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The vulnerability of Mediterranean coastal areas in response to sea level dynamics: a short review of causes, effects and open questions

Abstract: Mastronuzzi G., Scicchitano G., *The vulnerability of Mediterranean coastal areas in response to sea level dynamics: a short review of causes, effects and open questions.* (IT ISSN 0391-9838, 2026). The world's coastal area is now directly affected by global warming. A significant portion of the world's population lives in the Mediterranean basin and exerts strong direct human pressure on coastal areas and river basins. River management plans, residential and industrial structures, and coastal protection projects result in the loss of a large portion of the sediments that rivers deliver to the sea, together with the continued and extensive use of coastal areas. This results in a negative sediment budget and reduced resilience of mobile coastal systems. Moreover, the rise in eustatic sea level resulting from glacier melt threatens coastal areas characterized by low rocky coasts and coastal plains. Negative vertical land movements amplify this effect in the low-lying areas with a significant regional and local contribution, often linked to human activities. Sea warming and the release of thermal energy generate intense marine meteorological phenomena known as "medicanes", whose impact on the coastal zone leads to frequent flooding. The possible tsunami impacts could not be counteracted by the coastal landscape which is in evident and continuous degradation. The combination of sea level rise, paroxysmal weather processes and human activity amplifies erosional processes and reduces the ability of coastal systems to adapt to new conditions; this increases the vulnerability of coastal plains, inducing more and more real risk situations.

Key words: Climatic change, Sea level changes, Extreme marine events, Coastal dynamics, Coastal vulnerability.

Riassunto: Mastronuzzi G., Scicchitano G., *La vulnerabilità delle aree costiere mediterranee in risposta alla dinamica del livello del mare: una breve rassegna di cause, effetti e questioni aperte.* (IT ISSN 0391-9838, 2026). L'intera area costiera del pianeta è direttamente interessata dagli effetti del riscaldamento globale. Una parte significativa della popolazione mondiale vive nel bacino del Mediterraneo ed esercita una profonda pressione diretta sui bacini fluviali e sulla costa ad essi sottesa. I piani di gestione fluviale, le strutture residenziali e industriali presenti lungo la fascia costiera e gli interventi di protezione costiera insieme alla continua ed estensiva occupazione delle aree costiere determinano la sottrazione dei sedimenti che i fiumi rilasciano in mare alla naturale dinamica litorale. Ciò comporta un bilancio sedimentario negativo e una ridotta resilienza dei sistemi mobili costieri. L'innalzamento del livello del mare dovuto allo scioglimento dei ghiacciai minaccia di sommergere le piane costiere e le coste basse e rocciose. I movimenti di abbassamento della superficie topografica amplificano questo effetto con un significativo contributo regionale e locale, spesso legato alle attività umane. Il riscaldamento del mare e il rilascio di energia termica a loro volta generano intensi fenomeni meteomarini noti come "medicane", il cui impatto sulla fascia costiera porta a frequenti inondazioni. I possibili impatti degli tsunami potrebbero non essere contrastati dal paesaggio costiero, in evidente e continuo degrado. La combinazione dell'innalzamento del livello del mare, degli eventi meteorologici, di processi geologici parossistici e dell'attività antropica amplifica i processi erosivi e riduce la capacità dei sistemi costieri di adattarsi alle nuove condizioni. Ne consegue l'aumento della vulnerabilità delle aree costiere, inducendo sempre più situazioni di rischio reale.

Termini chiave: Cambiamento climatico, Variazioni del livello del mare, Eventi marini estremi, Dinamica costiera, Vulnerabilità costiera.

INTRODUCTION

Over the past 20 years or so, there has been a significant growth in studies aimed at assessing the effect of the present sea-level rise (SLR) and its dynamics as the consequence of climatic changes on a global scale. Between the end of the 20th and the beginning of the 21st century, the scientific community, after having developed the concept of a sea level varying over time, undertook a detailed reconstruction of its temporal evolution. Numerous international IGCP projects under the umbrella of UNESCO and the IUGS (Pirazzoli, 1983; Murray Wallace, 1999; Long and Islam, 2004; Engelhart *et al.*, 2016; Switzer *et al.*, 2012) enabled a detailed reconstruction of the sea-level changes. The study of the accuracy with which sea-level markers indicate its past position has improved the reliability of re-

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constructed sea-level curves also in relation to vertical land movements. As consequence, the concept of the relative sea level varying from site to site also in absolute value has been recognised as conditioned by local tectonic, geodynamic, isostatic, steric factors as well as by natural or man-induced subsidence, in the context of a general rise due to the melting of continental ice covers (e.g.: Rovere *et al.*, 2016a,b; Antonioli *et al.*, 2018, 2025).

While the sea level – theoretically – changes with the same speed at the global scale, since almost each coastal area of the planet is characterized by vertical land movements at different amplitudes, today it is accepted that at the local scale it may instead change at different rates.

The combination of sea level rise and subsidence increases the risk of flooding in many coastal areas. Due to their intrinsic features, many of the world's coastal plains are characterized by subsiding topography. At the same time, they exhibit mobile coastal systems under stress due to deficits in sediment budgets or excessive human activity. Their inability to follow and adapt to rising sea levels places all plains at real risk of submersion or flooding due to the impact of exceptional marine events (e.g.: Aucelli *et al.*, 2018; Antonioli *et al.*, 2020; Marsico *et al.*, 2017; Anzidei *et al.* 2023; Bonaldo *et al.*, 2019; Scardino *et al.*, 2022; Rizzo *et al.*, 2025 and references therein).

GENERAL PRINCIPLES

Present sea-level rise (SLR), resulting from the melting of continental ice sheets, is one of the most evident consequences of global warming. Low-lying coastal areas are particularly exposed to sea level change, both temporary (inundation from storm surges and tsunamis) and definitive (submersion from sea transgression). At the local scale, vertical land movements (VLMs) – including both natural uplift and subsidence and anthropogenic subsidence – can amplify or reduce the magnitude of sea level changes (SLC), thereby determining local relative sea level rise (RSLR; e.g.: Lambeck *et al.*, 2011; Chelli *et al.*, 2017; Anzidei *et al.*, 2014; Vecchio *et al.*, 2024 and references therein). This process, together with the progressive reduction of the coastal sediment budget due to different direct and indirect human impacts, contributes to reducing the elasticity of the mobile coastal systems that protect coastal plains.

The local magnitude of RSLR is related to climatic variations but also to vertical movements of the topographic surface due to tectonic and isostatic causes, natural compaction of sediments and steric processes due to thermal expansion or contraction of oceans. The equation that includes all the processes that determine RSLC can be expressed as:

1 - $\Delta\zeta rsl=\Delta\zeta E+\Delta\zeta I+\Delta\zeta T+\Delta\zeta S+\Delta\zeta SC$

In which $\Delta\zeta rsl$ (relative sea level) is the sum of the eustatic ($\Delta\zeta E$), isostatic ($\Delta\zeta I$), tectonic ($\Delta\zeta T$), steric ($\Delta\zeta S$) and sediment compaction ($\Delta\zeta SC$) contributions.

At the local scale, the impact on the environment due to anthropogenic activity can be really high; that occurs when it is connected to the extraction of fluids (e.g. hydrocarbons and/or groundwater) or when the presence of residential or productive settlements amplifies the sediment compaction. In some areas, the contribution of anthropogenic activities can play an important role and must be considered in RSLR assessments. According to Mastronuzzi *et al.* (2020), the sum of anthropogenic contribution ($\Delta\zeta A$) is introduced as:

2 - $\Delta\zeta rsl=\Delta\zeta E+\Delta\zeta I+\Delta\zeta T+\Delta\zeta S+\Delta\zeta SC+\Delta\zeta A$

In consequence, the relative local sea level is the sum of global, regional, and local processes, e.g., subsidence, isostasy, tectonics, and human activities, which are variable in space and time. The detailed knowledge of local VLM has a key role in defining the impact of future RSLR on coastal plains. At medium/short-term scale, their combination will determine different scenarios of submersion and flooding at the occurrence of a paroximal event such as tsunami and storm surge due to exceptional storm, medicanes and tropical cyclones.

PAST, PRESENT AND FUTURE SEA LEVELS

All of Earth's coastal areas, in their complex and dynamic nature, are a 3D space in which the active processes in the hydrosphere, atmosphere and lithosphere transfer energy and matter, interacting with each other (e.g.: Mastronuzzi *et al.*, 2005, 2006; Church *et al.*, 2010; Aucelli *et al.*, 2022 and references therein; fig. 1). The result is a physical space characterized by extreme geodiversity, with different landforms and processes that maintain an "instant dynamic equilibrium". Within it, ecological niches are established; here the most complex biological associations represent the biodiversity of the emerged and submerged coastal environment.

On our changing planet, the Mediterranean region hosts approximately 450 million people; a possible increase to 700 million is expected by 2100. The highest population density is found in some large coastal city areas, located on coastal plains near the mouths of main rivers. Many productive areas – agricultural, industrial, tourism-related – and strategic infrastructures – railways, ports and airports – as well as important archaeological and architectural sites or ecological niches and thousands of small towns and villages are highly exposed, directly or indirectly, to sea-level rise since they are located less than 2 m above current sea level (Papathanassiou and Gabrielides 1999; Antonioli *et al.*, 2020; Anzidei *et al.*, 2014, 2023; Vecchio *et al.*, 2024).

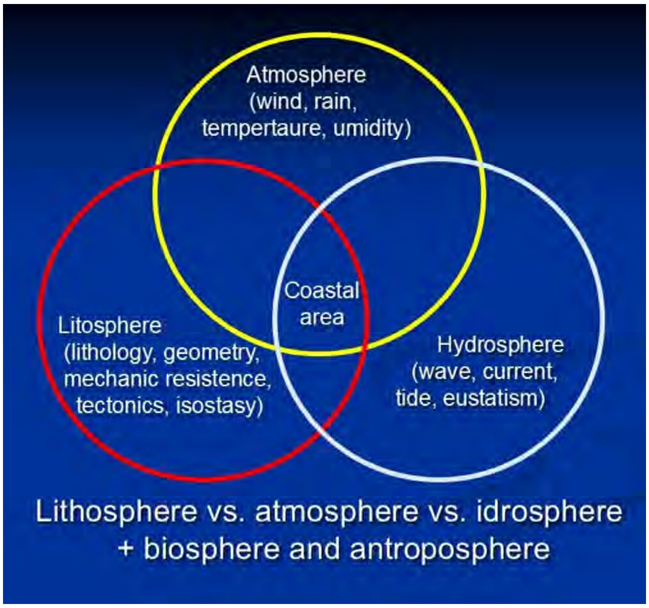

Figure 1 - The coastal zone's physical configuration is the result of the interaction of processes active in the atmosphere, hydrosphere, and lithosphere. These processes define a 3D space in which the local geodiversity is the cradle of the biodiversity (Mastronuzzi *et al.*, 2020).

The past

Coastal areas of the Mediterranean Basin have been shaped by superimposition of tectonic, climatic, eustatic, and glacio-hydro-isostatic contributions all together responsible – with different effectiveness – for relative sea level changes during the Pleistocene and Holocene (e.g.: Antonioli *et al.*, 2018; Anzidei *et al.*, 2021; Vacchi *et al.*, 2016; Stocchi *et al.*, 2017; Mattei *et al.*, 2018 and references therein). As result, significant landscape changes occurred during the last glacial cycle (132 *ka*-present; e.g.: Mastronuzzi *et al.*, 2018a; Valenzano *et al.*, 2018; Capolongo *et al.*, 2022; Niccolini *et al.*, 2025); during this span of time, the morphological evolution of the renewed coastal areas has been strongly influenced first of all by the lithostructural setting and the inherited morphography of the past submerging continental slopes, by climatic and sea changes and then by variations in relief energy (e.g.: Miyauchi *et al.*, 1994; Santoro *et al.*, 2009; Capolongo *et al.*, 2022 and references therein). Sea level changes were determined by the cyclic melting/growth of ice sheets. In particular, between approximately 132 and 116 kyr, during the last Interglacial (LIT), in a period warmer than the current climate, the melting of continental ice masses led to a rise in eustatic sea level of approximately +7/8 m compared to the present one (e.g.: Amorosi *et al.*, 2014; Antonioli *et al.*, 2018; Rovere *et al.*, 2016a,b; De Santis *et al.*, 2024 and references therein). Conversely, about 20,000 years ago, during a phase of climatic cooling (LGM - Last Glacial Maximum), continental glaciers developed and reached their maximum extent, causing a eustatic sea level drop of approximately 120/130 m (Antonioli *et al.*, 2009; Lambeck *et al.*, 2014; 2018; Anzidei *et al.*, 2014 and references therein). Many features of the present morphology of the coastal landscape are the result of these impressive changes.

By using geomorphological, geological, and geochronological data, it has been possible to reconstruct with satisfying accuracy the evolution of the coastal areas back in time to approximately 125 kyr ago. Significant geomorphological and paleontological evidence provides information on paleoclimatic variations and marine paleolevels. The analyses allow us to obtain chronological constraints for variations in sea level and coastal landscape, allowing us to understand the phenomena responsible for them. The elevation at which MIS5e sea level indicators are today provides a first approximation of the direction, magnitude and differences along the coast of the VLMs over the last 125 kyr (e.g.: Mastronuzzi *et al.*, 2011; Di Bucci *et al.*, 2011; Anzidei *et al.*, 2014; Rovere *et al.*, 2016; De Santis *et al.*, 2024 Antonioli *et al.*, 2025 and references therein).

The sequence of the events that have occurred with different rhythms and speeds over the last approximately 20 kyr has reshaped the coastal area (e.g.: Clottes and Courtin, 1994; Mastronuzzi *et al.*, 2007a; Capolongo *et al.*, 2022); throughout the planet and in the Mediterranean too, it acquired the features of a landscape due to the continuous interaction between climate and meteomarine variability, the local endogenous and exogenous dynamics, the characteristics of rocky bodies in a not steady equilibrium state.

The geological record becomes more complete for the Holocene period; a rich dataset (geological, morphological, stratigraphic, paleontological, archaeological enriched by instrumental data) provides new constraints on geophysical models of the relations between eustasy and isostasy at regional scale and more precise estimates of VLM for the last 20 kyr. In particular, the reconstruction of rates and trends of sea level rise in the last 3 kyr has been favoured by the availability of a large number of archaeological data recognisable all along the Mediterranean Basin; over time, it has been the cradle of civilizations, cultures and home to many coastal settlements (e.g.: Pagliarulo, 2006; Auriemma and Solinas, 2009; Anzidei *et al.*, 2011a,b; 2016; Lo Presti *et al.*, 2014; Orrù *et al.*, 2014; Benjamin *et al.*, 2017; Mastronuzzi *et al.*, 2017; Aucelli *et al.*, 2018a,b, 2019; Mourtzas *et al.*, 2023 and references therein). Actually, between 20 kyr and 7 kyr ago, the sea level has had a fast rapid rise of around 113/123 m. It is possible to hypothesize a dramatic net mean rate of 8.6/9.4 mm/yr; some periods may have been characterized by higher rates (Benjamin *et al.*, 2017). In this phase the dynamic coastal landscape was characterized by rapid successive cycles of construction-demolition-submersion that are difficult to identify in their coastal morphological expressions since destroyed or submerged, but recognizable in the succession of sediments from marshy areas or in karst cavities. Coastal plains were the first to be submerged (e.g.: Antonioli *et al.*, 2009; Di Rita *et al.*, 2011) as were karst caves shaped in the carbonate units outcropping along high continental slopes reached by the sea (e.g.: Clottes and Courtin, 1994; Bard *et al.*, 2002; Antonioli *et al.*, 2004; Mastronuzzi *et al.*, 2007a; Stocchi *et al.*, 2017 and references therein), and as were filled the external part of the rivers valleys (e.g.: Mastronuzzi and Sansò, 1998; Tropeano *et al.*, 20; Valenzano *et al.*, 2018). The coastal areas that emerged in the Upper Paleolithic (up to about 12 kyr BP with the sea level at about 35 m below the present one) and in the Mesolithic and early Neolithic were rapidly submerged up to about 7.5 kyr. Contextually, starting about 7 kyr ago, sea level rise began to slow; until the second half of the 19th century, it rose at rates of around 1 mm/yr (Antonioli *et al.*, 2009; Lambeck *et al.*, 2011; Benjamin *et al.*, 2017; fig. 2). In this phase the large contributions of the rivers – still free to carry out their action of erosion, transport and accumulation not impacted by anthropic significant hydraulic works of flow regimation – and the decrease in the relief energy determined a coastal positive sedimentary budget allowing the grown of alluvial and coastal plains despite the sea level rise (e.g.: Mastronuzzi and Sansò, 2012; Chelli *et al.*, 2017; Caporizzo *et al.*, 2024a, b and references therein). The combined action of sea and wind shaped mobile systems in rapid progradation along the seaside of the coastal plains (e.g.: Mastronuzzi and Sansò, 2002; 2012). Although at a lower rate, even in this phase the submergence of areas characterized by the outcrop of tenacious lithostratigraphic units best resisting to the energy of the sea dynamics occurred. These changes have been different from place to place – and still are, depending on (ì) of the outcropping rocky bodies, (ìì) of the vertical movements of the ground due to isostasy, tectonics or subsidence, (ììì) of the zonal climatic characteristics, (ìv) of the hydrological characteristics of river catchments, (v) of the characteristics of the seabed of the continental shelf.

The present

In a world undergoing global climate warming- resulting from the sum of the natural variation in solar energy inputs connected to astronomical cycles and the increase in anthropogenic greenhouse gases in the atmosphere – the coastal environment is exposed to significant pressures of both direct and indirect origin. At global and regional scales, the major causes of pressure on physical dynamics are represented by the "environmental pollution" such as the increase in thermal energy and in anthropic impact on the coastal area or in its basin catchment. The extreme disequilibrium in the coastal areas is linked to the accelerated variations in sea level and its movements induced by a different distribution of excess energies compared to the past.

Since the industrial revolution of the second half of the 19th century, the average well-being of the world's population, and consequently its numbers, has increased dramatically together with settlement, production, commercial and, in some places, tourism activities along the coasts and correlated areas. These involve the continuous release of CO_2 and other greenhouse gases into the atmosphere. The most evident consequence is rapid warming, which is leading to the melting of large masses of continental ice, in the Arctic and Antarctica, which flow into the sea, raising

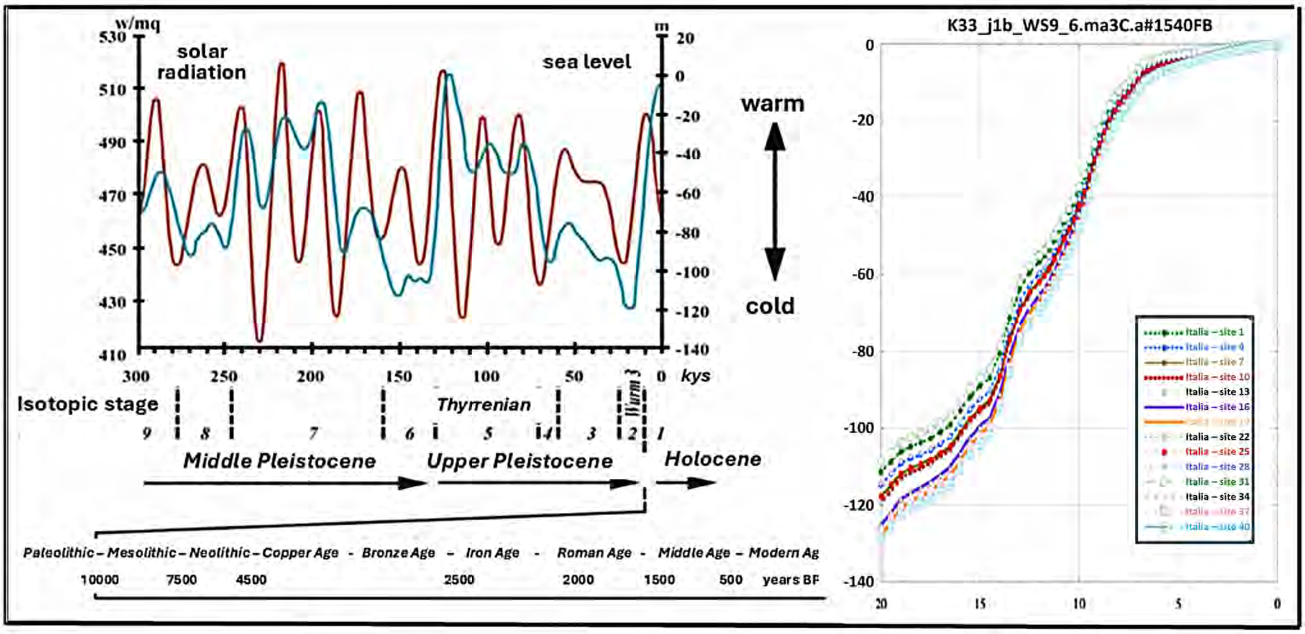

Figure 2 - On the left (2a), sea level variations over the last 300,000 years; for the most recent part, the archaeological nomenclature is reported (modified by Mastronuzzi *et al.*, 2020); on the right (2b), the curve of sea level variations for Italy over the last 20,000 years (Lambeck *et al.*, 2011).

its levels (fig. 3). Many papers focussed on recent and current global sea level trends at global scale (e.g.: Lambeck *et al.*, 2014; Cazenave *et al.*, 2022; Meyssignac and Cazenave, 2012; Chambers *et al.*, 2017; Zerbini *et al.*, 2017; Pandzic *et al.*, 2024; Forster *et al.*, 2024 and references therein). Tide gauge data available since the late 19th century highlighted that the eustatic global mean sea level (GMSL) began to rise rapidly starting about on 1880 CE at a rate of around 1.7 mm/yr, about double to that of 7 kyr ago (Church *et al.*, 2010; Church and White, 2011; Spada and Galassi, 2012; Dangendorf *et al.*, 2017). The analysis of data from radar altimeters showed that contemporary GMSL is rising at a much higher rate with respect to the previous decades, hyperbolically increasing its rise (Cipollini *et al.*, 2017; Cazenave *et al.*, 2018; Adebisi *et al.*, 2021). Ablain *et al.* (2009) estimated a mean SLR of 3.3 ± 0.4 mm/yr during 1993-2009, more than three time that of 7 kyr ago.

Moreover, the seas are heating up, and thermal expansion is also causing their volume to increase, contributing to the progressive SLR. The relevance of the phenomenon is highlighted by the latest Assessment Report (AR6), published by the Intergovernmental Panel on Climate Change (IPCC) in 2021. Today, the WCRP Global Sea Level Budget Group (2018) estimates the global SLR at a rate of 3.1 ± 0.3 mm/yr during the period 1993-2018, with an acceleration of 0.1 mm/yr^2 (see: Rizzo *et al.*, 2025). Despite behaving like a wave (Mörner, 1996), it has almost a same absolute speed approximately throughout the planet; but it has a relative speed different (equation 2 in the present text) from site to site, depending on local geological conditions and anthropic activities. In the Mediterranean, the flow of incoming water resulting from the melting of the continental ice covers at the poles, is slowed down by the conformation of the Strait of Gibraltar, so much so that the rise is less rapid, but still disturbing, close to 1.8-2.2 mm/yr. Unluckily, the typical morphodynamic and the local geological features of the coastal plains and mobile systems accentuate the phenomenon so much (e.g.: Pirazzoli, 2005; Simeoni *et al.*, 2007; Simeoni and Corbau, 2009a; Corbau *et al.*, 2022; Scardino *et al.*, 2020; 2022; Petio *et al.*, 2024; Rizzo *et al.*, 2025).

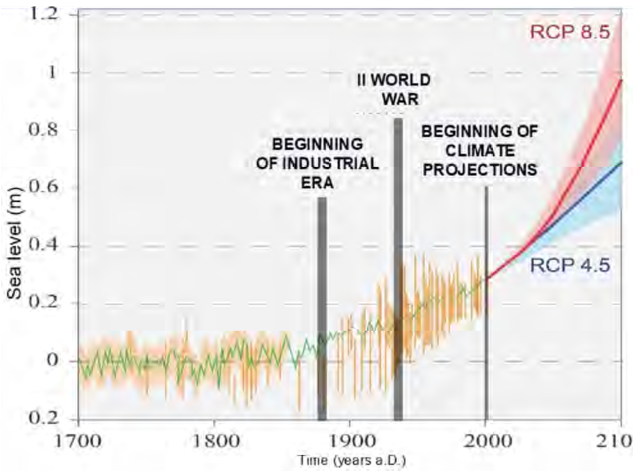

Figure 3 - Sea level trend in the recent past and in projections according to the RCP4.5 and RCP 8.5 scenarios, respectively characterized by CO2 emissions into the atmosphere stabilized at half of today's levels by 2080 and by their growth at the same current rates (mod. in Antonioli *et al.*, 2017).

Low-lying areas, such as large river deltas and coastal plains – but also gently sloping rocky areas – suffer dramatically the combined effect of sea level rise and of land subsidence (e.g.: Lopez-Doriga and Jimenez, 2020; Pappalardo *et al.*, 2021; Nicholls *et al.*, 2021; Vecchio *et al.*, 2024). In the Mediterranean basin, several coastal areas are affected by land subsidence, leading to high rates of relative sea level rise. Near Ravenna (Italy, Northern Adriatic) the combined effects of subsidence due to the sediment compaction in a delta area whit the subsidence induced by fluid extraction (hydro carbons and/or groundwater) produced coastal subsidence up to 0.53 m in the span time 1984-2016. Not so far, data collected from in situ tide gauges indicate that in the subsiding area of Venice, sea level has been rising at higher rates both historically and in the recent period (2000-2024) respect to the most stable areas of Genoa and Trieste, both on rocky coasts, where the sea level trends appear relatively similar (e.g.: Vecchio *et al.*, 2024; Anzidei *et al.*, 2024; Rizzo *et al.*, 2025). The Venice area, northeastward to the articulated Po river delta system, is affected by sediments compaction, long term tectonic subsidence and extensive anthropogenic load (see caption of fig. 2; Simeoni and Corbau, 2009a; Corbau *et al.*, 2019a,b; 2022). Moreover, remote sensing data indicate subsidence rates of the topographic surface estimated from 8 to 3 mm/yr in Egypt along the Nile delta and of 1.0-2.3 mm/yr at the mouth of the Ebro in Spain. In the first case, the present rate of relative sea level rise reaches a maximum of about 10 mm/yr; in the second one it reaches a rate of about 4.5 mm/yr (see: Rizzo *et al.*, 2025).

In Southern Italy, the semi-graben between Sila and Pollino Gropus along the Calabrian Arc in the Appenninic chain, is loaded by alluvial sediments from Crati and Sibari rivers; here the area of the ancient *Sýbaris* (VII century BC - VI century CE) is exposed to the rising freshwater table as result of RSLR (Pagliarulo, 2006; Mastronuzzi *et al.*, 2018b). The effects of the sea level rise is not only readable on the surface but in a three-dimensional (3D) physical environment (Parise *et al.*, 2015; Rizzo *et al.*, 2025). Rising sea levels are followed by increased penetration of the salt wedge under the coastal aquifer. The latter, attacked by excessive withdrawals, tends to salify, becoming brackish if not salty; the process contributes to coastal desertification due to the inability of some plant species to survive in contact with waters that are not very salty. Dramatic examples are recorded along the coastal area of Cilento in Campania (fig. 4), in Veneto and Emilia Romagna, in northern Apulia (Aucelli *et al.*, 2017; Corbau *et al.*, 2022; Petio *et al.*, 2024).

Figure 4 - The pine wood of Cala del Cefalo in Cilento (Campania, Italy) has been almost completely destroyed by the combination of rising sea levels, strong erosion, and salification of the fresh water aquifer (Photo: A. Sorrentino).

The result is the more or less fast – but steady – inland movement of the shoreline; that is contrary to what happened until the '60s of the 20th century, because no sediments arrive on the coast from the river catchment useful to reconstruct the mobile coastal systems and their sand reserves currently in consumption. As if that wasn't enough, the Mediterranean region, is considered as a "climate change hotspot" since it is warming 20% faster than the global average (Giorgi, 2006; Cramer *et al.*, 2020). In addition, meteomarine phenomena – like the genesis of large storms including the now looming "medicanes" (e.g.: Martinelli *et al.*, 2010; Lionello *et al.*, 2020; Flaounas *et al.*, 2022; Kushabaha *et al.*, 2024; Scicchitano *et al.*, 2020; 2021; 2022 and references therein) – and possible tsunamis (e.g.: Mastronuzzi, 2010; Mastronuzzi *et al.*, 2013; Lario *et al.*, 2011; Scicchitano *et al.*, 2012; Smedile *et al.*, 2020; Anzidei *et al.*, 2014; Regnauld and Mastronuzzi, 2015; Vott *et al.*, 2011; Scardino *et al.*, 2020; De Martini *et al.*, 2021; Costa *et al.*, 2022 and references therein) can cause lost in human lives and damage on to anthropic structures discharging their energy in a short time and at higher and higher altitudes inland. In the subsoil, the temporary seawater penetration due to the inundation causes salinization of fresh water inducing severe implications on agriculture, freshwater availability, and human settlements. Rising sea levels coupled with intense weather events have caused a significant increase in the frequency and severity of flood events in the Venice area. In the last 50 years the incidence of the *acqua alta* (= high water) cases in Venice have grown hyperbolically. It increased from two cases recorded during 1880, to more than 20 cases across 2020: in an area in which normal tide range is of about 0.60 m, sea waters, jointly to rain and rivers flows, are pushed into the lagoon until reaching the maximum level never recorded of 1.94 m at the Punta Salute tide gauge on 4 November 1966 (e.g.: Pirazzoli and Umgiesser, 2006; Lionello and Scarascia, 2018; Lionello *et al.*, 2020; Alberti *et al.*, 2023; Faranda *et al.*, 2023; Anzidei *et al.*, 2024 and references therein).

The incapacity of mobile coastal systems to oppose energy inputs because of their lack of "elasticity" is already determining the erasure of their landmarks from the local topography. Their destruction eliminates a significant bul-

Figure 5 - (2025) Present day state of the dune belt of the mobile coastal system at Torre Canne between the municipalities of Fasano and Ostuni, near the city of Brindisi (Puglia, Italy) (left), and (2001) at the cliff shaped in the backdune sequence at the mouth of the Bradano River, on the border between Puglia and Basilicata regions (right).

wark against the attack of coastal erosion exerted by the rise in sea level and the decrease in sediment budgets (e.g.: Bruun, 1969; Rizzo *et al.*, 2025). The permanent submersion of extensive coastal areas is now an indisputable and extremely evident fact along the coasts from Margherita di Savoia to Siponto in Puglia, where new marshy areas literally surround residential villages (Petio *et al.*, 2024; fig. 7) or in Po River Delta (Corbau *et al.*, 2022).

The future

The IPCC proposed future scenarios of sea level changes (e.g.: IPCC, 2014; 2021 and bibliography reported therein); different scenarios correspond to different expected variations of the CO^2 emissions and other greenhouse gases into the atmosphere (fig. 8). In the RCP2.6 scenario, which envisages their desirable halving by 2050, the expected increase by 2100 is estimated up to approximately 0.30 m; that of the RCP 8.5 scenario, the worst, which instead hypothesizes a growth in greenhouse gas emissions at current rates, is estimated at +1.10 m relative to a baseline of 1995-2014 (IPCC, 2021). Respectively, by 2300 the sea level rise forecasts are +1 and around +3 m, perhaps +7 m.

These numbers are not corrected by site-specific geological and morphodynamic features. The implementation of these data for coastal plains, produces dramatic scenarios (e.g.: Antonioli *et al.*, 2020; Marsico *et al.*, 2017; Aucelli *et al.*, 2018b; Bonaldo *et al.*, 2019; Scardino *et al.*, 2020; Scicchitano *et al.*, 2021; Anzidei *et al.*, 2023; Vecchio *et al.*, 2024, Rizzo *et al.*, 2022; Vandelli *et al.*, 2023) corresponding to losses of areas of coastal plains due to submersion which in some cases reach around 5000 km^2 as for the north-western Adriatic. The recent SAVEMED-COASTS2 project (www.savemedcoast s2.eu/index.php/it/), for example, identifies 163 coastal plains across the Mediterranean Sea that will be impacted by sea level rise with a total submergence of approximately 38,529 km^2 which corresponds approximately to 5.5 million football pitches (Anzidei *et al.*, 2024). In these drammatic scenarios, it is not a coincidence that the possible most affected countries are characterised by extensive deltaic areas like in France (Rodano River and connected lagoonal areas for about 3681 km^2), Italy (Po River and others for 10,060 km^2) and Egypt (Nilo Rivers for about 12,879 km^2) (Vecchio *et al.*, 2024) (fig. 9). Furthermore, the heat exchange between the atmosphere and the oceans causes an increase in sea temperature. In addition to rising sea levels, larger thermal balances lead to the genesis of increasingly intense meteomarine phenomena, Mediterranean tropical cyclones, which animate storm surges which in turn push enormous quantities of seawater towards the coastline. This results in a rapid local increase in sea level as in Syracuse and along the Sicilian coasts with the arrival of Zorbas in 2018 or along the coast of Ionian Basilicata in September 2019 in which temporary sea level rose up to 1.5 m have been observed (Scicchitano *et al.*, 2020, 2021).

For instance, in the already mentioned Venice Lagoon, local land subsidence estimated from the analysis of Sentinel-1 images acquired between 2015 and 2019 combined with data of SLR projections, make a scenario of RSLR of 0.3 m by 2050 and 0.82 m by 2100 (Tosi *et al.*, 2024; Vecchio *et al.*, 2024).

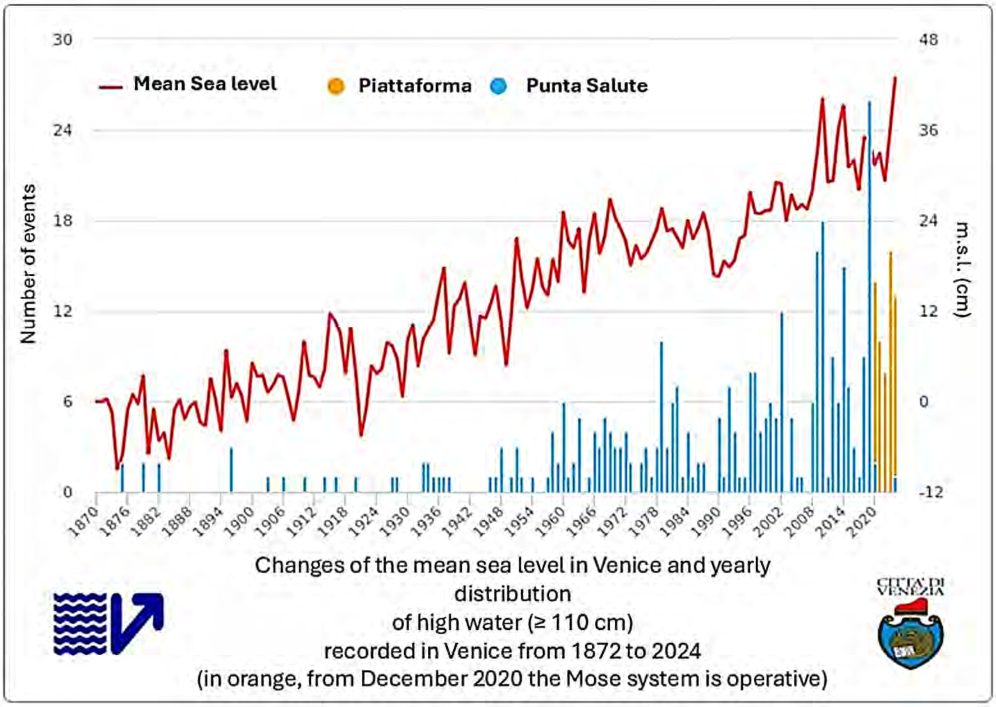

Figure 6 - Distribution of the tide and the phenomenon of high water in Venice over the last 150 years or so; the rapid increase in their frequency is evident since 1960 (https://www.comune.venezia.it/it/content/centro-previsioni-e-segnalazioni-maree).

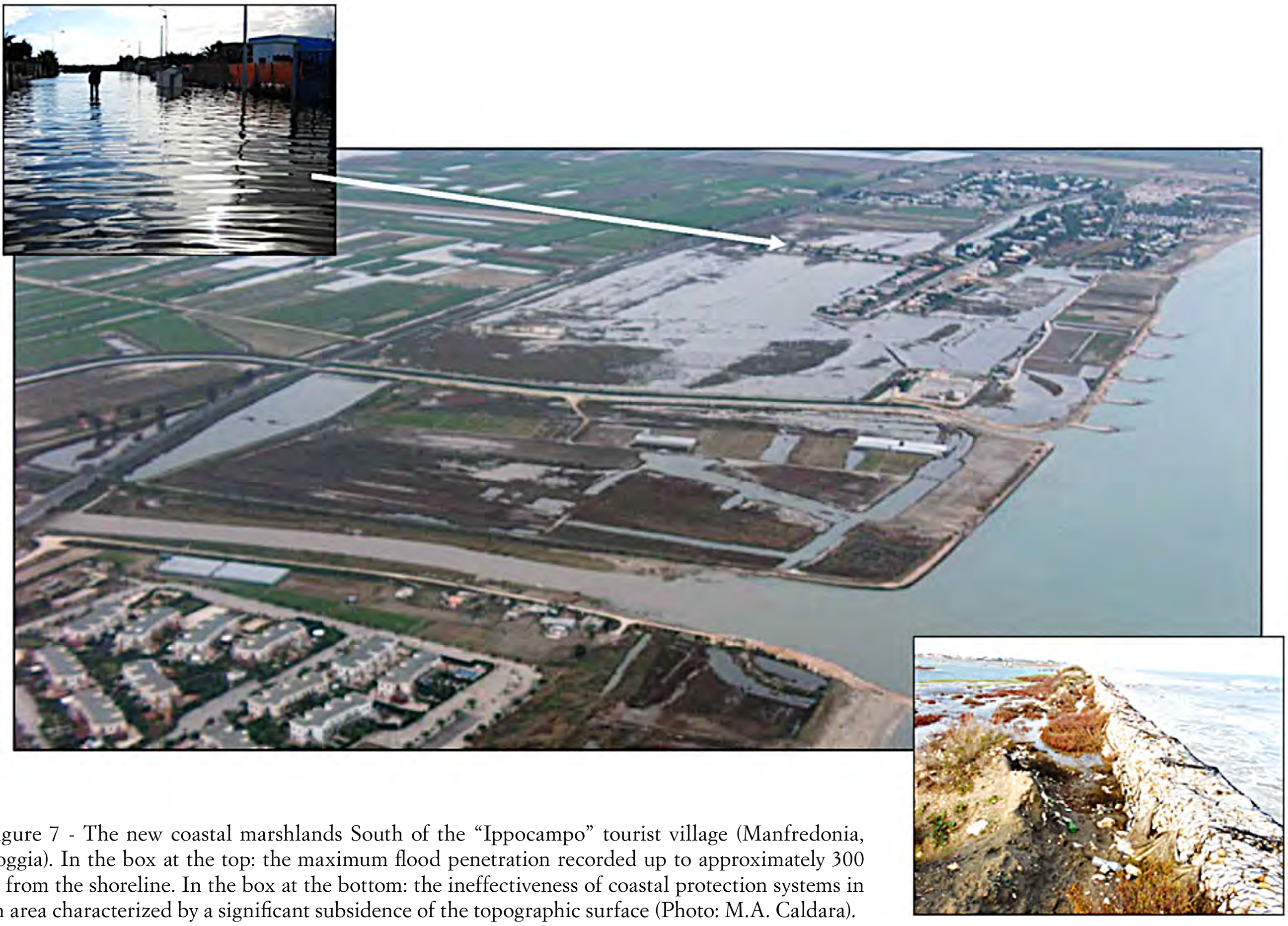

Figure 7 - The new coastal marshlands South of the "Ippocampo" tourist village (Manfredonia, Foggia). In the box at the top: the maximum flood penetration recorded up to approximately 300 m from the shoreline. In the box at the bottom: the ineffectiveness of coastal protection systems in an area characterized by a significant subsidence of the topographic surface (Photo: M.A. Caldara).

DISCUSSION

We are accustomed to thinking that human activities along the coastline isn't the cause of coastal dynamics that alter the landscape but rather the victims. This is not the case, or at least it is no longer the case. Very often, almost always, the opposite is true. Construction of ports, airports, industries, and urban structures on the coastal area, modifications to river catchments and mouths, have always been carried out throughout history. Perhaps with greater foresight and awareness, perhaps without illusions of omnipotence, many coastal areas could have been spared. In the Mediterranean basin, the long succession of civilizations that made maritime trade their wealth rarely built port facilities along mobile coastal systems. Based on current geological knowledge, we can say that Venice was built in the most inappropriate location from a morphodynamic perspective, with techniques that only partially withstood the site's specific characteristics and dynamics: long-term tectonics, the nature of the sediments, subsidence from sedimentary and anthropogenic load, combined with the continuous rise in sea level – slow until the mid-19th century, then increasingly rapid thereafter – define vertical movements of generalised subsidence incompatible with the presence of one of the most precious and elegant expressions of urban settlement. Other large cities overlooking the Mediterranean, perhaps less architecturally vulnerable, are exposed to the dramatic risk of submersion and flooding (fig. 9): i) Barcelona (approximately 1.6 million inhabitants, on the Llobregat delta); ii) Valencia (approximately 826,000 inhabitants, on the Turia River delta); iii) Thessaloniki (approximately 320,000 inhabitants, adjacent to the Vardar River delta Alexandria, about 5.6 million inhabitants). The entire Nile river delta suffers from a significant reduction in river sediment flow due to damming and control works carried out in its drainage basin. Subsidence from sediment load and coastal erosion is compounded by exposure to exceptional events. As early as 365 AD, the city was struck and seriously damaged by the tsunami generated by the strong earthquake that originated west of the island of Crete (e.g.: Pirazzoli *et al.*, 1996; Stiros, 2011; Polonia *et al.*, 2013), which caused approximately 50,000 deaths according to contemporary chronicles (Ammianus Marcellinus, *Res Gestae,* 26, 10, 15-19).

The regulation of waterways and the obstruction of coastal sediment flows represented by ports, offshore defences, breakwaters, reinforced estuaries, and groynes – only partially justified by local, manifest risk situations – reduce the resilience of coastal systems. Effectively, many of these struc-

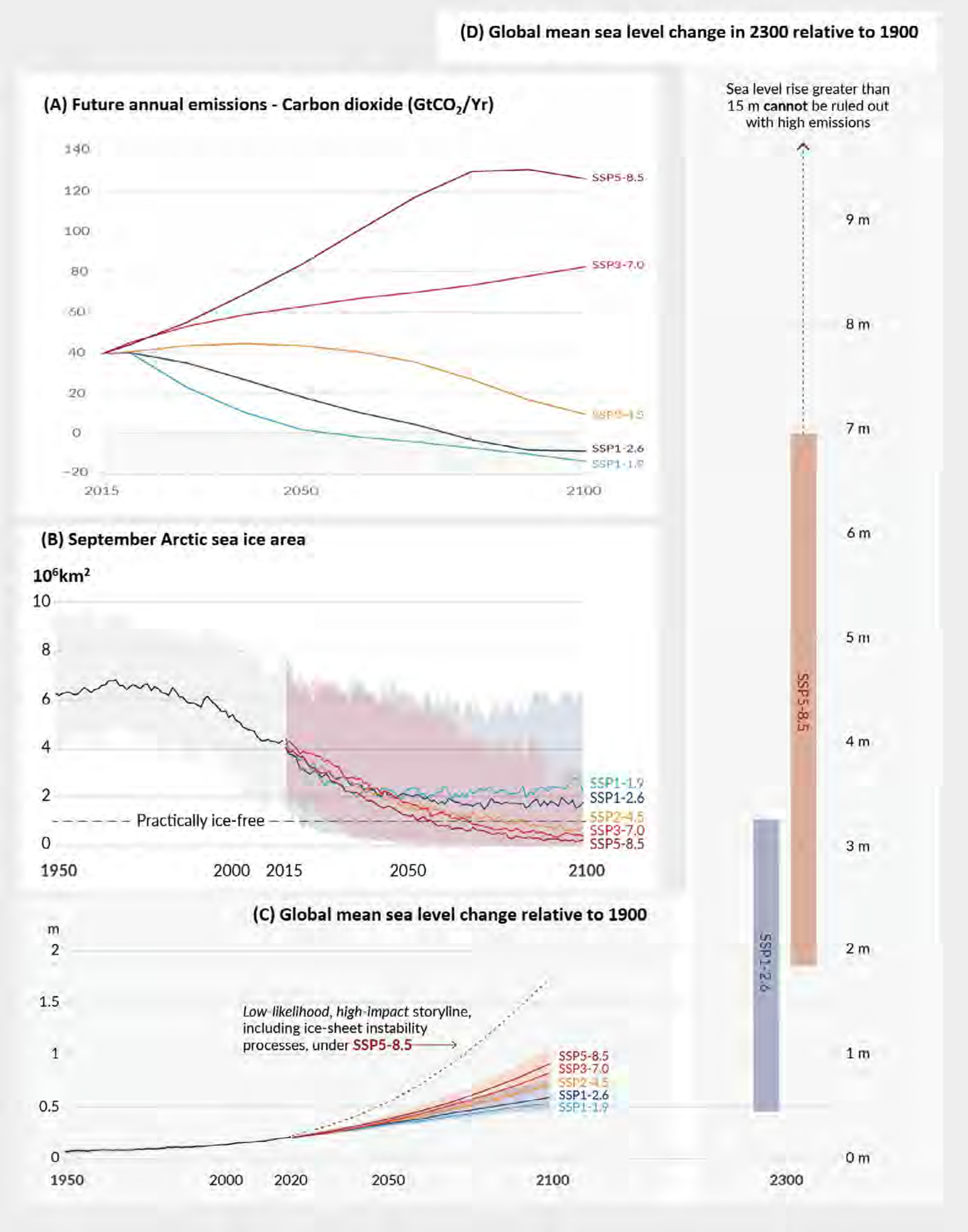

Figure 8 - Forecast scenarios of possible sea level changes for 2100 (c) and for 2300 (d) as a function of: a - CO2 emissions into the atmosphere; b - possible changes in the extent of sea ice for the Antarctic area according to data recorded between 1950 and 2015 and the scenarios in (a) (mod by IPCC, 2021).

tures protect limited coastal sectors. Actually, in the case of many Adriatic ports on the Italian coast, breakwaters favor the presence of advancing beaches; but those sediments stop unnaturally and are subtracted from the leeward beaches. The sedimentary budget of the leeward beaches becomes negative since sediments no longer arrive in sufficient quantities to replace what the sea and local agents wear away and remove over time. In Italy, the Apulia region is affected by the alteration of coastal drift in the Northern Adriatic and is an example of the trans-regional nature of erosion phenomena. Its entire Adriatic coast suffers from a significant reduction in the contribution of coastal drift (fig. 10). North and south of the Gargano Promontory, several stretches of coastline reveal eroded dunes with the roots of trees and shrubs now in the sea. The aforementioned case of the new salt marshes near Margherita di Savoia and Siponto highlights the tendency for a new physical landscape to develop along the coastal area, independently of the human presence that caused the changes and only subsequently became their victims. Along the Ionian coast of Apulia and of Basilicata, the situation is similar, if not worse: at the mouth of the Bradano and Basento rivers, the dune system has been completely eroded due to the construction of permanent tourist residential structures (fig. 11).

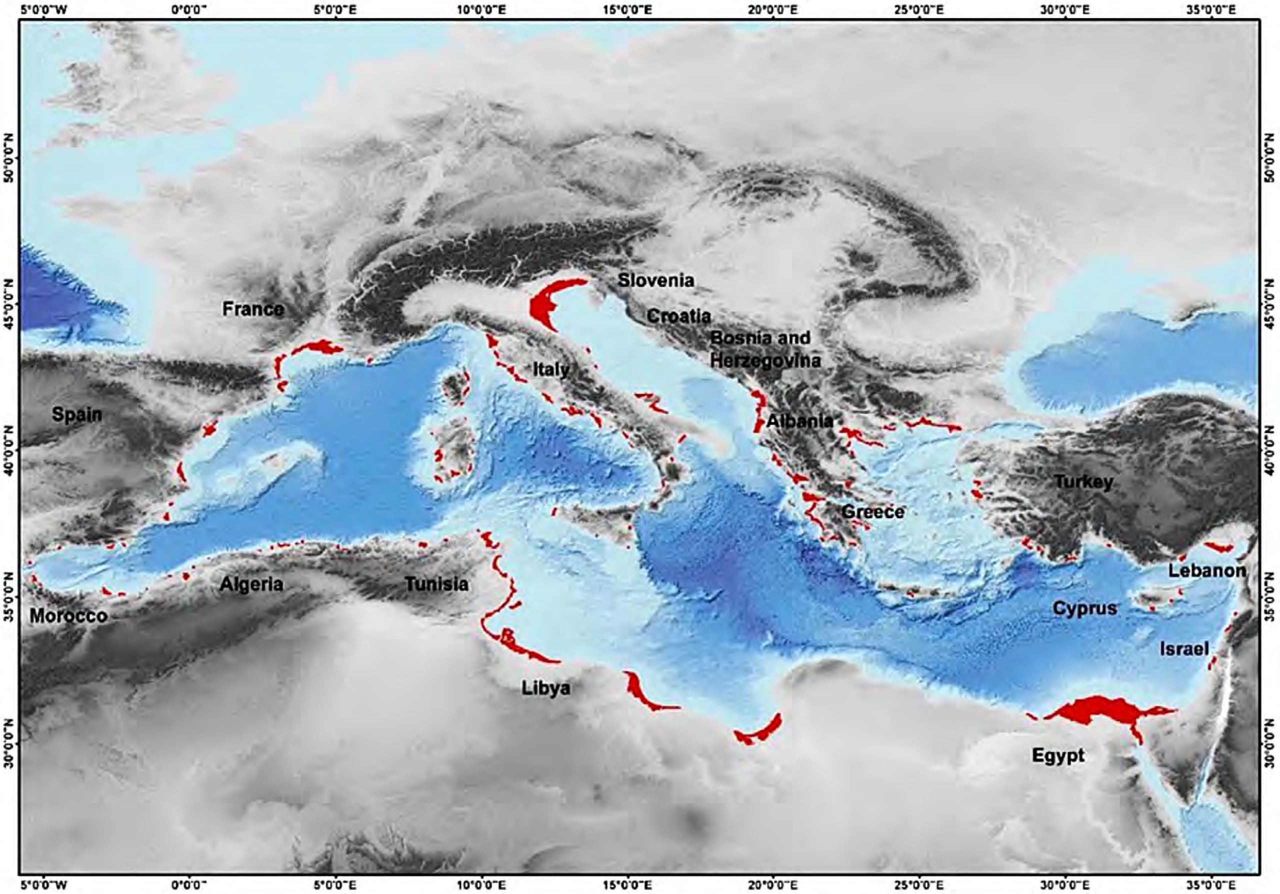

Figure 9 - Distribution of coastal plains in the Mediterranean basin that are the most exposed to vulnerability from submersion or inundation according to the forecasting models developed by Vecchio *et al.* (2024).

In addition to the settlement, tourism (but also environmental sensitivity) requires the beaches to be cleaned using unselective methods of large quantities of plastic that washes onto them from the rivers and sea (Sasso *et al.*, 2025). If a plastic bottle is washed away, it carries with it the sand that fills it; mechanical means increasingly wear down the individual grains of sediment, which over time become lighter and susceptible to being transported offshore or to land by the sea or wind. In Greece, the beach is so precious that cleaning is carried out there with human-operated rakes. Every day, swarms of tourists individually carry away just a few grams of sand on their feet, in umbrellas, and in bags: those few grams become tens of cubic meters with the total number of bathers and the repetition of the bathing seasons. Beaches and dunes are no longer supplied with the precious sands carried to the sea by rivers; river management works, precious as they are, silently but daily subtract millions of cubic meters of sand from the beaches. And to access the beaches as easily as possible, the dunes are penetrated with gaps that are also accessible to cleaning vehicles, and they are demolished to build villages, campsites, beaches, and restaurants with a sea view. Each of those gaps increases the quantity of sand that is lost in the coastal areas behind the dunes due to the wind. This model of urbanization and exploitation of the coastal area has significantly reduced the elasticity of the dune systems and their capacity for resilience; today they are no longer able to rebuild themselves and play a protective role for the areas behind the dunes from the continuous processes of submersion and flooding (e.g.: Rodella *et al.*, 2017; Piscitelli *et al.*, 2018; Corbau *et al.*, 2019a,c and references therein) The mobile coastal system, therefore, does not follow the sea level according to the classic model of Bruun (1962). Nor does it grow seaward as it did between 7 kyr and the second half of the 20th century in the presence of a positive sediment budget. In the absence of replenishment, it is gradually demolished and loses its role as a passive defence against the SLR and storm surges (e.g.: Scardino *et al.*, 2020; 2022; Scicchitano *et al.*, 2020; 2021; 2022; Rizzo *et al.*, 2025 and references therein) (fig. 12). The resilience of mobile coastal systems to the change in sedimentary budget and to extreme marine events (storms, medicanes, and tsunamis) together with the RSLR induced by the interplay of SLR and the VLMs define the future of coastal plains and their dynamic tendency according to the Valentin's diagram (Valentin, 1952) (fig. 13).

In recent years, many national and international projects have been supported to evaluate the human impact on the coast, risk assessment and climate change adaptation. Copernicus Climate Change Service (C3S) provides free downloadable climate datasets for the European region (https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview). C3S provides the monitoring of the long-term evolution of sea level, and a user-friendly interface for the daily change in GMSL measured by satellite altimetry from January 1993 to June 2023, with an associated uncertainty of 90% confidence level and the relative trend over the accounted period. To promote access to the most updated sea level projections for five different climatic scenarios, namely the Shared So cio-economic Pathway (SSP) and their distribution, a dedicated web-tool has been released by NASA (https://sealevel.nasa.gov/ipcc-ar6-sea-le vel-projection-tool?type=global). At European scale SAVEMEDCOASTS-1 (https://www.savemedcoasts.eu/index.php) and SAVEMEDCOASTS-2 projects (https://www.savemedcoast s2.eu/index.php/it/) are focused on a rigorous methodology to map submersion scenarios due to SLR (Vecchio *et al.*, 2024; Anzidei *et al.*, 2021, 2023). At Italian scale two recent Projects of National Interest by MUR - Ministero of Università e Ricerca - Project GAIA - "Geomorphological and hydrogeological vulnerability of Italian coastal areas in response to sea level rise and marine extreme events" and Project "ARCHIMEDE - Multidisciplinary approach to better define vulnerability and hazard of Medicanes along the Ionian coasts of Sicily", are focused on the evaluation of the effect of sea level rise in terms of impact on coastal areas due to submersion and inundation by extreme waves and severe meteomarine events. With a holistic approach other projects like "MICA - Mitigation of Climate Change Impacts on Human Health and Improvement of Well-being through

Figure 10 - Effect of the construction of a reinforced mouth on the Saccione River on the border between Puglia (Southward, on the background) and Molise (Northward, on the foreground); this results in a strong regression of the shoreline in Puglia and its disproportionate progradation in Molise in the sopraflutto area compared to the coastal drifting here directed from NNW to SSE (Photo: M.A. Caldara).

Figure 11 - 2016, July: state of the mobile coastal system at the Argonauti tourist village and harbor, built starting on the first year of XXI century, at the mouth of the Basento River (Matera, Basilicata); the progradation in the sopraflutto zone with respect to the coastal drift, here directed from SSW to NNE) and the dramatic retreat in the sottoflutto zone are evident (from Google Earth).

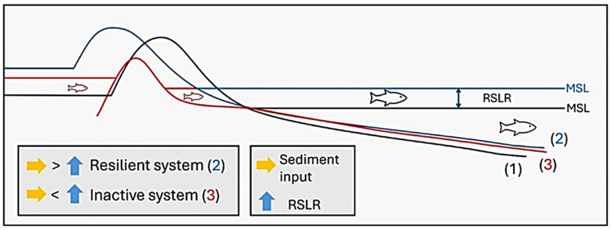

Figure 12 - Sketch representing the possible scenarios of a mobile coastal system in response to RSLR starting from the present morphology (t1 - black); in the case of a resilient system (t2 - blue), future MSL will result in a landward migration of the coastal environments due to a natural coastal adaptation; whilst, in the case of an inactive system (t3 - red), the erosion process will prevail with consequent coastal retreat, submersion and inundation of the low-lying areas (mod by Rizzo *et al.*, 2025).

One Health Approach", supported by EU - Interreg VI-A IPA South Adriatic are devoted to evaluating the effects of SLR on human health.

EuroSea (https://eurosea.eu/outputs-reports/) and the CoCliCo service (https://coclicoservices.eu/) international projects have developed specific mapping and visualization tools. For the Mediterranean coasts several reviews contributions have been focused on the concepts of coastal vulnerability and risk and to the accuracy of the methods adopted to assess them (see Rizzo *et al.*, 2025 for a critical synthesis).

CONCLUSIONS

Everywhere on the planet, coastal plains and the mobile coastal systems are elements of the landscape strictly interconnected in their dynamics. Their survival depends on the balance between the energy of the sea's movements, its relative and absolute rise, and on the quantity of sand that those movements allow to accumulate and not disperse. Sea levels are rising at an ever-increasing rate, and future scenarios put millions of square kilometers at risk of submersion and inundation, partly due to changes in local weather patterns. Regulating waterways, building ports and breakwaters has stopped sand from drifting along the shoreline and removed sediment from the sedimentary budget of many beaches; some, however, benefit from this, but with a devastating impact on the aesthetic value of the landscape. Beaches no longer have sand; on a local scale, the available one is broken up by disruptive cleaning techniques. Tourist traffic leads to unintentional sand removal, which is negligible individually but staggering if considered as a sum. Dunes have been destroyed to create access to beaches or to build villages. In several areas, coastal lagoons have been generated where rising sea levels and storm surges have swept away the already diminished natural defences or breakwaters, demonstrating their uselessness as well as their economic and landscape costs.

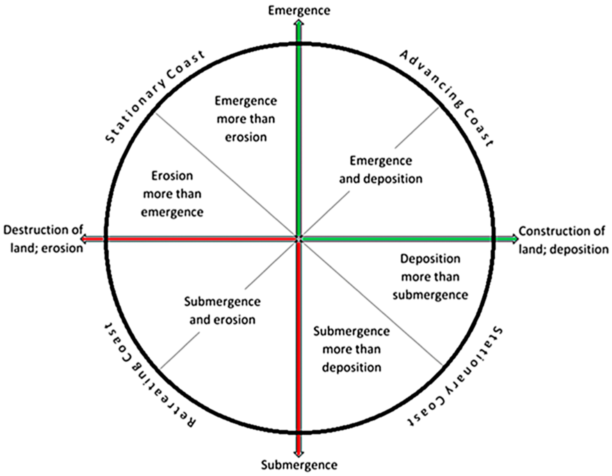

Figure 13 - Valentin Diagram permits to evaluate the tendency of the shoreline change in combination with relative sea-level rise and vertical land movements (from Valentin, 1952).

Few or no systematic action has been taken at the scale of extended physiographic unit to protect coastlines and try to limit the effects of the interconnected phenomena of erosion, submersion and inundation. Aware that the eustatic sea level could rise approximately 1.01 m by 2100 CE, it is necessary to: ì - reduce global warming by reducing greenhouse gas emissions; ìì - expand knowledge of processes and sites with an approach that considers physiographic units, including at the transnational level; ììì - rebuild mobile coastal systems, restoring their elasticity and resilience, allowing them to be supplied by sediments from river basins and the sea; iv) redesign the 3D use (fresh water included) of the coastal area in a ICZM context by reviewing its development plans. The "coast" of tomorrow will be completely different from that of today, with dynamics, surface extents, landscape, and groundwater depths affected that are different from those of today; the anthropic presence too will be bigger in term of people density and covered surfaces. We cannot think to the tomorrow's elections; we must think to beyond tomorrow about the future of everyone, not just a portion of the population. Science, in its many facets, has profound methodological and technical expertise; using science saves time, money, and lives. Planning now with scientific insight is the only viable strategy to reduce the vulnerability of the coastal areas and of the about a billion people who will live there.

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