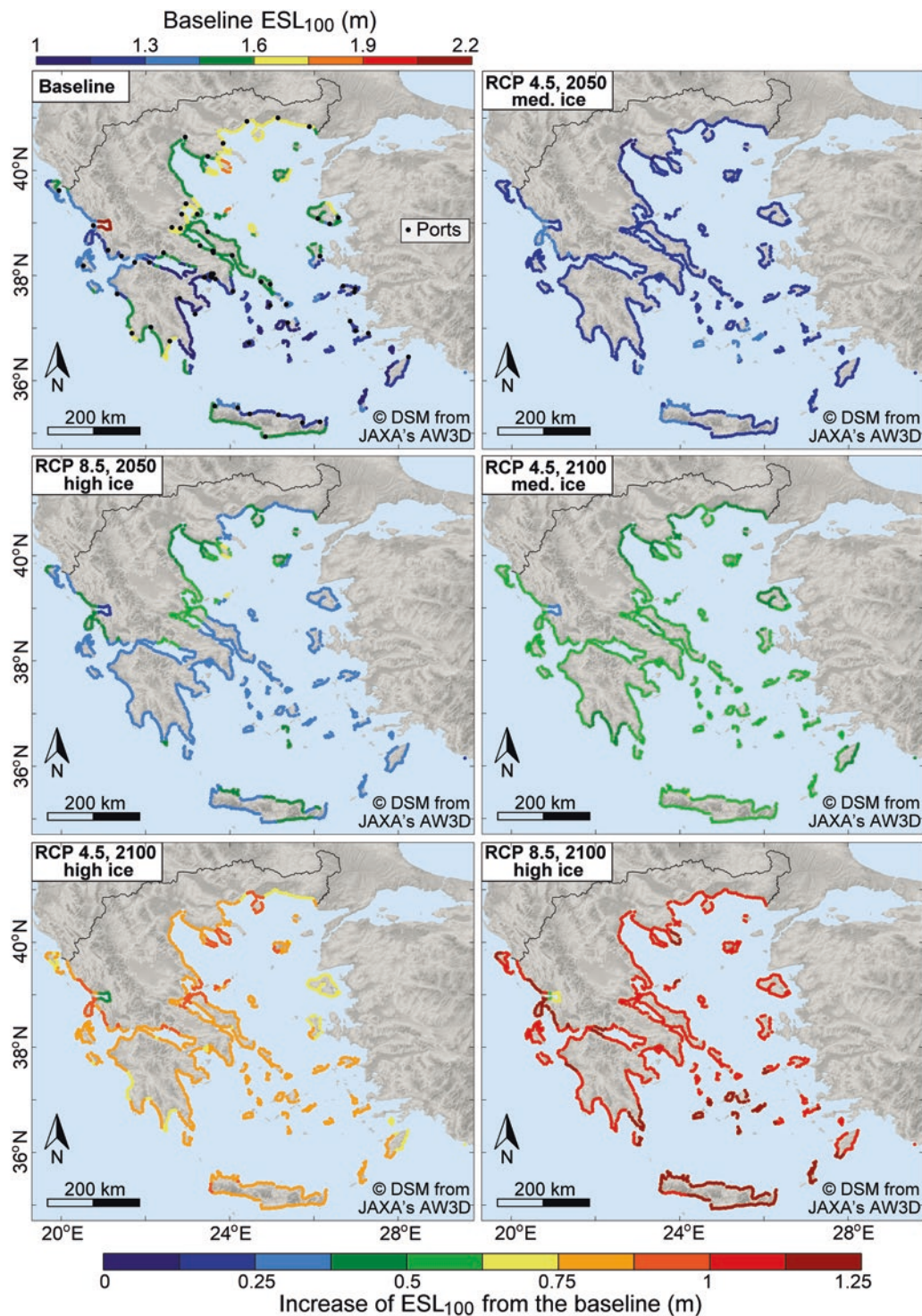


Fig. 21.3 Baseline (1980–2014) ESLs₁₀₀ (1 in 100-year events) and their projections along the Greek coastline for 2050 and 2100 under the RCPs 4.5 and 8.5 and different ice-melt scenarios

The location of the major (64) seaports is also shown (see also Fig. 21.1). Original data from <https://data.jrc.ec.europa.eu/collection/liscoast/datasets>

Results show that by 2050, the *RSLR* will force irreversible retreats between 3.5 and 15 m, depending on the beach bed slope, sediment size, and wave forcing. However, due to the mostly small *BMW*s of the Greek beaches, at least 10%

of all beaches will permanently retreat by 50% of their recorded *BMW*s in the best-case scenario, i.e., according to the most conservative projections (see above) and under the RCP4.5 and medium ice-melt scenario. By 2100, much more

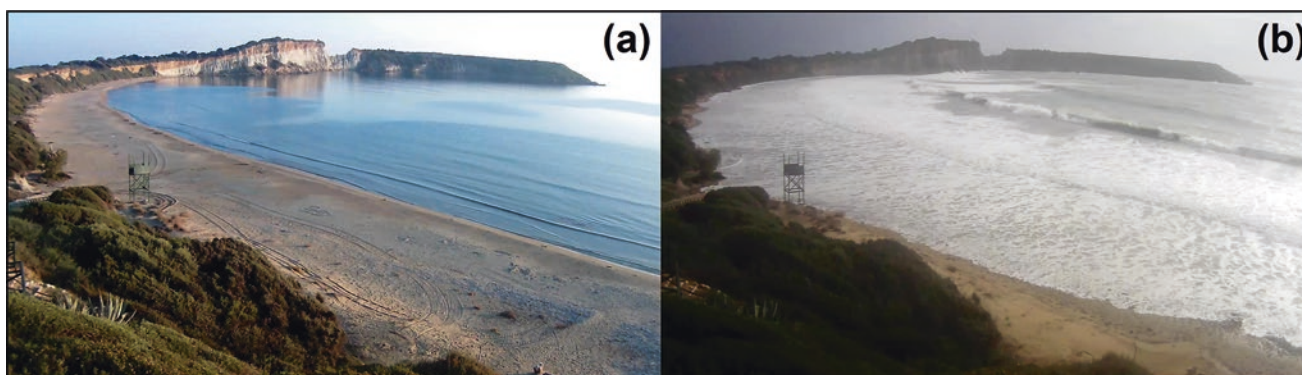


Fig. 21.4 Retreat/inundation of Gerakas beach (Zakynthos, Fig. 21.1) under a moderate storm event: (a) before the storm (3 November 2014); (b) during the storm (8 November 2014). Gerakas beach forms part of a NATURA 2000 site, being a very significant *Caretta caretta* nesting site in Greece (National Marine Park of

Zakynthos); thus, its erosion/inundation (and consequent decrease in its nest carrying capacity) can have very adverse environmental implications.

severe impacts are projected. Under the *RCP4.5* and medium ice-melt scenario, at least 10% (most conservative estimations) and up to 67% (most impacting estimations) of all Greek beaches will retreat by distance equal to or greater than their present *BMW*s, whereas under the *RCP8.5* and high ice-melt scenarios, at least 40% (and up to 89%) of Greek beaches will retreat by a distance at least equal to their current *BMW*s. In the absence of inland accommodation space for beach rollover and/or effective coastal protection (Vousdoukas et al., 2020), the projections indicate severe impacts on the coastal natural and human environment, particularly in 3S tourism destinations, important ecologically coasts and areas with increased density of backshore infrastructure and assets.

With regard to extreme storm events, our projections indicate that the $ESLs_{100}$ in 2050 will result in storm-induced shoreline retreats of between 17 and 59 m, under the most conservative and most impacting projections and under the *RCP4.5* and *RCP8.5* scenarios, respectively. Even in the best-case scenario (*RCP4.5* and medium ice-melt scenarios), the $ESLs_{100}$ will induce (temporarily) total erosion/flooding of at least 56% of all Greek beaches (42% of beaches fronting assets). In 2100, impacts will be worse. Even under the *RCP4.5* and medium ice-melt scenarios, at least 64% of all Greek beaches will be completely eroded (49% of beaches fronting assets), at least temporarily. Impacts are projected to be extremely severe under the *RCP8.5* and high ice-melt scenario, as at least 76% of all Greek beaches (57% of beaches fronting assets) will be overwhelmed. These projections suggest that, even if the beaches might eventually recover, there will be devastating flood damages/losses for their backshore ecosystems, infrastructure, and assets.

In addition to the impacts that Greek beaches (and their backshore ecosystems, infrastructure, and assets) are projected to face, there will also be very substantial effects on

the critical infrastructure at the coastline, such as seaports. Seaports, which are vital socio-economic links in Greece, will be affected by various climatic hazards, including the *RSLR* and extreme events as well as extreme heat, precipitation, and winds (UNCTAD, 2020). Regarding the flood hazard under extreme events, this will increase with time and the severity of the climatic scenario, as $ESLs_{100}$ is projected to almost double in some areas, for example, in Crete (Fig. 21.3). These projections are in broad agreement with those of Christodoulou and Demirel (2018), who suggested that by the end of the century, 169 Greek seaports of all sizes (and 64% of all EU seaports) will be flooded during extreme storms.

Other Coastal Hazards and Impacts

In addition to coastal flooding forced by *RSLR* and extreme storm events, the Greek coastal zone will face a plethora of other hazards that may induce very significant impacts, including those from changes in the riverine water and sediment fluxes to the coast, precipitation, extreme temperatures, wildfires and last, but not least, potential earthquakes and tsunamis.

Regarding the riverine flooding and the water and sediment fluxes to the coast, these are controlled by climate, lithology, land use, fluvial morphodynamics, and the presence of river management schemes. Generally, there are already decreasing water and sediment fluxes to the Greek coast due to decreasing precipitation (UNECE, 2020) and the construction of many dams/reservoirs that, by trapping sediments, induce morphological changes to their downstream riverbeds and coasts, particularly when coupled with natural and/or anthropogenic subsidence in low-elevation coasts (Poulos & Collins, 2002; Besset et al., 2019).

The Greek deltaic coasts have changed significantly over the past decades. Although there are some examples of delta progradation (e.g., Karymbalis et al., 2017), most Greek deltaic coasts are under retreat. In the Nestos delta (Fig. 21.1), upstream dams have caused significant downstream changes and ecological deterioration (Sylaios & Kamidis, 2018). In the Axios and Aliakmon rivers, water and sediment discharges have decreased by approximately 51% and 90% and 39% and 76%, respectively, impacting river lowlands and coasts and inducing land subsidence and coastal erosion, as well as occasional nearshore eutrophication (Dimitriou et al., 2018). In the Strymonas River, flow has become a trickle due to high irrigation demands, and a salt wedge has been reported in the lower river channel intruding up to 4.6 km upstream, with a retention time of 10–20 days (Zachopoulos et al., 2020). The Evros deltaic plain (Fig. 21.1) has also been impacted by the construction of more than 25 upstream dams that have caused an 80% reduction in suspended load over the period 1945–2017, as well as by the transformation of about 40% of its deltaic plain to agricultural land; these changes have forced significant morphological changes at the river mouth (Karditsa et al., 2020). In addition, increasing nutrient fluxes from agricultural soil washouts, sewage effluents, and marine aquaculture have resulted in coastal water eutrophication and harmful blooms, as is the case, e.g., in the Kalloni (Arhonditsis et al., 2002) and Maliakos (Varkitzi et al., 2018) Gulfs. Herbicides, biocides, corrosion inhibitors, artificial sweeteners, pharmaceutically active compounds (PhACs), and endocrine disrupting chemicals (EDCs) also enter the coastal waters (Nödler et al., 2016), but their fate and related health and environmental risks are not yet well assessed.

Climate change may further decrease river and sediment flows. Decreases in precipitation and increases in dry periods are projected for Greece under CV&C. Sustained annual precipitation (over a 5-day period) and the number of days with precipitation exceeding 20 mm will decrease under all climatic scenarios, whereas the number of consecutive dry days will increase (e.g., UNECE, 2020). In the Arachthos River (Fig. 21.1), the dry period duration could be doubled, forcing streamflow reduction and stress and degradation of the river and coastal ecosystems (López-Ballesteros et al., 2020). For the Evrotas River (Fig. 21.1), hydrological simulations under different CV&C scenarios showed that the already low river flows would become much lower (Querner et al., 2016), potentially exacerbating the impacts from aquifer overexploitation that are observed in many coastal areas (Kazakis et al., 2016). In the Tsiknias River (Lesvos, Fig. 21.1), a general upward trend of actual evapotranspiration losses in the Kalloni Basin and an extension in the ‘pools’ and ‘drying stream bed’ have been predicted for the winter months of its aquatic states, which can have severe ecological implications (Koutsovili et al., 2021).

In addition to the rise in mean temperatures, Greece is also projected to face increases in extreme temperatures. Warm spell duration will increase, together with the number of hot days (temperatures >30 °C) that are projected to reach up to about 60 days annually in the period 2051–2080 under RCP8.5 (UNECE, 2020). These climatic conditions will, among others, have significant implications for wildfires (Diakakis et al., 2016). Wildfires can be devastating for coastal ecosystems, communities, and assets (Kalabokidis et al., 2016; Lagouvardos et al., 2019), as the extremely destructive wildfires of August 2021 have shown.

Extreme temperature increases will also create significant challenges for critical coastal infrastructure in Greece. For example, seaport operations (and possibly the infrastructure itself) could be seriously impacted due to increasing health and safety concerns and energy needs (and costs) for cooling (Monioudi et al., 2018). Our assessment of future extreme heat waves under CV&C for 64 major Greek seaports indicates that the 1 in a 100-year heat wave event will increase in both magnitude and frequency. Heat waves having the magnitude of the baseline 1 in a 100-year heat wave (the mean of the 1976–2005 period) are projected to occur on average every 8.5 years (range 1–35.9 years) under a mean temperature increase of 1.5 °C above the pre-industrial times (Special Warming Level – SWL of 1.5 °C, expected to be reached by the 2030s, see IPCC (2018)); every 3.6 years (range 1–35.9 years) under a SWL of 2 °C (expected by the 2050s), and every 1.6 years (range 1–35.9 years) under a SWL of 3 °C (expected in the beginning of the next century) (Fig. 21.5). Such increases will also have significant impacts on other coastal infrastructure and socio-economic activities, including, e.g., coastal airports, roads, and railways (UNECE, 2020), the urban environment, and the sustainability of the Greek 3S tourism (e.g., Mazarakis et al., 2014).

The Greek coastal zone also faces large geophysical hazards, as it is located within a major seismic zone that has produced powerful earthquakes since antiquity (e.g., Papazachos & Papazachou, 1997). The earthquake hazard is high everywhere in terms of the most common earthquake magnitude scales (Burton et al., 2004), with many coasts of the Ionian, northern Peloponnese, and northern and southern Aegean islands facing a very high seismic hazard on the basis of the peak ground acceleration (<http://www.share-eu.org>). Due to the nature of the hazard, future projections are based mostly on extrapolating approaches of previous events, and mitigation efforts have focused on risk retention through increased built environment resilience (e.g., Sarris et al., 2010).

In addition to the seismic activity, the Greek coastal zone faces a tsunami hazard considered among the highest in the eastern Mediterranean (Papadopoulos et al., 2010). Earthquakes and submarine landslides are the principal tsunamigenic mechanisms, although volcanic eruptions/collapses, such as that of the Late Minoan Santorini eruption,

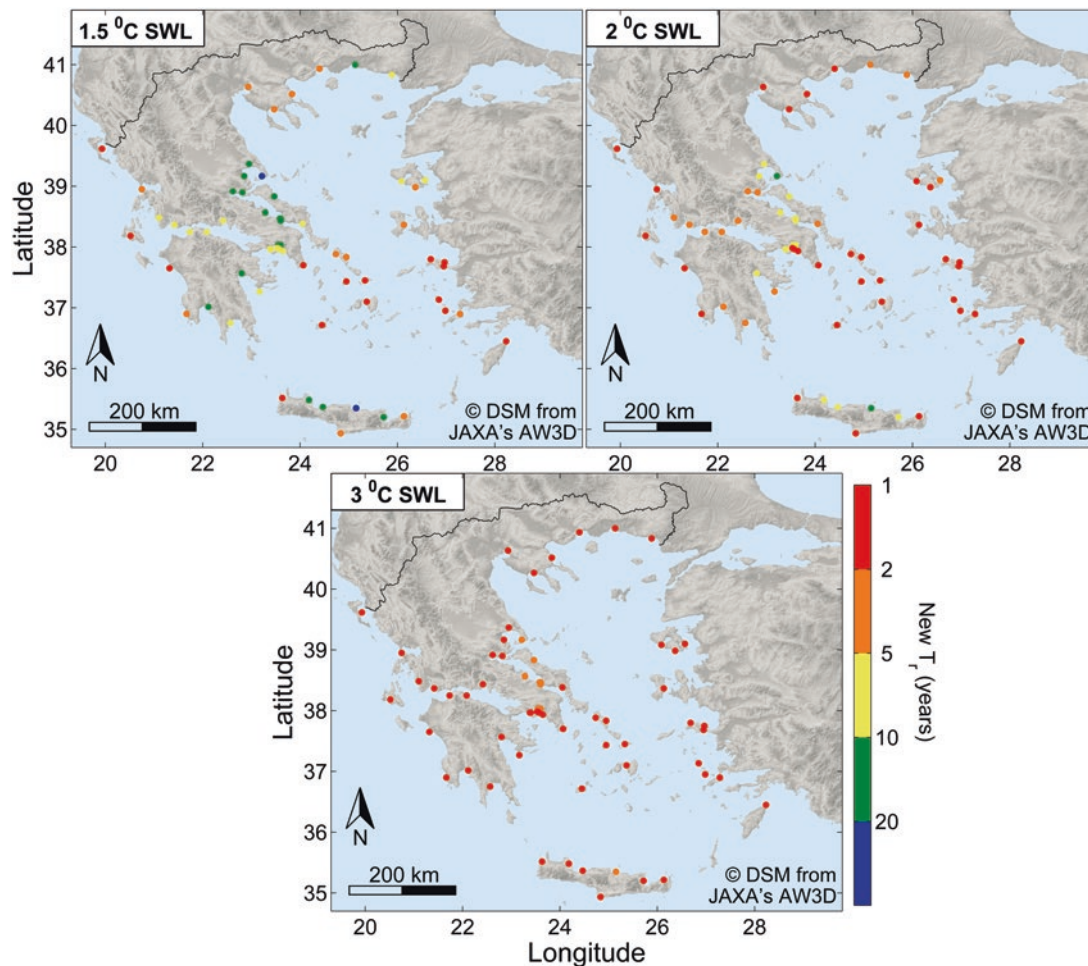


Fig. 21.5 Change in the return periods of the baseline (1976–2005) 1 in a 100-year extreme heat event at 64 Greek ports. (Data for coastal areas from Dosio et al. (2018))

have also produced catastrophic tsunamis. There is a widespread perception that large tsunamis do not present a high hazard for the Greek coast (Papadopoulos et al., 2014), although analysis of historical records as well as numerous studies have brought to light sedimentological, geomorphological, and geo-archeological footprints of past tsunamis in many coastal areas (Fischer et al., 2016; Werner et al., 2017; Obrocki et al., 2020). Karambas and Hasiotis (2012) simulated landslide-induced tsunami generation and propagation in the Aegean Sea and found that the complicated geomorphology, abrupt bathymetric changes, and intriguing island patterns can cause rotation of tsunami waves and extreme water elevations in many coastal settings. It is noteworthy that while tsunami waves have a short duration, their footprint in the coastal landscape and the damages and losses they incur can be significantly higher than those inflicted by energetic storms. Therefore, strong crisis management policies and actions are required, particularly as the near-field (local) tsunami generation in the area does not allow for effective Early Warning Systems (Heidarzadeh et al., 2017).

Discussion and Concluding Remarks

The results show that the Greek coastal zone faces large threats from a variety of hazards, some of which are projected to be exacerbated by *CV&C*. Slow-onset *RSLR* and extreme storm events will have very substantial and increasing impacts on the Greek beaches and coastal infrastructure, assets and activities. Under the slow-onset *RSLR*, there will be very significant effects on beach widths and, therefore, on the beach carrying capacity for 3S tourism from (at least) the 2050s. Impacts will further escalate by the end of the century, when at least 40% (and up to 89%) of all Greek beaches will retreat by a distance at least equal to their current *BMW*s under the *RCP8.5* and high ice-melt scenario.

In the absence of adequate inland accommodation space for beaches to rollover and/or effective coastal protection schemes, the *RSLR* will potentially have devastating effects on coastal natural and human systems. Tourism, for example, will be particularly affected by the projected large decreases in dry beach width, a critical control of the beach resilience

and recreational carrying capacity; this may affect considerably the future hedonic value of the Greek beaches and the value of associated assets (e.g., Gopalakrishnan et al., 2011). Future extreme events will further exacerbate these impacts, with very severe flood damages and losses projected for the backshore ecosystems, infrastructure and assets, even if the fronting beaches eventually recover.

Critical infrastructure located along the coastal front, such as seaports, will face significant challenges. Our findings indicate a high and growing potential for climatic changes to cause both flooding during extreme events and operational disruptions due to the increasing frequency and magnitude of heat waves. It should also be noted that these projections do not consider the possible deterioration of Medicanes. Given these findings, it is critical to undertake detailed risk assessments and develop management plans that will prioritize resilience and adaptation. Such measures are urgently needed because of the significant implications for disaster risk reduction, property values, future tourism revenues, insurance costs, transport accessibility, and international and national trade.

It should be noted that the above coastal retreat/flooding projections are subject to uncertainties. First, projections of coastal morphological change involving different spatiotemporal scales can have interdependencies that constrain their accuracy (Ranasinghe, 2016); for instance, coastal response to extreme events will likely be different in, e.g., 2050 when the coastal topography might have adjusted as a result of the then mean sea level and/or the many preceding extreme storm events. Secondly, the projections do not account for other potential coastal erosion factors, including: the diminishing coastal sediment supply due to (increasing) upstream river management schemes (e.g., Velegrakis et al., 2008; Kontogeorgos et al., 2017); the hazardous impact of the future riverine flash flood events projected to increase (Nabih et al., 2021), the presence and/or future evolution of natural coastal ecosystems, such as the nearshore *Posidonia* fields and/or beachrock outcrops (Vousdoukas et al., 2012); and coastal protection schemes that may affect the response to *RSLR* and extreme events (Vousdoukas et al., 2020). Thirdly, these projections do not consider impacts of compound flooding from the combination of extreme marine and fluvial/pluvial flooding (UNFCCC, 2020). Finally, coastal impacts will also depend on future socio-economic development, which might also change over time.

Main coastal hazards and impacts affecting the Greek coastal zone have been presented above. However, in order to assess the coastal zone risk, relevant information on all risk determinants is required (IPCC, 2014). In addition to current and future coastal hazards, coastal risk also depends on: the current and future exposure of natural and human coastal systems present in the hazard zones and, thereby, subject to potential damages and losses (e.g., O'Neill et al.,

2017); and the vulnerability of coastal ecosystems, communities, assets, and activities that make them susceptible to damages/losses and is controlled by physical factors and resources, the available human and economic resources as well as policies, regulation, and management. However, information on all risk determinants is not easy to collate and project, particularly at local scales (UNFCCC, 2020).

To reduce (and adapt to) coastal risks, reduction of vulnerability is key. Coastal zone vulnerability depends on many factors, including policies and regulation that can reduce exposure, such as the allocation of 'setback' and 'no-build' zones at the coastline and coastal flood plains, the planning/implementation of appropriate coastal protection and management schemes as well as regulation to protect and reverse degradation of ecosystems that provide natural protection to coasts.

CV&C adaptation and resilience-building for coastal areas and their populations, infrastructure, assets, and services is a matter of strategic importance and increasing urgency (Lenton et al., 2019). This has been recognized by the international community, and in recent years, there have been some noteworthy developments relevant to the adaptation of the Greek coastal zone to *CV&C*. These include, among others, the 2019 declaration of the European Parliament of a climate and environment emergency (European Parliament, 2019); the 2019 UN Climate Action Summit (<https://www.un.org/en/climatechange/un-climate-summit-2019.shtml>); and the 2021 EU Climate Change Adaptation Strategy, which envisions 'that in 2050, the EU will be a climate-resilient society, fully adapted to the unavoidable impacts of climate change' and aims to realize this vision 'by making adaptation smarter, more systemic, swifter, and by stepping up international action' (European Commission, 2021). Also relevant is the Regional Climate Change Adaptation Framework for the Mediterranean Marine and Coastal Area, 2016, endorsed by the 19th Meeting of the Contracting Parties to the 1995 Barcelona Convention (Decision IG.22/6) (UNEP-MAP, 2016), as well as development strategies for the European and Greek coastal zones that promote the sustainability of coastal ecosystem services, such as the 2014 EC Communication 'A European Strategy for more Growth and Jobs in Coastal and Maritime Tourism' and other relevant 'Blue Growth' policies.¹

For policies to be effective in addressing the challenges posed by climate change in the Greek coastal zone, it is crucial for these to be supported by robust legal/regulatory frameworks. Such frameworks can facilitate proactive initiatives aimed at strengthening coastal adaptation and disaster resilience, incentivize funding for climate change adaptation

¹See <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0086> and https://ec.europa.eu/growth/sectors/tourism/offer/maritime-coastal_nn.

efforts, facilitate the transfer of adaptation technologies, and increase the availability of climate data at the local level. Furthermore, legal and regulatory instruments can enhance accountability and public participation in adaptation-related decision-making processes and promote better investment decisions (UNCTAD, 2020).

There are various international conventions to which Greece is a State Party that may be of relevance for the management of CV&C risks and adaptation and resilience-building in its coastal zone. The 1992 UN Framework Convention on Climate Change (UNFCCC) and the 2015 Paris Agreement specifically address the need for adaptation to climate change and call for the preparation of National Adaptation Plans. Additionally, several international legal instruments deal with various environmental aspects that could affect adaptation to climate variability and change (CV&C) in coastal areas. These include the Conventions on:² Biodiversity (1992), Environmental Impact Assessment (1991 Espoo), Wetlands (1971 Ramsar), Access to Information and Public Participation in decision-making (1998 Aarhus), as well as Regional Agreements for protecting marine and coastal environments, such as the Barcelona Convention (1995) and its Protocols.

Of particular significance is the 2008 Integrated Coastal Zone Management (ICZM) Protocol, which, inter alia, envisages allocation of a 100 m setback zone inshore of the highest storm wave reach (runup) projected under CV&C where no future development is allowed (Art. 8.2). However, Greece is among the few EU Mediterranean countries that have not yet ratified the ICZM Protocol, although it has also been ratified by the EU (Council Decision 2010/631/EU).

In addition, there are various European legal instruments, which specifically address coastal zone risks and prescribe actions that mitigate such risks and facilitate resilience and adaptation to CV&C. These include the Water Framework Directive (2000/60/EC), the Flood Risk Directive (2007/60 EC), and the Marine Spatial Planning Directive (2014/89/EU), as well as the amended Environmental Impact Assessment (EIA) Directive (2014/52/EU), which explicitly requires consideration of climate change impacts as part of the assessment process for large infrastructure projects, including in coastal zones. Effective implementation of these international and European legal instruments at the national level will be critical for the effective management of the coastal risks in Greece under a changing climate. Of particular significance is the implementation of the Flood Risk Directive (2007/60/EC); the first phase of its implementation that deals with the current flood risk has been concluded, and now Greece is in the second phase of its implementation that

requires flood risk assessment and management under climate change (<https://floods.ypeka.gr>).

At the EU level, of particular importance is also the very recent adoption, in July 2021, of a new EU Climate Law,³ which was initiated by the European Commission (European Commission, 2020). The legislation sets out a binding objective of climate neutrality in the Union by 2050 and a binding target of reducing net domestic Greenhouse Gas (GHG) emissions by at least 55% compared to 1990 levels by 2030. In addition, the new EU Climate Law envisages strong action on climate change adaptation and resilience-building, including ‘continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in accordance with Article 7 of the Paris Agreement’ and related stocktaking starting in 2023. The Regulation, which entered into force on 29 July 2021, and is directly applicable and effective in all EU Member States from this date, will have clear and important benefits for efforts at climate-resilience-building and adaptation in the coastal zone. At the same time, there could be potential effects for Greek coastal tourism, as a result of accelerated mitigation efforts in accordance with the new law.

It should be noted, however, that while regulation may have a crucial role in minimizing exposure or vulnerability to coastal risks in the Greek coastal zone, it is important that any implemented measures should not lead to unintentional ‘maladaptation’ that could restrict or hinder future adaptation options. The uncertainty surrounding climate change projections, along with the long-term nature of investment decisions and infrastructure planning, construction, and operation, may present specific difficulties. Therefore, adaptation frameworks for the Greek coastal zone should allow for adaptable and flexible responses, as well as consider potential irreversible changes.

It is essential to incorporate sustainability considerations and risk assessment into coastal management frameworks, policies, and regulation in the Greek coastal zone. The development of appropriate integrated coastal zone management (ICZM) plans and the modernization of administrative procedures regulating the planning and implementation of technical measures should be prioritized to address the projected coastal erosion and flooding. The preservation of the ‘natural heritage’ of coastal ecosystems is also crucial, and the effects of coastal erosion on the integrity of backshore ecosystems should be taken into account (e.g., Biel et al., 2017).

²For further details of the relevant International and European legislation see UNCTAD (2020).

³Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’), <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119&from=EN>.

Management of the socio-economic effects of the CV&C impacts on the Greek coastal zone should also be considered as a matter of priority. Development plans should include assessments of the potential costs and benefits of coastal protection schemes and other adaptation options (e.g., Narayan et al., 2016), including the allocation of 'setback' zones for the future development of the Greek coastal zone; in this context, a major step toward resilience will be the ratification and effective implementation of the 2008 ICZM Protocol to the 1995 Barcelona Convention.

To effectively manage the risks of coastal flooding and erosion in the Greek coastal zone, it will be necessary to implement robust monitoring programs and well-planned and potentially costly beach restoration and protection schemes. As coastal erosion/retreat will be driven by the RSLR and extreme events, replenishment schemes that raise coastal assets and extend beaches seaward may be required (e.g., Asariotis, 2020). Beach nourishment schemes will also be necessary, particularly for economically important beaches (Andreadis et al., 2021), due to the critical role beaches play in the local economy and the low effectiveness of hard coastal works such as breakwaters in protecting beaches from the RSLR. Therefore, it is important to carefully consider the availability and accessibility of appropriate sedimentary material for coastal fill and beach nourishment, with marine aggregates being a particularly suitable option (e.g., Hasiotis et al., 2020). The sustainability of suitable marine aggregate deposits should be ensured, and their protection and management should be considered a priority in future Greek marine spatial planning, in accordance with EU Directive 2014/89/EU.

In some cases, where effective coastal fill and replenishment schemes may prove to be environmentally unsound and/or prohibitively expensive, significant (or, even, total) beach loss may become inevitable, with potentially important socio-economic consequences.

It should be noted that although this study has focused mainly on coastal flooding and erosion, there could be other significant CV&C effects that might constrain the sustainable development of the Greek coastal zone, such as future freshwater shortages, particularly in the large number of Greek islands (e.g., Ault, 2016); declining desirability of the touristic destination due to unfavorable bioclimatic changes (Mazarakis et al., 2014); deterioration of the coastal zone ecological status (e.g., De la Hoz et al., 2018); and related consequences for human welfare and health (e.g., Mora et al., 2017). Therefore, sustainable development of the Greek coastal zone will also require coordinated and coherent efforts to maintain a good environmental status, improve the water quality and optimize natural resource utilization. This will require several measures, including the implementation of stricter domestic wastewater treatment, upgrading of coastal infrastructure and assets

using environmentally friendly technologies, the rational use of fertilizers, pesticides and herbicides in coastal agricultural land, and removal of litter from the nearshore seabed.

In conclusion, this overview has shown that the Greek coastal zone faces a plethora of hazards that can have significant (and even devastating) impacts, some of which are projected to increase under the climate variability and change. Coastal retreat/erosion is particularly worrying, as it is going to affect both natural and human coastal systems with increasing severity in the course of the century. Science-based assessments of coastal retreat/erosion and flooding are essential for effective coastal management and the smooth implementation of adaptation plans, as well as the allocation of resources for adaptation to be prioritized. These assessments should be accessible to planners, managers, stakeholders, and the wider public.

Acknowledgments AV, IM, OT, ET, TH and OA gratefully acknowledge support received under the project 'Coastal Environment Observatory and Risk Management in Island Regions AEGIS+' (Contract Number: MIS 5047038) under the operational programme 'Competitiveness, Entrepreneurship and Innovation 2014-2020', funded by the European Fund of Regional Development through the National Strategic Reference Framework 2014-2020 (NSRF).

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