

PROJECTIONS OF FLOODING AND EROSION IN COASTAL ZONES OF ANDALUCÍA (SPAIN) FOR THE XXI CENTURY: A PROBABILISTIC APPROACH

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We present a general methodology to obtain probabilistic projections of erosion and flooding impacts for the present century that takes into account: (1) the stochastic character of climate and its variability at different time scales; (2) the joint effect on the coast of maritime and fluvial events; (3) the presence of infrastructures that interfere with the hydrodynamic and sedimentary processes, such as dams in the river course, harbors, and promenades; (4) the availability of sediment, its 3D spatial layout, as well as its granulometry and degree of consolidation. The methodology has been implemented all along the almost 1000 km of the Andalusian coast. Results highlight the importance of the consideration of a given time horizon and, when necessary, the seasonal variability for the authorization of uses and concessions in the littoral zone. They also show that the stochastic approach for the assessment of uncertainty of these phenomena can provide legal certainty to the decisions made by the administration and the economic relationships in coastal zones.

Keywords: erosion-flooding, climate change, probabilistic methodology

1. INTRODUCTION

Littoral zones possess a high environmental and economic value. They are also valuable because they can mitigate the consequences of hazardous natural events. Despite their importance, the irrational occupation of the coast has often been justified for economic reasons. However, the concentration of population and economic activities considerably increases the risk of economic and environmental losses. In addition, according to the fifth assessment report of the Intergovernmental Panel of Experts on Climate Change (IPCC, 2023), the situation will worsen in a scenario of global change at 2100 horizon where sea level rise and variations in climate patterns will occur concurrently with an increase in the coastal population. The situation is critical on the Andalusian coast that hosts more than 60% of its population. In this zone, the variety of coastal morphologies and the type and intensity of human induced stresses, will bring up different management problems that will require innovative, informed-based solutions to mitigate/adapt to climate change (CC) impacts or even to rearrange existing developments.

The current situation does not favor compliance with European Directives. Specifically, it clearly deviates from the principles of the Directives 2000/60/EC and 2014/89/EU. On the other hand, the current Spanish Coastal Law must be considered as it establishes technical criteria for determining the curve delimiting the envelope of the places that are reached by the sea water and other curves related to the shoreline. Those criteria, despite being formulated in terms of probability, provide fixed curves and do not consider (i) the random nature of the climate and the changes in the shape of the coast and (ii) the long-term climate variability in a global change scenario. However, these aspects show that these curves have a position that varies randomly in time and space.

In Andalusia (Spain), the service of the regional government in charge of the management of authorizations for the use and occupation of the coastal zone has promoted, for the exercise of their responsibilities with legal support, the development of a methodology to study the spatial and temporal variability of the coast in a CC scenario and its implementation along its approximately 1000 km of coast. In this article we present the methodology developed within the framework of the so called ICCOAST project and its application along the Andalusian coast.

Research on long-term coastal processes has often relied on reduced-complexity models with simplified geometries and fixed conditions. Baquerizo and Losada (2008) highlighted that deterministic approaches fail to account for the randomness of events like storms, emphasizing the need for statistical tools to handle uncertainty in predictions. Some jobs have addressed this problem in the last decades.

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Studies such as those by Reeve and Spivak (2004), Payo et al. (2002), Davidson et al. (2010) and Vitousek et al. (2021) used simulations and statistical analysis to forecast shoreline evolution.

Recent research has focused on the impact of CC on coastlines. Studies like those by Zacharioudaki and Reeve (2011), Wainwright et al. (2015), Álvarez-Cuesta et al. (2021), Vitousek et al. (2021), Toimil et al. (2021, 2023) investigated coastal recession using climate projections and models that account for longshore or/and cross-shore processes, as well as sea-level rise.

Additionally, conceptual works like those of Ranasinghe (2016) and Splinter and Coco (2021) have outlined key challenges, such as assessing local-scale impacts addressing non-stationarity and the limitation of the assumption of unlimited sediment supply, as well as accounting for wave and river-flow influences.

This study presents a methodology for jointly projecting coastal erosion and flooding impacts caused by climate change developed by the University of Granada (UGR) as part of the ICCOAST project. The methodology has been implemented in the Andalusian provinces of Huelva, Cádiz and Málaga by the Temporary Joint Venture Estudio 7-SandS and in Granada and Almería by UGR.

This work incorporates several novel aspects: (1) accounting for the non-stationarity of climate forcings as in Cobos et al. (2022 a, b) (2) using a multivariate non-stationary ensemble approach to model future climate with the approach proposed by Lira-Loarca et al. (2021), (3) jointly analyzing maritime and hydrological agents, including sediment supply from rivers and ephemeral streams, and their effects on sea levels and flooding, and (4) employing a morpho-dynamic model that considers the impact of infrastructures on hydrodynamics as well as sedimentary processes, and sediment characteristics like granulometry, 3D distribution, and consolidation as in Torrecillas et al. (2024).

Impact assessments are conducted using statistical analysis of various indicators designed to support decision-making for managing land use and protection in Andalucía's public maritime-terrestrial domain. Probabilistic results are presented for different time horizons, including seasonal analysis for peak (April to September) and off-peak (October to March) tourist periods. The methodology is illustrated on the Andalusian coast, which features diverse coastal morphologies such as deltas, pocket beaches, headland bays, and landforms influenced by marine structures.

The paper is organized as follows. Section 2 describes the novel methodology for reproducing the flooding and erosion of Andalusian coast through a probabilistic approach. Section 3 shows the results of its application to a real beach at the province of Granada and an analysis of beaches under retreat along the coast of Granada and Almería. The concluding remarks close the paper.

2. METODOLOGY

The methodology is based on the work by Payo et al. (2008) and Baquerizo and Losada (2008). It starts with an initial configuration of a specific coastal area determined by bathymetry, terrain data such as sediment characteristics and land use, and the presence of infrastructures. Future climate projections made by climate services are also known. It consists of the following steps:

2.1 Characterization of the environment

The analysis of the physical environment leads to distinguishing the physiographic units in each littoral sector, which are divided into subunits based on the characteristics and relevant external forcings involved in the processes, where local actions exhibit similar ranges of variation.

2.2 Multi-model characterization and simulation of climate series

The projection data consists of realizations from different climate models, i.e., multivariate time series simulating how future climate could be for a representative concentration pathway (RCP) of greenhouse gases, with a total radiative forcing of 8.5 W/m² for the year 2100. Wave climate included significant wave height (H_s), peak period (T_p) and mean direction (θ_m) from PIMA Adapta project (Ramírez et al. 2019) for the models RCA4 - MPI-ESM-LR, CCLM4-8-17 - MIROC5, RCA4 - IPSL-CM5A-MR, RCA4 - HadGEM2-ES, RCA4 - EC-EARTH, RCA4 - CNRM-CM5, CCLM4-8-17 - CanESM2, ALADIN52 - CNRM-CM5. For the same models, wind information and meteorological tide were obtained from COPERNICUS. The precipitation of EURO-CORDEX comes from five

combinations of GCM-RCM (CNRM-CERFACS-CNRM-CM5, ICHEC-EC-EARTH, IPSL-IPSL-CM5A-MR, MOHC-HadGEM2-ES and MPI-M-MPI-ESM-LR). River discharge projections were available at COPERNICUS from *E-HYPEcatch* project for four models' combinations (REMO2009 - MPI-ESM-LR, RCA4 - HadGEM2-ES, RCA4 - EC-EARTH, RACMO22E - EC-EARTH). The mean sea level was taken from PIMA Adapta project (Ramírez et al., 2019) derived from twenty GCMs (MIROC5, MIROC-ESM-CHEM, MIROC-ESM, IPSL-CM5A-MR, GFDL-ESM2G, GFDL-CM3, GFDL-ESM2M, CNRM-CM5, ACCESS1.0, ACCESS1.3, HadGEM2-ES, CCSM4, CSIRO-Mk3-6-0, CanESM2, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M, NorESM1-ME, INM-CM4).

The characterization and simulation of the previous information of climate agents were performed using the work done by Cobos et al. (2022a) using *MarineTools.temporal* software (Cobos et al. 2022b). That characterization allowed the generation of new random time series with the same statistical properties as the original ones.)

2.3. Transformation of agents to the site

Hybrid techniques that combine statistical and numerical methods with physically based models to obtain information at the location are used. More precisely, a selection of representative climate states is made using the maximum dissimilarity algorithm (MDA). These climate states are transformed into location using numerical models that reproduce hydrodynamic processes. Specifically, the DELFT3D suite (Deltares, 2014) is used with data on waves, wind, and sea level at deep water, from which wave and sea level data are obtained in the study area - at depths on the order of 20-25 m. This includes mean sea level, astronomical and meteorological tides associated with wind, as well as wave-induced set-up. Additionally, using DELFT3D-derived level as a boundary condition in an outer area of the estuary, river flow, sediment supply, and level in the last stretch of the river are calculated. This is done either using an improved version of the Guadalfortran model (Ávila, 2007) or the Soil Conservation Service curve number method (USDA 1954).

The results obtained from this task are a time series of waves and sea level, and if applicable, river discharge and sediment supply at river mouths, in an area near each study section.

2.4 Modelling of morphodynamic processes

For this purpose, the CoastalME environment (Payo et al., 2017) has been implemented, using the CSHORE hydrodynamic model (Kobayashi, 2016) and a one-line type coastal evolution model. The model has been specifically improved for this study in collaboration with the British Geological Survey development team to account for: (1) the temporal variability of wave climate and sediment discharges from rivers and creeks, (2) the presence of rigid, non-erodible elements identified using geospatial cadastral information and the BTN25 database, (3) seabed sediment availability, incorporating six sediment layers with thickness that vary spatially and temporally based on effective transport described by Torrecillas et al. (2024). Calibration was performed using satellite-derived shorelines obtained from LandSat 7 through the Arosics and CoastSat tools.

2.5 Simulation of hydro-morphodynamic processes

Wave, water level, and sediment supply data are utilized to simulate the temporal evolution of the coastline using the CoastalME model. Throughout the simulation, hydrodynamic condition data are recorded at regular 3-hour intervals. Topobathymetric properties are stored at the start of each month, and during storms or high river discharge events, they are also saved every six hours, as well as at the beginning and end of these events. The criteria for defining maritime storms follow Lira-Loarca et al. (2020): a significant wave height threshold ($H_s^* = 1.5$ m), a minimum event duration ($d_o = 30$ h) and a minimum time interval between consecutive events ($\delta_o = 24$ h). For river discharges, a threshold of $Q^* = 3.6$ m³/s was identified as suitable for describing Poisson-like events with sediment contributions significant enough to be considered.

The result of this task are 20 equally likely realizations of the dynamic random sets that characterize erosion and flooding in the subunits in a CC scenario during 80 years from the beginning to 2020 to the end of 2099.

2.6 Statistical characterization of erosion and flooding

The random samples obtained from the simulation are analyzed using statistical techniques to characterize a series of random quantities defined according to the Spanish legal framework in regards of coastal protection and sustainable use, with the aim of easing the decision-making process of persons of the Andalusian administration in charge of the authorizations and concessions for the use and/or occupation of land in the public maritime-terrestrial domain and in the easement area for protection of the coasts. Results allow to associate a probability of occurrence with different events related to erosion and flooding in the future at different time horizons (t_H) corresponding to the years 2025, 2030, 2035, 2050, 2100 and distinguishing, whenever applicable, two seasonal periods (P_T) corresponding to peak and off-seasons for tourist in addition to the yearly scale. Those periods range from April 1st and September 30th for the peak tourist season (P_{TA}) and from October 1st to March 31st (P_{TB}) for the off-season for tourists. Some of the analyzed statistical quantities are:

- Shoreline, defined as the intersection curve of the plane of the maximum equinoctial spring high tide with the ground up to 2100 - at a time horizon t_H for each P_T season (Figure 1).
- Mean sea level line, obtained as the intersection curve of the plane of the local mean sea level - at a time horizon t_H for each P_T season (Figure 1).
- Limit to where the waves reach- defined as the envelope curve of the maximum run-up position at a time horizon t_H for each P_T season (Figure 1).
- Dry beach area lost relative to the initial dry beach with dry beach defined as the area between the landward limit of the beach and the level reached by the waves.
- Limit of the permanently flooded area within a time horizon t_H .
- Average annual erosion/accretion rate up to 2100 in a series of sections normal to the initial shoreline position.
- Entry (or not) into a severe regression situation of the area represented through the section due to experiencing a shoreline retreat of more than n meters in m consecutive years and, if applicable, the year in which it enters this situation. The curve obtained for $n = 5$ and $m = 5$ is related to the one indicated in the General Coastal Regulation (RD 876/2014, of October 10).

For all the random quantities, except for the last one, the information provided are georeferenced lines of mean position and 95% confidence bands, as well as the 5th and 95th percentiles.

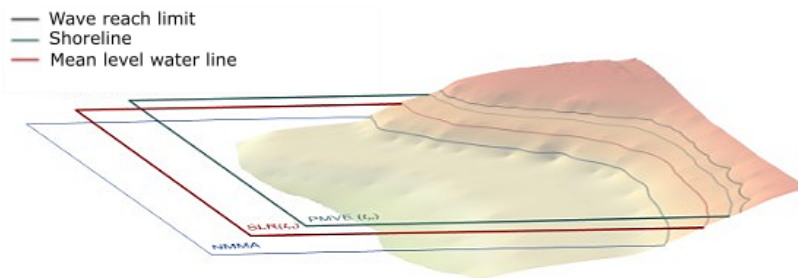


Figure 1. Sketch of the shoreline, mean sea level and limit to where the waves reach at time horizon t_H

3. APPLICATION TO THE ANDALUSIAN COAST

We present in this section some of the results of its application to the coast of Andalusia, that extends from the mouth of the Guadiana River to the mouth of the Almanzora River. One of its shores faces the Atlantic Ocean, while the other faces the Mediterranean Sea, resulting in a coastline with a great variety of typologies, subject to very different climatic conditions (Losada et al. 2009). The Andalusian coast is distinguished by a vast array of geomorphological traits, including coastal plains, rugged bluffs, sandy shores, and several coastal mountain ranges. It comprises three distinct regions: (i) a western segment extending to the Strait of Gibraltar, exposed to significant ocean swells from the Atlantic Ocean, characterized by a mesotidal nature and a prevalence of sandy formations, estuaries, and tidal marshes; (ii) the Strait of Gibraltar, where the exchange of water bodies between the Mediterranean Sea and

Atlantic Ocean occurs; and (iii) the eastern sector (Mediterranean Sea), subjected to milder waves, microtidal conditions, and a higher presence of rocky and cliffed shorelines, along with narrow beaches, deltas, and lagoons (Morales, 2019).

The coast was divided into 18 zones, using both human-made and natural limits, such as the presence of ports with structures reaching maximum depths, geological faults, or steep profiles with a reducible continental shelf. Figure 2 shows the study site, and a detail of the subunits considered within the provinces of Granada and Almería. It also includes information about the river courses and the location of points of employed time series.

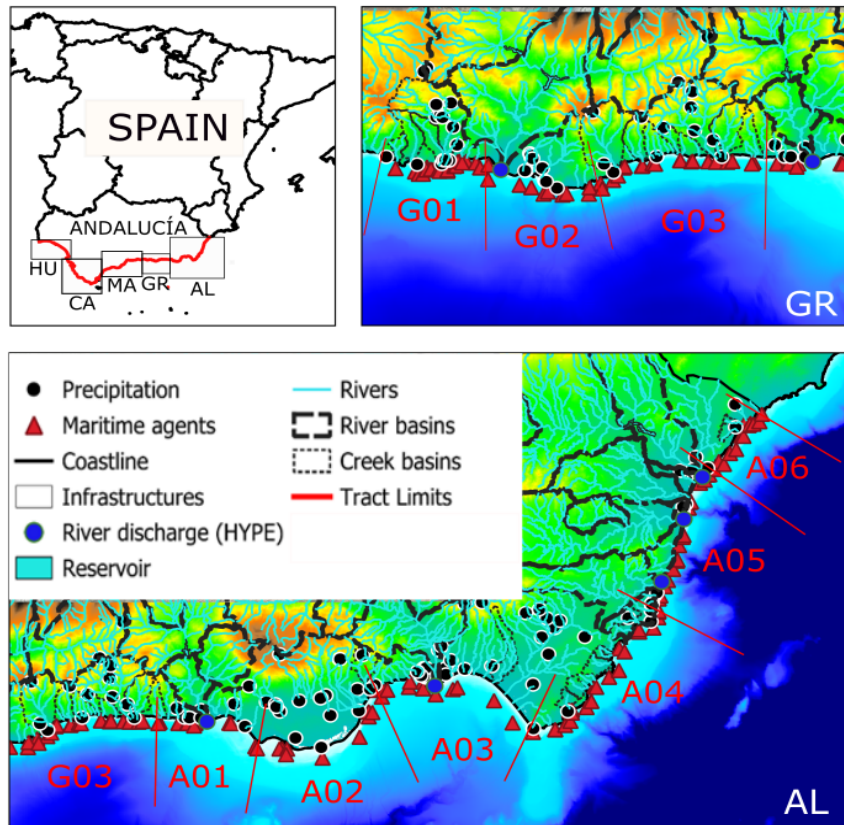


Figure 2. Physical environmental characterization

Figure 3 shows the marginal fits obtained for model MIROC used for the considered atmospheric and wave climate variables used for wave characterization (significant wave height, H_s ; peak period, T_p ; mean wave direction, θ_m ; wind intensity, V_v ; wind direction θ_v ; and storm surge ($M - Meteo$). It also shows the coefficients of the vectorial autorregressive model that relate the values at a given time (denoted by t) with the three previous values (denoted by $t-1$, $t-2$, and $t-3$). The remaining values (up to $t-71$) are omitted due to space constraints. In this regard, in the Figure 4, the results of the ensemble mean result of the consideration of all models listed in section 2.2. are presented. The strong seasonal character of all the variables can be appreciated, with a milder climate in the period from April to September that justifies the consideration of the two touristic seasons for the analysis.

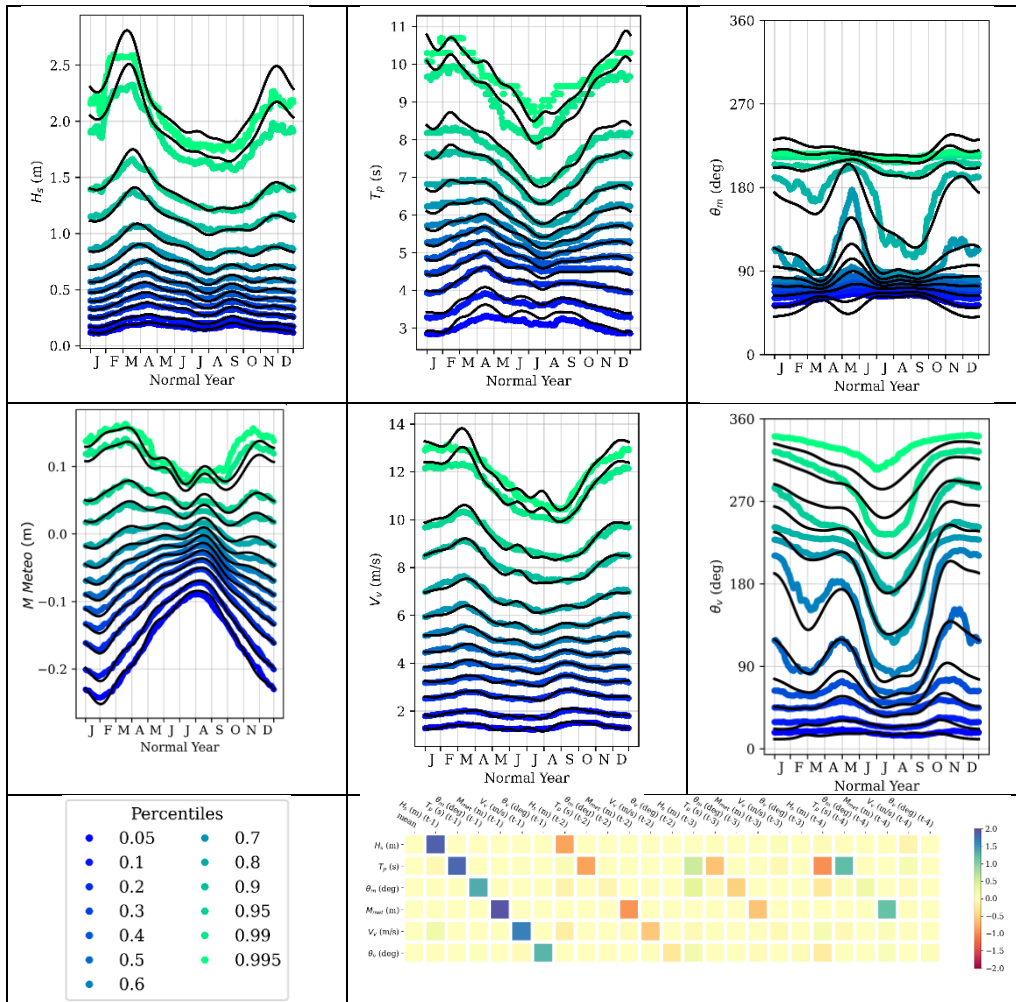
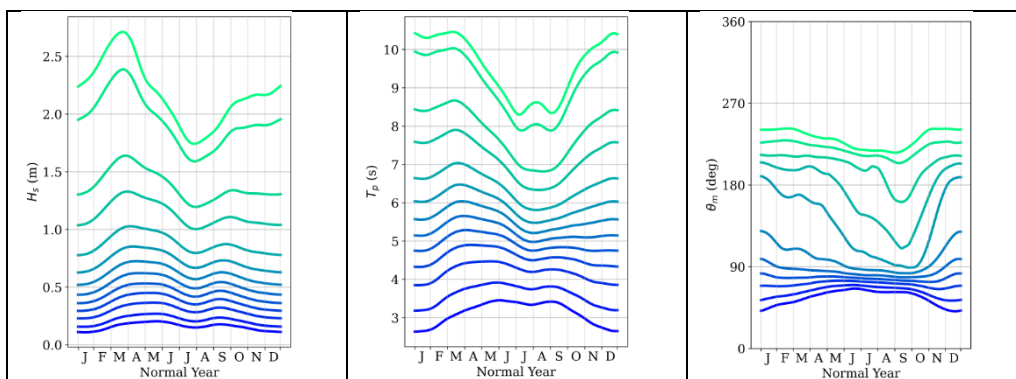


Figure 3. Non-stationary marginal empirical and fitted distributions and some VAR coefficients for atmospheric and wave climate obtained for model MIROC



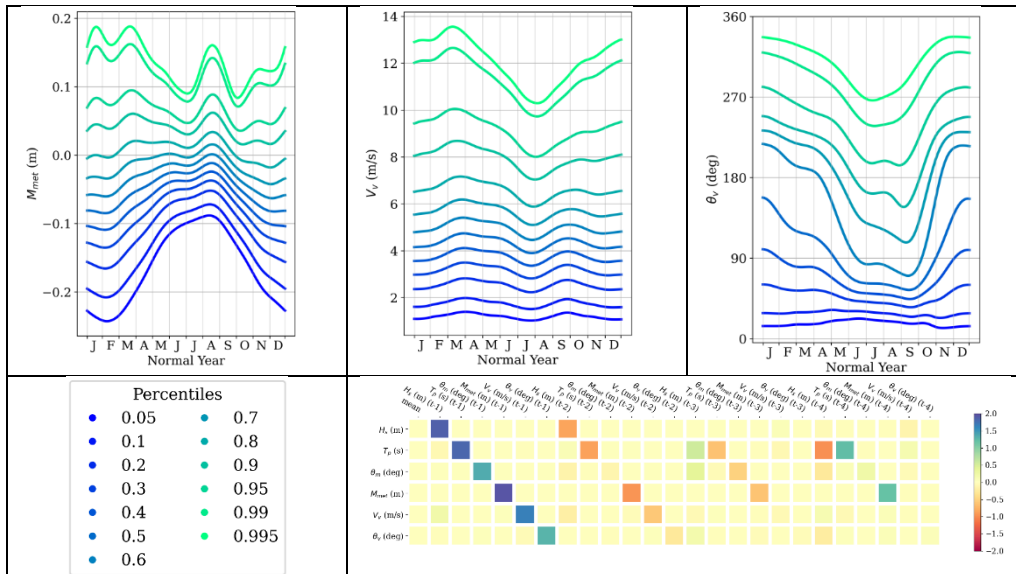


Figure 4. Non-stationary marginal ensemble fitted distributions and some VAR coefficients for atmospheric and wave climate

The results of the analysis of the variables indicated in Section 2.6 for Las Azucenas beach, in the physiographic unit G02, are shown below, with its initial configuration presented in Figure 5. Two rubble-mound breakwaters are grey solid colored and an ephemeral river course which margins are plotted with a grey solid line flow in between. The initial positions of the shoreline and the mean sea level are also shown.

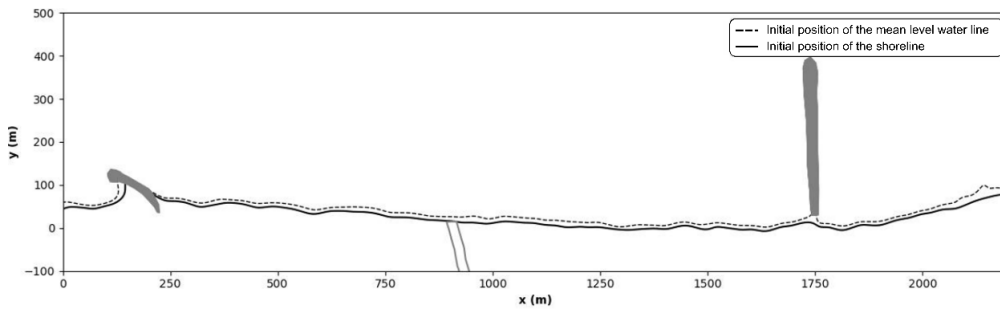


Figure 5. Sketch of the Las Azucenas beach area

Figures 6, 7 and 8 show the mean value of the mean-level line as well as the 5th and 95th percentiles at different time horizons taking the year as a base and for each tourist season. It can be observed that the sediment contribution from the creek favors the formation of a lobe close to the mouth. Erosion is expected all along the coast and differences between the 5 % and 95 % can reach 25 m approximately. The curves obtained for the seasons and the whole year differ in a significant way.

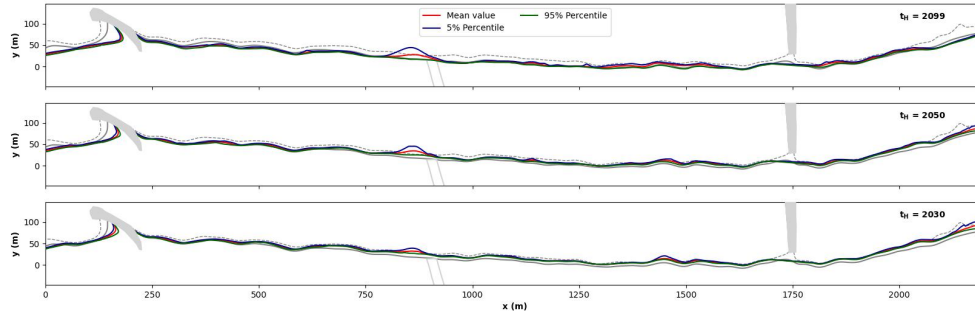


Figure 6. Characterization of the mean-level line (\bar{y}) at $t_H = 2030, 2050$ and 2099

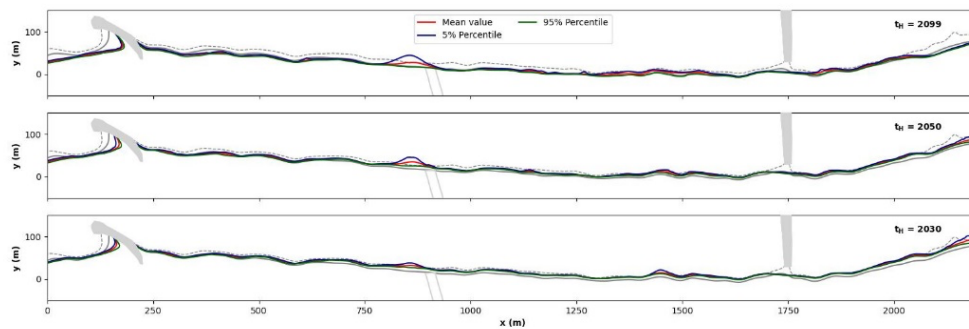


Figure 7. Characterization of the mean-level line (L_M) at $t_H = 2030, 2050$ and 2099 for the season P_{TA}

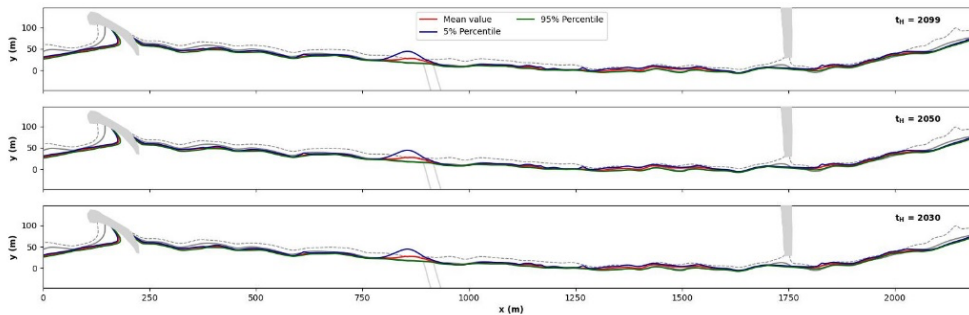


Figure 8. Characterization of the mean-level line (L_M) at $t_H = 2030, 2050$ and 2099 for the season P_{TB}

Figure 9 shows the lines related to the limit where waves reach at different time horizons taking the year as a base. This line is related to that defined in the Spanish law as the landward boundary of the maritime-terrestrial zone. A consistent retreat can be observed within a band which boundaries correspond to the 5 % and 95 % percentiles that are 10 m apart for all the t_H values. Figures 10 and 11 show the results for each touristic season. While the differences between the largest and lowest percentiles are small for the P_{TB} season, for the P_{TA} season they are close to 20 m for the year 2030 and about 7 m for 2050 and 2099. This information is very relevant for the authorization of uses and concessions in the littoral zone.

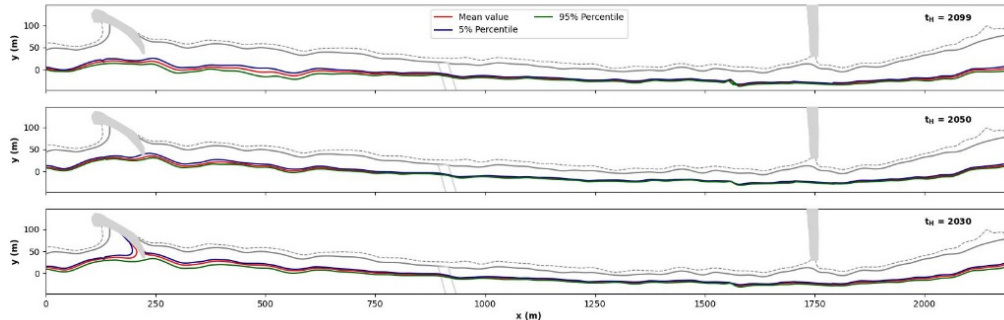


Figure 9. Characterization of the line reached by waves at $t_H = 2030, 2050$ and 2099

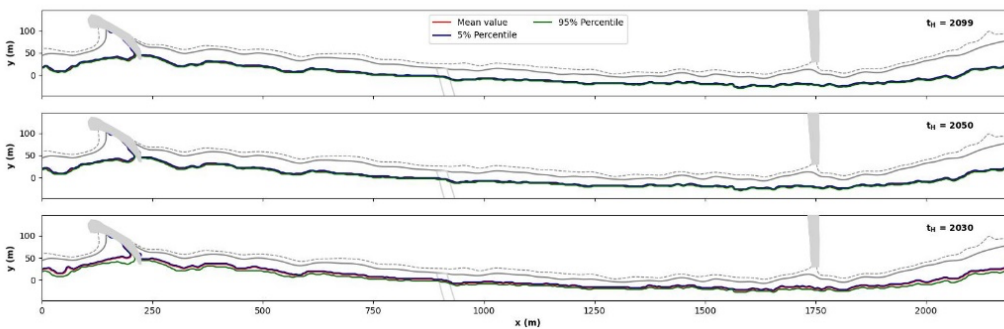


Figure 10. Characterization of the wave reach line at $t_H = 2030, 2050$ and 2099 for the P_{TA} season

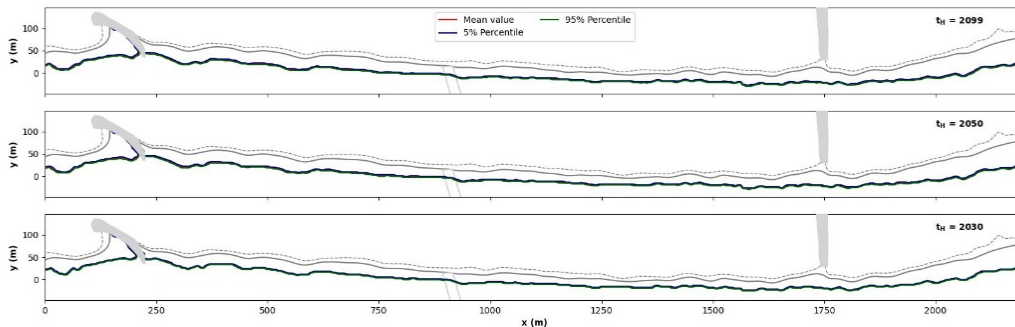


Figure 11. Characterization of the wave reach line at $t_H = 2030, 2050$ and 2099 for the P_{TB} season

According to the law, the Spanish administration may declare a specific coastal stretch to be in a state of severe regression if a retreat of the shoreline of more than 5 meters per year has been recorded in each of the last five years, if it is deemed unlikely to recover its previous state through natural processes. To assess the sensitivity of this criterion's definition to parameter values, Figure 12 presents a matrix highlighting in red the beaches along the coasts of Granada and Almería where the upper shoreline has retreated by more than n meters per year in each of the last m years. The figure also indicates the probability of an occurrence obtained for each beach. For $n = 5$ and $m = 5$, that corresponds to the legal criterion, only two beaches would be declared to be in severe regression, but for other combinations of (n, m) the results would significantly differ. It is remarkable that only one beach consistently appears in the more restrictive conditions.

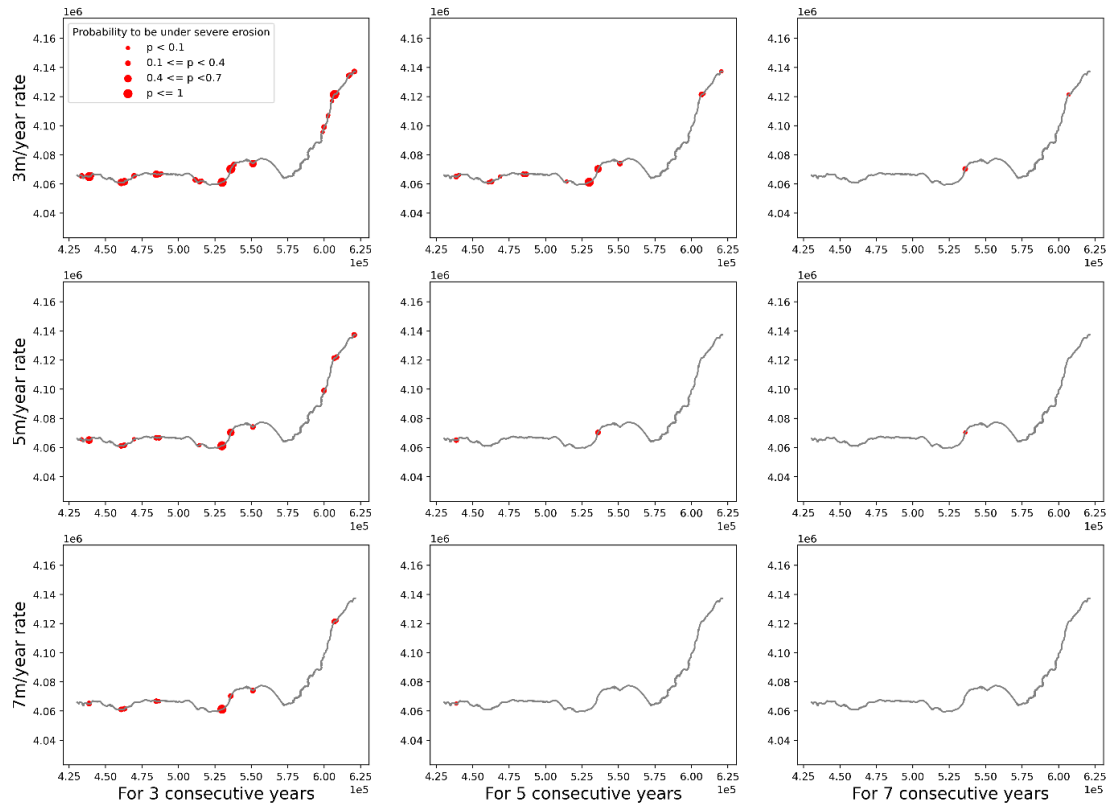


Figure 12. Beaches along the coast of Granada and Almería experiencing a retreat of more than n meters over m years for different values of n and m .

4. CONCLUDING REMARKS

We have presented a methodology to make joint projections of erosion and flooding coastal impacts due to climate change developed within ICCOAST project that, to the authors' knowledge, accounts for the first time for the sediment supply by watercourses in an approach that couples fluvial and maritime hydro-morphodynamic processes, the geological setting, the presence of obstacles and the non-stationarity of climate. In addition, it assesses the intrinsic uncertainty of a set of indicators defined in accordance to Spanish Law aimed at guiding the administration for the exercise of their responsibilities with legal support.

Due to the extension of its application (more than 1000 km of the Andalusian coast), some simplifications have been done. First, a reductionist morphological model is used, in which cross-shore processes are not accounted for, which implies to rely on an equilibrium beach profile and to assume that advances or retreats due to cross-shore transport are perturbations over the long-term coastal change (Payo et al. 2017). In both the Atlantic and Mediterranean Andalusian coast, wave climate comes from almost two distinct modal directions arriving obliquely to the coast, and under such conditions transport in the alongshore direction dominates the sediment budget (see e.g. Fredsoe and Deigaard, 1992). However, cross-shore transport may play a key role in short-term variations, particularly during the storm conditions and recovery and it may interact with long-shore transport.

In addition, the methodology decouples the hydrodynamic and morpho-dynamic processes, although proven to be valid for a few years, it does not account for the nonlinear character of the coastal system that might have effects overall (De Vriend et al. 1993).

Regarding sea level rise, the model does not account explicitly for the so called Bruun effect (1954, 1962) like other works like Álvarez-Cuesta et al. (2021) and Toimil et al. (2021). This approach is closer to the one by Ranasingue et al. (2012) that use synthetic climate and sea level data to force a morphological model.

Estuarine processes are not included in the analysis and, therefore, the results in the proximities of large river mouths should be taken with caution.

Despite those simplifications, the methodology has the advantage of being modular so that any of the modules can be modified to include other processes and improvements for the analysis of a particular coastal stretch.

The statistical analysis of random quantities includes some lines relevant for the management of the coast in the framework of the Spanish legislation. In particular, the extent of wave reach and the conditions that determine severe erosion. Regarding the first one, it limits the maritime-terrestrial zone in which, among other restrictions, there can be no land under ownership other than that of the public domain of the state. According to the law, its delimitation will need to be revised along time. The presented statistical approach highlights the usefulness of defining this line in terms of probability and the consideration of different time horizons. Furthermore, the results related to the declaration of severely regressing areas reveal the arbitrariness of the legal criterion.

The non-stationary way of dealing with climate agents allow to distinguish the results for two different touristic seasons associated to yearly climate variability. Significant differences are found for peak and off seasons, which knowledge allow the administration to make informed-based decisions about authorizations for the use and occupation of the coastal zone.

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REFERENCES

- Álvarez-Cuesta, M., A. Toimil and I.J. Losada. 2021. Modelling long-term shoreline evolution in highly anthropized coastal areas. Part 2: Assessing the response to climate change. *Coast. Eng.* 168. 103961.
- Ávila, A. 2007. Procesos de múltiple escala en la evolución de la línea de costa. *PhD thesis. Universidad de Granada*. In Spanish. 161pp.
- Baquerizo, A. and M.A. Losada. 2008. Human interaction with large scale coastal morphological evolution. An assessment of the uncertainty. *Coastal Engineering*. Special Issue. Vol. 55, pp. 569-580.
- Cobos, M., P. Otiñar, P. Magaña and A. Baquerizo. 2022a. A Method to Characterize Climate, Earth or Environmental Vector Random Processes. *Stochastic Environmental Research and Risk Assessment*.
- Cobos, M., P. Otiñar, P. Magaña, A. Lira-Loarca and A. Baquerizo. 2022b. MarineTools.temporal: A Python package to simulate Earth and environmental time series, *Environmental Modelling & Software*, Volume 150, 2022,105359.
- Davidson, M.A., R.P. Lewis and I.L. Turner. 2010. Forecasting seasonal to multi-year shoreline change. *Coastal Engineering*, 57(6), 620–629.
- Deltares. 2014. Delft3D-WAVE, Simulation of short-crested waves with SWAN, User Manual. Version 3.03. *Deltares*, The Netherlands.

- De Vriend, H.J., M. Capobianco, T. Chesher, H.E. de Swart, B. Latteux and M.J.F. Stive. 1993. Approaches to long term modelling of coastal morphology: A review. *Coastal Engineering*, 21 (1-3): 225-269.
- Fredsoe, J. and Deigaard, R. (1992) Mechanics of Coastal Sediment Transport. *World Scientific*.
- IPCC. 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [A. J. P. Canadell, et al. (eds.)]. *IPCC*.
- Kobayashi, N., 2016. Coastal sediment transport modeling for engineering applications. *J. Waterw. Port Coast. Ocean Eng.* 142 (6), 03116001.
- Lira-Loarca, M. Cobos, M.A. Losada and A. Baquerizo. 2020. Storm characterization and simulation for damage evolution models of maritime structures. *Coastal Engineering* Vol. 156, pp 103620.
- Lira-Loarca, M. Cobos, G. Besio and A. Baquerizo. 2021. Projected wave climate temporal variability due to climate change. *Stochastic Environmental Research and Risk Assessment*.
- Losada M.A., M. Ortega-Sánchez M, A. Baquerizo, J.M. Santiago. 2009. Los cambios de morfología en la costa andaluza. *Enciclopedia Proyecto Andalucía*. Tomo II Ecología. Capítulo 9. Ed. X. Niell. Publicaciones Comunitarias S.L.
- Morales, J.A. 2019. (Ed.) The Spanish Coastal Systems. Dynamic Processes, Sediments and Management, 1st ed.; *Springer*: Berlin/Heidelberg, Germany. p. 823.
- Payo, A., A. Baquerizo and M.A. Losada. 2002. One-line model with time dependent boundary conditions. *Proc. of the 28th Int. Conf on Coastal Engineering*. Vol. 3 pp. 3046-3052.
- Payo, A., A. Baquerizo and M.A. Losada. 2008. Uncertainty assesment: application to the shoreline. *Journal of Hydraulic Research*. Vol. 46, Extra Issue 1, pp. 96–104.
- Payo, A., D. Favis-Mortlock, M. Dickson, J.W. Hall, M.D. Hurst, M.J.A. Walkden, I. Townend, M.C. Ives, R.J. Nicholls, and M.A. Ellis. 2017. Coastal Modelling Environment version 1.0: a framework for integrating landform-specific component models in order to simulate decadal to centennial morphological changes on complex coasts, *Geosci. Model Dev.*, 10, 2715-2740.
- Ramírez, M., M. Menéndez, P. Camus, I.J. Losada. 2019. Tarea 2: Proyecciones de alta resolución de variables marinas en la costa española. Elaboración de la metodología y bases de datos para la proyección de impactos de cambio climático a lo largo de la costa española. *IH Cantabria*.
- Ranasinghe, R. 2016. Assessing climate change impacts on open sandy coasts: A review. *Earth-Sci. Rev.* 160, 320–332.
- Ranasinghe, R., Callaghan, D. and Stive, M.J.F. 2012. Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Climatic Change* 110, 561–574
- Reeve D.E. and M. Spivack. 2004. Probabilistic methods for morphological prediction. *Coast Eng* 51(8 9):661–673.
- Splinter K.D. and G. Coco. 2021. Challenges and Opportunities in Coastal Shoreline Prediction. *Frontiers in Marine Science*. Vol. 8.
- Toimil, A., Camus, P., Losada, I. J., & Alvarez-Cuesta, M. (2021). Visualising the uncertainty cascade in multi-ensemble probabilistic coastal erosion projections. *Frontiers in Marine Science*, 8, 683535.
- Toimil, A., Álvarez-Cuesta, M., & Losada, I. J. (2023). Neglecting the effect of long-and short-term erosion can lead to spurious coastal flood risk projections and maladaptation. *Coastal Engineering*, 179, 104248.
- Torrecillas, C., A. Payo, M. Cobos, H. Burke, D. Morgan, H. Smith, and G.O. Jenkins. 2024. Sediment Thickness Model of Andalusia's Nearshore and Coastal Inland Topography. *J. Mar. Sci. Eng.* 12, 269.
- USDA. 1986. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55). *Soil Conservation Service*.
- Vitousek, S., L. Cagigal, J. Montano, A. Rueda, F. Méndez, F., Coco, G., and P.L. Barnard. 2021. The application of ensemble wave forcing to quantify uncertainty of shoreline change predictions. *Journal of Geophysical Research: Earth Surface*, 126, e2019JF005506.
- Vitousek, S., P.L. Barnard, P. Limber, L. Erikson, and B. Cole. 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research: Earth Surface*, 122(4), 782–806.

- Wainwright, D. J., Ranasinghe, R., Callaghan, D. P., Woodroffe, C. D., Jongejan, R., Dougherty, A. J., ... & Cowell, P. J. (2015). Moving from deterministic towards probabilistic coastal hazard and risk assessment: Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia. *Coastal engineering*, 96, 92-99.
- Zacharioudaki, A., and D.E. Reeve. 2011. Shoreline evolution under climate change wave scenarios. *Climatic Change*, 108,73–105.