Coastal and Offshore Science and Engineering

Impact of Climate Change on Coastal Runup Along the Apulian Coast

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ABSTRACT

Wave runup, the maximum vertical level above still water reached by waves on the foreshore, is a key parameter for evaluating coastal dynamics, flooding, and erosion hazards. This study applies a computationally efficient, basin-consistent procedure to estimate present and future wave runup along the Apulian coastline (southern Italy), used here as a representative Mediterranean case study. The coastline is divided into DIVA (Dynamic Interactive Vulnerability Assessment) segments, each linked to the nearest WAM (WAve Model) grid point providing significant wave height and mean period data. Runup is computed using the empirical Stockdon formulation from WAM simulations forced by COSMOMED011 wind fields, covering the historical (1959–2005) and future (2006–2100) periods under RCP4.5 and RCP8.5 scenarios. Changes between time slices (2021–2040, 2041–2060, 2081–2100) and the baseline (1986–2005) are assessed using the Mann-Whitney U test at the 90 % confidence level. Results show a decrease in mean and maximum wave runup, larger under the high-emission scenario and toward the end of the century, when average reductions are about 10% along the coastline, with local maxima up to approximately 13%. However, this reduction is insufficient to compensate for projected sea-level rise, implying that the combined risk of coastal erosion and flooding will continue to increase. The proposed framework provides a transferable and efficient method for first-order assessment of climate-driven coastal hazards along data-limited Mediterranean shorelines.

KEYWORDS: Wave runup, Coastal Erosion, Apulian coastline, Empirical formula (Stockdon), Climate Change

1. INTRODUCTION

The coastal zone represents a dynamic interface between land and sea, hosting diverse ecosystems, critical economic activities, and densely populated settlements. These areas are particularly vulnerable to natural and anthropogenic pressures, including waves, tides, currents, sediment transport, and sea-level variations, which continuously reshape coastlines. As climate change accelerates sea-level rise and modifies storminess patterns, coastal regions worldwide face increasing risks of erosion, flooding, and habitat loss.

The Apulia region, located in southeastern Italy, offers an illustrative case study for analyzing such risks. Its coasts encompass diverse geomorphological settings, with sandy beaches being especially exposed to storm surges, erosion, and long-term shoreline retreat (Dal Barco et al., 2024). Given the region's cultural, agricultural, and touristic importance, assessing its future vulnerability is essential for supporting

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policymakers, engineers, and coastal managers in the development of effective adaptation strategies.

A key process shaping coastal response is wave runup, defined as the maximum vertical extent of wave uprush above the still water level (Stockdon et al., 2006; Pillai et al., 2019). Runup plays a central role in coastal flooding, dune overtopping, and beach erosion, as it delivers much of the wave energy to the upper foreshore (Ruggiero et al., 2001). Its magnitude depends on wave characteristics (height and period), beach slope, and nearshore bathymetry. Consequently, shifts in wind and wave regimes induced by climate change are expected to alter runup patterns, with direct implications for coastal hazards.

In recent decades, growing attention has been devoted to understanding how climate change will affect coastal hazards through combined changes in sea level, storm surge, and wave dynamics. Several studies have highlighted the role of wave runup in modulating flooding and erosion risks, showing that even moderate shifts in wave climate can substantially alter coastal vulnerability (Harris et al., 2010; Serafin & Ruggiero, 2014).

Various approaches have been proposed to estimate wave runup, ranging from early empirical formulations developed for limited slope ranges and specific beach types (Hunt, 1959; Holman, 1986; Mase, 1989; Ahrens, 1981) to physics-based numerical models such as XBeach (Rutten et al., 2021; De Beer et al., 2021) and SWASH (Damiani et al., 2018). Empirical approaches, such as the formulation proposed by Stockdon et al. (2006), remain widely used because of their simple analytical form, limited data requirements, and ability to capture first-order runup variability across different beach states. The Stockdon formulation explicitly accounts for both dissipative and reflective beach conditions through the Iribarren number, although its accuracy can vary depending on local morphology and wave conditions. Its application in the Mediterranean has been documented in several studies, including analyses of pocket beaches in the Eastern Mediterranean (Vousdoukas et al., 2009), sandy coasts along the Tyrrhenian Sea (Di Luccio et al., 2020), and microtidal beaches on Mallorca Island in the north-western Mediterranean (Agulles et al., 2024), highlighting both its applicability and limitations under regional morphodynamic variability.

While process-based models can simulate storm-driven runup and overtopping under complex hydrodynamic conditions, their high computational demand limits their use for regional-scale and multi-decadal assessments. In this context, the Stockdon formulation provides a practical framework for evaluating climate-driven changes in wave runup along heterogeneous coastlines such as Apulia, while acknowledging uncertainties related to local geomorphological variability and extreme beach types.

The present research aims to demonstrate a methodological procedure for assessing current and future wave runup conditions along the Apulian coastline. Historical simulations (1959–2005) are compared with future projections (2006–2100) under Representative Concentration Pathways RCP4.5 and RCP8.5, corresponding to intermediate- and high-emission scenarios of greenhouse gas concentrations (IPCC, 2007). Beyond its regional focus, the study is intended to provide a transferable framework for integrating climate projections into coastal hazard assessments, thereby bridging the gap between climate modeling and coastal risk management.

2. METHODOLOGY

This study integrates climate model outputs, wave simulations, and empirical formulations to estimate present and future wave runup conditions along the Apulian coastline. The approach combines wind forcing from a high-resolution regional climate model, wave propagation simulated with the WAM spectral model, and runup estimates derived from the Stockdon et al. (2006) empirical parameterization. The Apulian coastline, located in southern Italy and bordered by the Adriatic and Ionian seas (Figure 1), is an excellent case study because of the presence of different coast morphologies: long sandy beaches, pocket beaches, rocky coasts, some of them with high cliffs.

Figure 1. Mediterranean Sea map with subdivisions, straits, islands, and countries. Modified from OH-237, CC-BY-SA 4.0. The study area is marked with the black rectangle. https://commons.wikimedia.org/wiki/File:Mediterranee_02_EN.jpg

2.1. The Stockdon's empirical formula

Wave runup is estimated using the empirical parameterization proposed by Stockdon et al. (2006). In this formulation, runup depends on the foreshore slope (β_f), the offshore significant wave height (SWH H_0), and the deep-water wavelength (L_0), and is expressed as:

$$R_2 = 1.1\left(0.35\left(\beta_f(H_0L_0)^{1/2}\right) + \frac{\left[H_0L_0\left(0.563\beta_f^2+0.004\right)\right]^{1/2}}{2}\right) \qquad (1)$$

where R_2 is the 2% exceedance value of runup. This expression has two limits, depending on the Iribarren number (sometimes called dynamic beach steepness) $\xi_0 = \frac{2^{1/2}\beta_f}{w^{1/2}}$, that is the ratio between foreshore slope and the square root of the offshore wave steepness $w = \frac{2H_0}{L_0}$ (Battjes, 1974):

- Dissipative conditions ($\xi_0 < 0.3$), where the Iribarren number is low and runup is expressed as $R_{2ds} = 0.043\ (H_0L_0)^{1/}$
- Reflective conditions ($\xi_0 > 1.25$), where infragravity wave contributions can be neglected and runup simplifies to $R_{2rf} = 0.73\ \beta_f\ (H_0L_0)1/2$

The Stockdon's formula can be rearranged to emphasize the role of the wave steepness and the beach slope by defining an amplification factor A= $R_2/\ H_0$, which in general is

$$A = 1.1\sqrt{\frac{2}{w}}\left[0.35\beta_f + \frac{1}{2}\left(0.563\beta_f^2 + 0.004\right)^{1/2}\right] \qquad (2)$$

with $A_{ds} = 0.043\sqrt{\frac{2}{w}} \approx 0.0608w^{-1/2}$ and $A_{dsrf} = 0.73\ \beta_f\sqrt{\frac{2}{w}} \approx 1.033\beta_f w^{-1/2}$ for dissipative and reflective conditions, respectively.

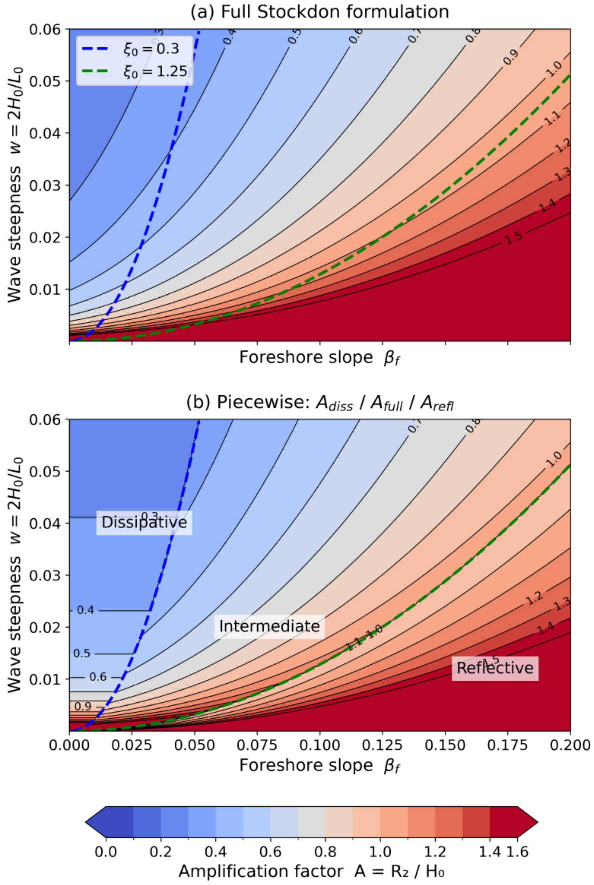


Figure 2. Amplification factor $A = R_2/H_0$ as a function of foreshore slope (β_f) and wave steepness ($w = 2H_0/L_0$). Left panel: results obtained from the full Stockdon et al. (2006) empirical formulation. Right panel: Piecewise implementation applying the limiting expressions for dissipative ($\xi_0 < 0.3$) and reflective ($\xi_0 > 1.25$) conditions, and the full formulation for intermediate regimes. Dashed lines mark the

theoretical regime boundaries ($\xi_0 = 0.3$ *and* $\xi_0 = 1.25$*). The color scale represents the magnitude of the amplification factor, increasing from light blue (low runup) to deep red (high runup). Labeled regions indicate the morphodynamic classification of the beach response: Dissipative, Intermediate, and Reflective.*

Figure 2 illustrates how the amplification factor A varies as a function of the foreshore slope β_f and offshore wave steepness w. The pattern reflects the combined influence of coastal morphology and offshore wave conditions on the relative magnitude of runup. Low values of A occur for steep waves (large w) and gently sloping beaches, while higher values correspond to flatter waves and steeper beach slopes. The dashed curves delimit the dissipative, intermediate, and reflective regimes. In the piecewise representation, the full Stockdon formula tends to underestimate/overestimate the runup for very small/steep slopes with respect to the limiting analytical expressions. However, this study has always used the full Stockdon formula (Eq. 1) to ensure a smooth transition along the coastline.

2.2. *Wave Model*

Wave simulations were performed with the third-generation spectral model WAM (Group, 1988), which resolves the generation and propagation of wind-driven waves. The model solves the spectral energy balance equation:

$$\frac{\partial F}{\partial t} + \nabla\left(C_g F\right) = S_{in} + S_{nl} + S_{ds} + S_{bf}$$

Where $\frac{\partial F}{\partial t}$ is the local time variation of the wave spectrum F, $\nabla\left(C_g F\right)$ is the divergence of the energy flux $\left(C_g F\right)$ where C_g is the group velocity. The terms on the right side indicate the source function: S_{in} is the wind input, S_{nl} are the nonlinear interactions due to the resonant wave-wave interactions, S_{ds} is the dissipation due to the white capping and S_{bf} is the bottom friction. These source terms are functions of the wave spectrum.

The WAM model was implemented on a 0.25° grid covering the Mediterranean Sea, with 12 directional bins and 25 frequency bins. Outputs include significant wave height, mean wave period, and wave direction at 3-hour intervals. For each DIVA coastal segment (Section 2.4), runup was calculated using wave conditions from the nearest WAM grid point. Specifically, the mean wave period (Tm) and SWH from WAM outputs were used in the Stockdon et al. (2006) formulation to calculate runup.

2.3. *Climate Simulations*

The WAM simulations were forced with wind fields from the COSMO-MED0.11 regional climate model (Conte et al., 2020). This dataset operates at ~12.5 km horizontal resolution and provides continuous coverage for both the historical period (1960–2005) and future projections (2006–2100) under Representative Concentration Pathways (RCP4.5 and RCP8.5; Moss et al., 2010). The model outputs include precipitation, near-surface temperature, wind fields, radiation fluxes, and humidity. For this study, 10 m wind speeds were extracted and used to drive WAM, thereby generating wave conditions consistent with climate forcing.

2.4. *DIVA Segmentation*

Coastal segmentation was performed using the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel & Klein, 2009), which represents the Apulian coastline as a series of linear units characterized by 160 parameters describing local morphology, population, and hazard characteristics. The horizontal length of segments varies between 403 m and 8,874 m, reflecting differences in parameter requirements. DIVA provides segment-averaged slope parameters defined over homogeneous coastal units at the subregional scale, rather than detailed local morphodynamics. Consequently, small-scale morphological features such as beach cusps, berms, pocket beaches, cliffs, or localized seasonal variability are not resolved. This limitation may introduce uncertainty in local wave runup estimates, particularly along reflective or highly variable coastal sectors. Nevertheless, this approach provides a consistent regional-scale framework suitable for a first-order assessment of coastal runup changes. The DIVA model was developed to support large-scale risk and impact assessments related to sea level rise and is designed to be applicable across extensive coastal regions.

The data for the Apulian coastline were extracted from the version of DIVA implemented for the Mediterranean Basin (Wolff et al., 2018). The Apulian coastline was divided into 266 DIVA segments (Figure 3). Each segment was associated with a single offshore WAM grid point to provide consistent linkage between local coastal units and wave forcing conditions.

The association between DIVA segments and WAM grid points is performed using a point-based nearest-neighbor criterion: each DIVA segment is represented by its midpoint, and distance is computed between this segment center and the centers of the WAM grid points. Each segment is then linked to the single closest WAM grid point. In cases where multiple DIVA segments are closest to the same grid point, all such segments share that grid point as their offshore wave forcing. Due to this point-based approach and the coarse resolution of the WAM model, individual DIVA segments are always associated with exactly one WAM grid point and never span multiple grid points.

There is a clear difference in spatial resolution between the WAM wave model (0.25°, ~28 km) and the DIVA coastal segments. The WAM resolution represents offshore wave conditions and captures the large-scale variability of the Mediterranean wave field. Fine-scale wave variability at the coast is instead controlled by coastal geometry, shoaling processes, and segment-specific morphology, which are represented through the characteristics of the DIVA segments. Although the actual regime of each coastal segment depends on its specific wave and morphodynamical parameters, the diagram helps visualize how changes in either slope or offshore wave steepness can modify runup magnitude. In particular, gentle beaches with steeper waves are expected to show lower amplification, while steeper coasts exposed to flatter waves are associated with higher potential runup. This relationship provides a useful physical reference for interpreting modelled variations in runup intensity and their spatial heterogeneity along the Apulian coastline.

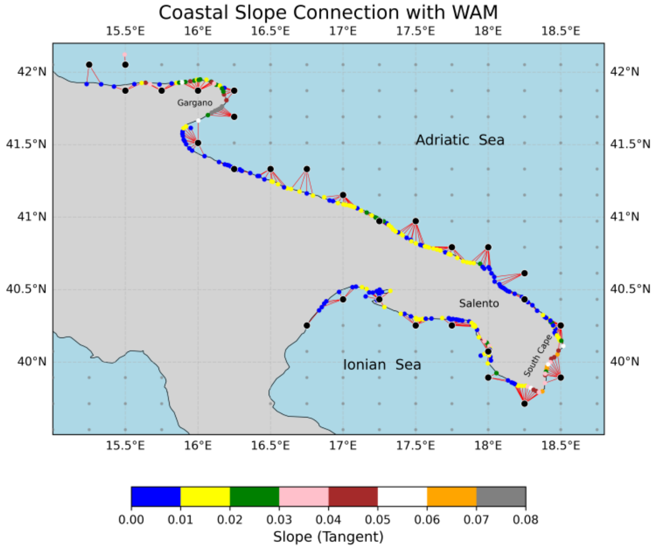


Figure 3. Segmentation of the Apulian coastline. Each segment is connected to the nearest WAM grid point used where offshore wave data are available for runup calculations (red lines). Dots show the location of the central point of the segment and colors denote the slope of the coast.

2.5. *Statistical analyses*

The analysis was structured into time slices consistent with IPCC (Chen et al., 2021) guidance:

- **Baseline** (1986–2005),
- **Near-term** (2021–2040),
- **Mid-term** (2041–2060),
- **Long-term** (2081–2100).

For each DIVA segment, four indicators were computed: mean annual runup, mean monthly runup, maximum annual runup, and maximum monthly runup. Differences between baseline and projected periods were evaluated separately for RCP4.5 and RCP8.5 scenarios.

Statistical significance was assessed using the non-parametric Mann–Whitney U test

at the 90% confidence level ($p < 0.1$). Segments with significant changes were identified and they are where climate change can potentially change the risk of erosion caused by runup.

3. RESULTS

3.1. Baseline conditions

Figure 4 shows the annual average and maximum runup (left and right panels, respectively) along the Apulian coast for the baseline period. Average runup values reach up to about 0.55 m, while maximum runup ranges from 1 m to 4 m. Both quantities increase with foreshore slope and are modulated by offshore significant wave height (SWH). The highest values occur where both SWH and slope are large under reflective conditions of the steep rocky coast near the southern cape, whereas the lowest values are found along the dissipative sandy beaches immediately south of Gargano, where both SWH and slope are small. Secondary maxima appear on the southern coast of Gargano and on both sides of the Salento peninsula (Ionian and Adriatic), associated with locally larger SWH and slope values.

Figure 5 presents the annual cycle of average and maximum runup for the baseline period. Both variables, together with SWH, exhibit higher values during winter (maxima in January–February) and lower values during summer (minima in May–June for the average and maximum runup, respectively).

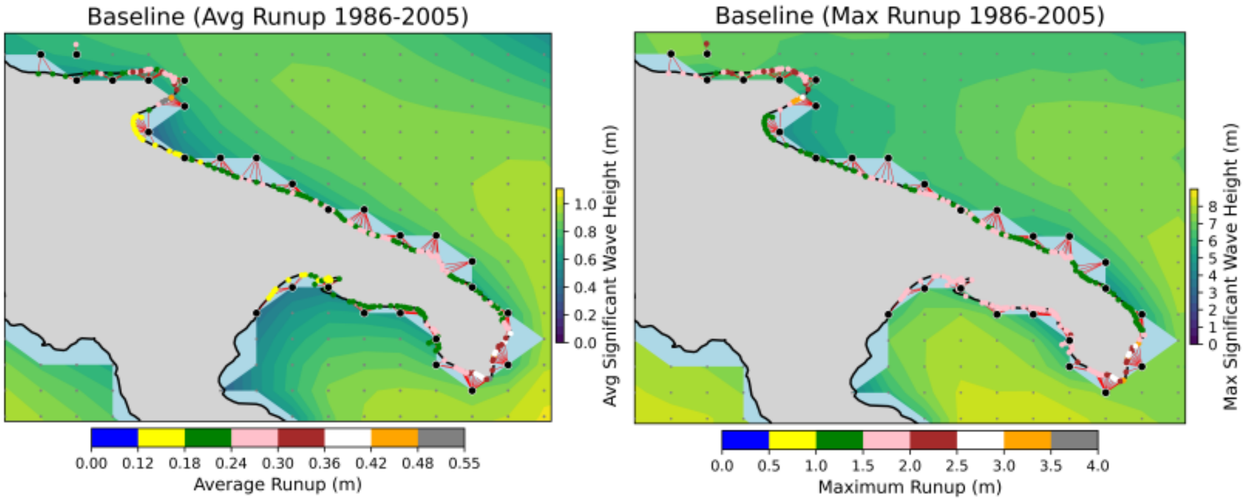


Figure 4. Left panel: dots along the coastline show the average runup for the period 1986-2005 and the background field the average offshore SWH. Right panel: same as left panel except it shows the maximum runup and SWH.

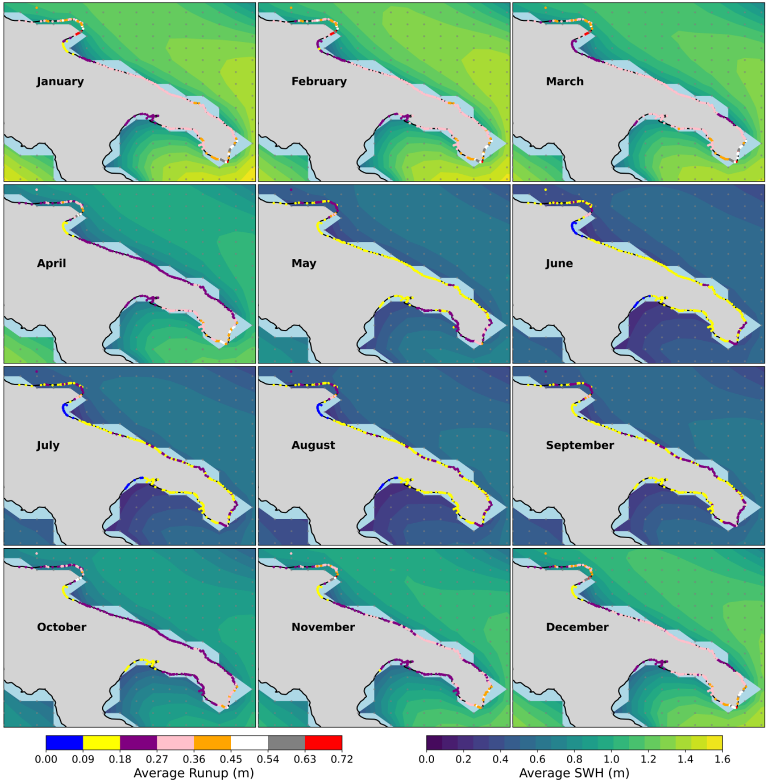
3.2. Projected changes in runup

Figure 6 displays projected changes in annual average runup along the Apulian coastline for different climate scenarios and time slices, expressed as anomalies relative to the baseline period. The results show a general decrease in runup over time, with only a few locations showing significant changes in the near term. Reductions are stronger for RCP 8.5 than for RCP 4.5. The largest runup decrease occurs in the long-term (2081–2100) under RCP 8.5 (Figure 6f), where SWH decreases by about 0.17 m along the southern edge of the domain. The consequent runup average reduction is 10.41% with local maxima up to 13% at the southernmost tip of Apulia compared with the baseline.

Figure 7 is analogous to Figure 6 but refers to maximum runup. A striking difference compared with average runup is the absence of points with statistically significant variations, plausibly reflecting the larger interannual variability of maxima, except for the long-term RCP 8.5, where a reduction in maximum runup is evident for the long-term RCP 8.5 projection along the Ionian coast of Salento with negative anomalies reaching about 0.4 m.

The statistical analysis of monthly-scale changes (Figure 8) confirms these tendencies. The percentage of points with significant differences increases over time and with emission scenario, though with some irregular behaviour in the near term when anomalies remain small. Generally, average runup tends to increase slightly in late spring and decrease for the rest of the year. The largest and most consistent decreases occur in the long-term RCP 8.5 case. Maximum runup shows a similar pattern but with smaller percentage changes. In both indicators, the fraction of segments with significant decreases is substantially greater than that with increases.

(a) Monthly Average Runup and Average SWH (1986–2005)



(b) Monthly Maximum Runup and Maximum SWH (1986–2005)

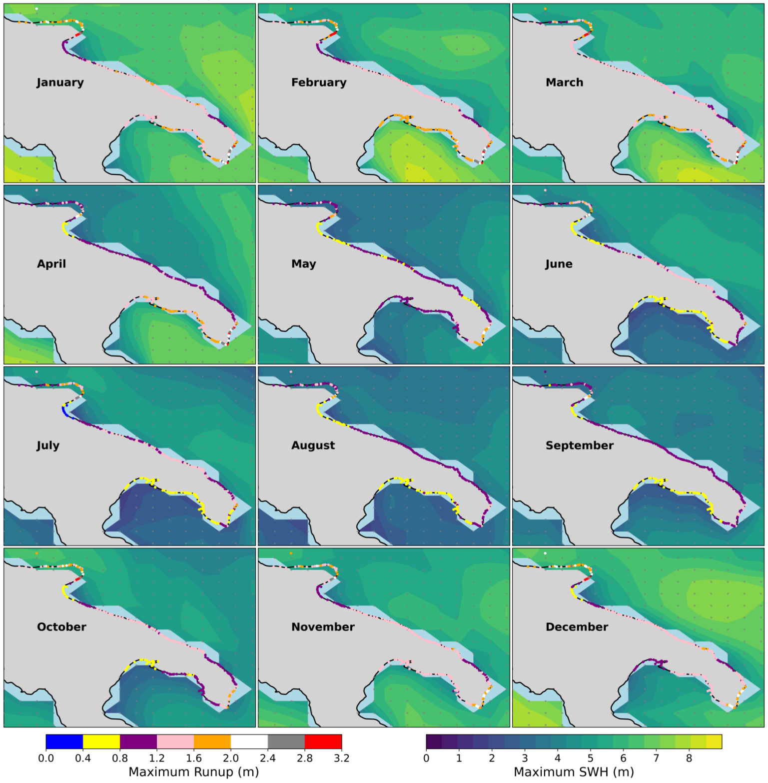


Figure 5. Annual cycle of Average Runup (a) and Maximum runup (b) during the baseline period (1986-2005). Each panel shows a single month. Dots along the coastline show the runup and the background field shows the offshore SWH.

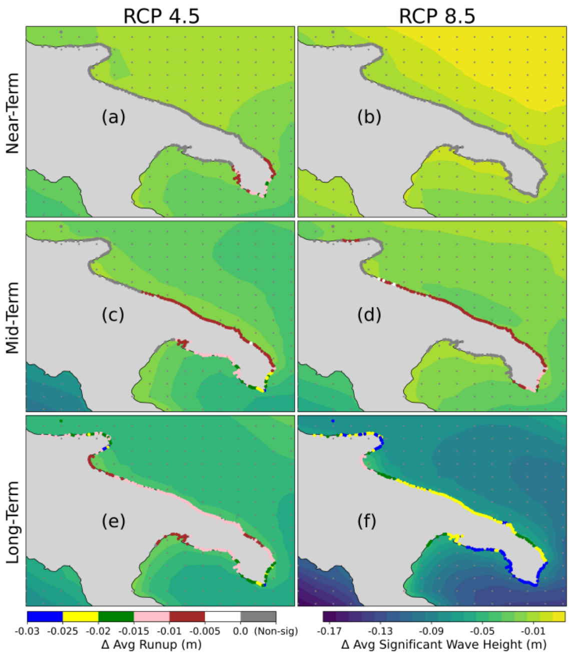


Figure 6: Projections of annual average runup (dots along the coastline) and offshore SWH (background field). Each panel shows differences with respect to the baseline (1986-2005). Color dots (left color bar) denote points where confidence level is higher than 90%. Grey dots denote segments with no significant change. Left column (a, c, e) and right column (b, d, f) considers the RCP4.5 and RCP8.5 scenarios, respectively. Rows refer to time slices: top row (a,b) near-term 2021-2040, middle row (c,d) mid-term 2041-2060, bottom row (e,f) long-term 2081-2100.

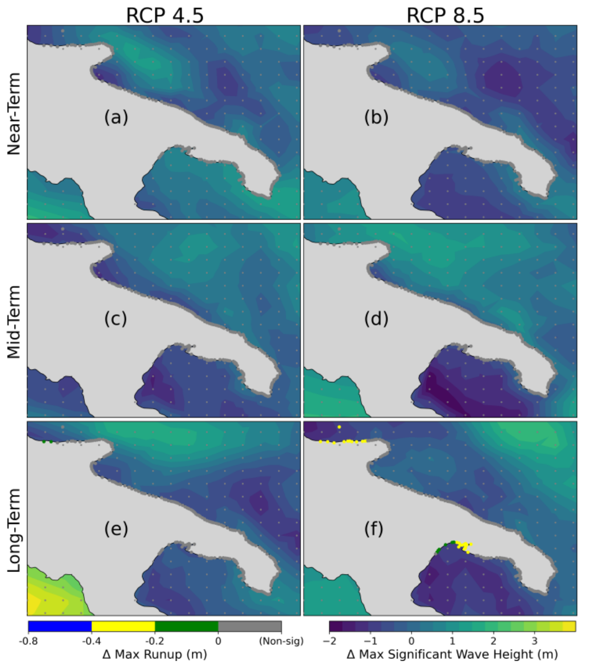


Figure 7. Same as figure 6 except it considers the annual maximum runup.

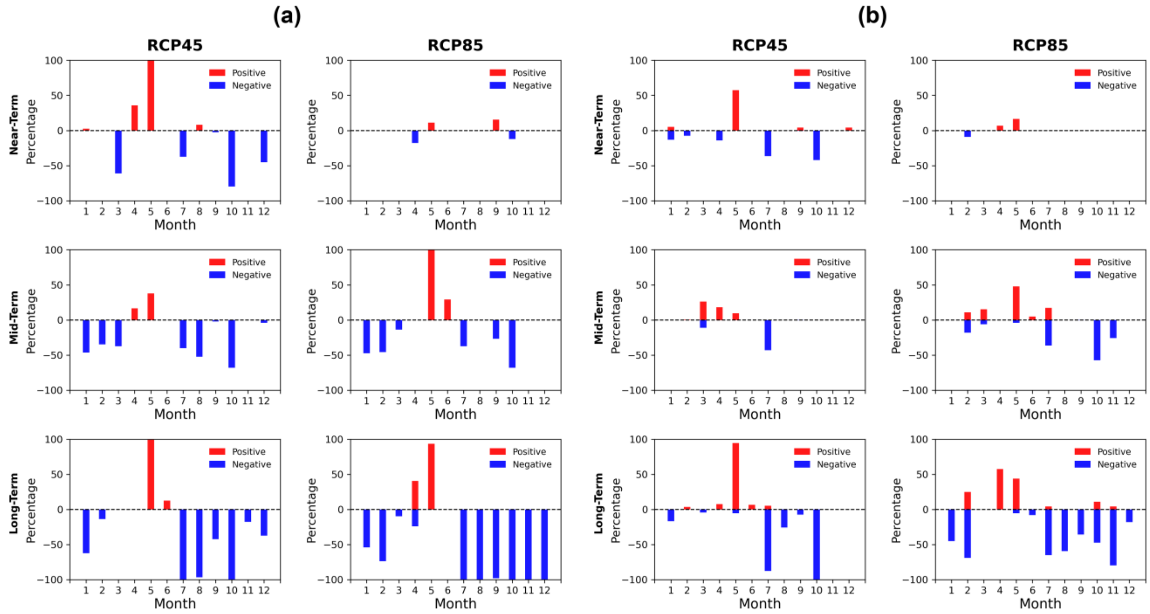


Figure 8. Percentage of segments with significant changes with respect to Baseline (1986-2005) at monthly scale for average (a) and maximum (b) runup. Blue/red bars indicate the fraction of negative/positive anomalies that are statistically significant at the 90% confidence level. Months are numbered along the x-axis. Panels consider different time slices (near, mid, long-term from top to bottom rows) and scenarios (columns).

4. DISCUSSION AND CONCLUSIONS

To evaluate the relevance and usefulness of this study, it is important to clarify the objectives of the adopted methodological framework. Its main purpose is to provide a computationally efficient, broad-scale, and approximate evaluation that allows comparison among coastal sectors regarding their potential exposure to future hazards. This approach can serve as a first screening tool to identify the stretches of coastline where more detailed, dynamically based modelling would be required. In this sense, the present study represents a preliminary step toward a comprehensive methodology for assessing the impacts of climate change on the coastal environment. Beyond the Apulian case, this framework provides a transferable approach for first-order coastal risk screening in other Mediterranean and semi-enclosed basins, where data limitations often hinder the use of fully dynamic models.

This procedure avoids the practical limitations of fully dynamic models such as XBeach (Rutten et al., 2021; De Beer et al., 2021) and SWASH (Damiani et al., 2018). Those models provide highly accurate results at local scale and for individual events (Stockdon et al., 2014), but their computational demand makes them unsuitable for large-domain or multi-decadal simulations. In contrast, the Stockdon formula offers a simple and robust tool for estimating runup, which, as shown in this study, can be effectively applied in multi-decadal, multi- scenario, and multi-model analyses along a coastline of about 865 km (Basso et al., 2013). Nonetheless, this empirical approach has inherent limitations: it cannot replace the precision of process-based hydrodynamic models and it is not universally accurate across all coastal settings.

A qualitative assessment of uncertainty is required when interpreting the runup estimates presented in this study. The Stockdon et al. (2006) formulation was originally derived and calibrated using observations from sandy, open-coast beaches, and although it conceptually accounts for both dissipative and reflective regimes through the Iribarren number, its applicability to rocky, steep, or highly reflective coastal sectors remains more uncertain. This aspect is particularly relevant for portions of the Apulian coast characterized by such morphologies, whereas a large fraction of the coastline is composed of sandy beaches, for which the formulation is more directly applicable.

Additional uncertainty arises from the wave forcing provided by the WAM model. In the Mediterranean Sea, characterized by complex coastal geometry and fetch-limited conditions, basin-scale wave models operating at resolutions comparable to that used here are widely adopted in the literature to simulate wave climate evolution and to produce wave projections. Differences among available wave datasets, including members of the MED-CORDEX ensemble, can lead to variations in wave heights and periods, and consequently in the derived runup estimates. At the same time, higher-resolution or nearshore models such as SWAN, SWASH, or XBeach can better resolve local wave transformation processes and alongshore variability, but their computational cost limits their applicability for multi-decadal, regional-scale assessments. In this context, the present study is intended to demonstrate a consistent and transferable framework for estimating wave runup along Mediterranean coastlines, rather than to provide definitive local-scale projections.

A critical factor in the analysis is the use of realistic values for the foreshore slope, which, together with SWH, plays a fundamental role in determining runup within the Stockdon formulation. Small variations in the slope can substantially modify the results. The Stockdon equation assumes an idealized rectilinear coastal profile and constant slope; therefore, it cannot adequately capture the influence of complex morphologies, tidal inlets, or the presence of coastal structures, marshes, or mangroves that can affect wave transformation near the shore. In this study, the foreshore slope values were estimated from the DIVA model and the corresponding land-elevation profiles. Small-scale morphological features such as beach cusps, berms, small bays, are not resolved. This can lead to some uncertainty in local wave runup estimates, especially along reflective or highly variable coasts. Future work will aim to refine these slope estimates, using higher-resolution coastal data and improved topographic information, and to recompute runup accordingly.

The computed mean and maximum runup values reach their largest magnitudes near the southern cape of Apulia, where steep slopes and large SWH combine to yield values exceeding 0.55 m (mean) and 4 m (maximum). Along the relatively flat Adriatic coastline, the maximum runup greater than 1 m is still common, and values above 1.5 m are found on the Ionian side. The seasonal cycle reveals that both runup and offshore SWH peak from December to March, corresponding to the most energetic winter conditions.

The runup projections presented here are consistent with the expected future attenuation of wave energy in the Mediterranean Sea reported by previous studies (Ibarra-Berastegui et al., 2025; Cherif et al., 2020; De Leo et al., 2024; De Leo et al., 2021; Lionello et al., 2008; MedECC, 2024). Both annual-mean and maximum runup tend to decrease with time and with emission scenario intensity, with the largest reductions occurring in the long-term RCP 8.5 simulations. On the monthly scale, this general decline is confirmed, except for late spring, when small positive anomalies appear and tend to grow with time and scenario severity. These results are coherent with the general Mediterranean tendency toward weaker wind and wave regimes combined with a persistent rise in mean sea level, confirming that Apulia reflects broader basin-scale coastal responses to climate forcing.

Overall, these results indicate that while runup intensity may slightly decrease under future climate conditions, the combined effects of sea-level rise (numerically much larger than the runup reduction resulting from this study) and ongoing coastal pressures will continue to enhance the vulnerability of low-lying Apulian beaches (Ali et al., 2022; Lionello et al., 2017).

The empirical framework applied here is intended to provide a practical first-order assessment of spatial patterns in projected wave runup change along the Apulian coast and similar Mediterranean settings, with modest computational requirements. From a coastal management and policy perspective, such a regional-scale assessment can support strategic planning by guiding the prioritization of monitoring efforts, adaptation measures, and resource allocation. At the same time, the results emphasize that broad-scale approaches are unable to fully resolve local-scale coastal processes and site-specific dynamics. Consequently, the coastal sectors identified as potentially more exposed should be the focus of targeted follow-up investigations using high-resolution, local-scale modelling. Overall, this study highlights the value of integrated regional-to-local assessment frameworks, in which regional analyses are used to guide and inform more detailed site-specific investigations, rather than to replace them

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OH-237 (2015, February 13) *Map of the Mediterranean Sea with subdivisions, straits, islands and countries* [Image]. CC-BY-SA 4.0. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Mediterranee_02_EN.jpg

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