Sea-level change and the supralittoral environment: Potential impact on a splashpool habitat on the Ligurian coast (NW Mediterranean)

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Abstract

Climate change is one of the primary causes of habitat modification in a wide range of environments. Great effort is being made in coastal environments to understand and forecast the potential effects of such processes, with Sea-Level Rise (SLR) being one of the most studied phenomena. This paper discusses the potential effects of various 2100 sea-level scenarios on greenhouse gas mitigation policies (Representative Concentration Pathways - RCPs). This research was carried out on a supralittoral habitat in Genova (Ligurian Sea) and covered an eventual change in environmental conditions caused by SLR, which could impact the resident Culicid *Acartomyia mariae*. The XBeach model was used to simulate the wave run-up caused by the various RCPs and to infer SLR effects on the *A. mariae* life cycle; the results were combined with data from field surveys. The model outputs revealed a variation in wave run-up oscillations under common wave conditions, which could affect the supralittoral area in terms of water input and hydric balance, as well as the *A. mariae* life cycle, which is temperature and salinity dependent.

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Key words: Sea-level rise; splashpools; coastal environment; models; *Acartomyia mariae*.

Acknowledgments: The authors would like to thank Silvia E. Smith, Ph.D., Biology Faculty, the University of New England for the first revision of English and the helpful suggestions provided.
The authors would also like to thank Prof. Luigi Pane for his valuable support during this research project.

Contributions: GB and LC have developed the idea, and they have identified the aims of the research. GB and MG have conducted the ecological sampling campaigns and laboratory analysis. LC and LM have modelled coastal morphology and wave run-up under several sea-level rise scenarios (through the implementation of an XBeach model suite). LC and GB have written and managed the manuscript. MF has supervised and coordinated the research activity and has provided suggestions and revisions during the writing of the paper.

Conflict of interest: The authors declare no conflict of interest.

Received for publication: 28 March 2022.
Revision received: 2 July 2022.
Accepted for publication: 2 July 2022.

Journal of Biological Research 2022; 95:10485
doi:10.4081/jbr.2022.10485

Introduction

Sea-level rise is one of the consequences of the complex of processes known as "Global Warming," which is a direct result of industrialization and other human activities (SLR). SLR can produce a wide variety of ecological, biological, geological, and socio-economic effects on coastal areas, primarily in already anthropized areas. Such effects can lead to substantial habitat modification and eventual loss of biodiversity. Mangrove forests, coastal lagoons, and coastal wetlands are among the most endangered habitats, and the possible impacts of SLR on them are widely investigated.[1-3]

SLR can cause "coastal squeeze" on rocky shores, which is defined as the loss of coastal habitats where the high water mark is fixed by a hard structure (e.g., a seawall) and the low water mark migrates landward.[4-6] SLR's effect on intertidal rocky zones, which are highly dependent on mean water levels, has received a lot of attention. Changes in the coastal slope and related communities,[7] as well as general habitat loss due to mean sea-level rise, were among the relevant habitat modifications.[8-11] However, the supralittoral zone received little attention, particularly in areas where tidal seawater input is negligible (e.g.,Western Mediterranean Sea).

The supralittoral zone is a transitional habitat that is influenced by both terrestrial and marine factors, specifically fresh (rainfall, run-off) and marine (splash, spray, run-up) water inputs.[12] Such inputs affect the splashpools and rockpools (temporary water collections) environmental variables (temperature, salinity, pH), and therefore the survival and distribution of the resident biota. Because these organisms are exposed to harsh environmental conditions, they develop physiological and ecological defense mechanisms that allow them to survive. Species in this unusual environment are highly vulnerable to environmental and climatic changes, and evidence of limited adaptation potential to environmental changes has been found in both on-field and laboratory studies.[13-14]

The Genova Nervi rocky shore (Ligurian Sea) offers a textbook rendition of this environment, and its ecology has been described in different studies. In this area, different resident species were identified, some of which inhabit these pools year-round, such as the harpacticoid copepod *Tigriopus fulvus* (Fischer, 1860), while others are strictly seasonal, such as the culicid *Acartomyia mariae* (Sergent & Sergent, 1903).[15-19]

A. mariae is found along the Western-Mediterranean coast, and in Italy it can be found along the Tyrrhenian coasts of the peninsula and the major islands, probably excluding south-western Sicily; in this latter area, it is replaced by the twin species *A. zammitii* (Coluzzi & Sabatini, 1968), which can be found along the entire Adriatic and Ionian coasts. The species that currently resides in the Genova Nervi splashpools[20] is *A. mariae*, which is known to be an obnoxious biter that frequently attacks humans and animals.[21] Despite the fact that *A. mariae* is not known to be a vector of human diseases, its population is usually monitored and, on occasion, controlled whenever the presence of these insects impacts anthropogenic activities in the coastal area. Females bite during the day, usually in cloudy weather, causing significant disruption to tourist activities. They may also be vectors for *Plasmodium relictum*, an avian parasite.[22] *A. mariae* larval stages are typically found in supralittoral pools, where adults can breed despite the negative effect that high water salinities appear to have on the broodstock.[23]

Thus comes the need to evaluate and forecast actual and future environmental conditions that might result from a substantial hydrological modification and their subsequent impact on coastal biocenosis.

Given the potential ecological impacts of SLR on a variety of taxa and human health,[24,25] we used the XBeach model to simulate a range of possible SLR scenarios to evaluate their impact on the splashpools of the rocky shore of Genova Nervi, aiming to identify possible coastal squeezes or habitat losses.

Given the presence of *A. mariae*, a common species in the study area,[20] we illustrated some potential effects of SLR on its distribution and presence. We simulated a change in wave run-up oscillations based on several greenhouse gas mitigation scenarios[26] and evaluated its impact on the splashpools area in terms of marine water input. The model's results were combined with an investigation conducted in 2013-14 regarding the seasonality of the presence of *A. mariae* larval stages and their relationship with the main environmental variables of the splashpools under consideration (salinity, water temperature, air temperature). The model outputs allowed us to speculate on a change in the water balance of the study area and subsequent environmental conditions that could be important for *A. mariae* development.

Materials and Methods

Study area

Nervi (NW Mediterranean, Ligurian Sea) is the easternmost neighborhood in the city of Genoa (Italy) and is developed on a marine terrace.[27] Below sea-level, the cliff reaches depths of 4–5 meters quickly, then continues with a softer slope (Figure 1), while the seafront is characterized by an active cliff, the top of which reaches 13 m above sea-level,[27] where it is possible to find the typical supralittoral conditions described earlier in this paper.

Genova Nervi splashpools are situated in a densely populated coastal environment. Around 1860, a 2-kilometer promenade was built, which is now recognized as the upper limit of the marine environment and a physical barrier separating the inland from the supralittoral zone. The rocky shore morphology concentrates temporary water collections (pools) in a relatively narrow strip parallel to the coastline, with a height span ranging from MSL to approximately 7 m. The coastal pools evaluated in this study were recently re-described from rockpools to splashpools,[17,28] as they receive saltwater inputs only from spray during heavy seas and storms, and are not tidally influenced.[12]

Sea-level projections

SLR projections for the year 2100 in Genoa by Kopp *et al.*[29] were used to simulate several sea-level conditions in the study area.

Three different greenhouse gases mitigation policies scenarios were considered, all of them based on three Representative Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, and RCP 8.5.[26] Such values identify the likely global mean temperature increases in 2081–2100, which are supposed to be of 1.9–2.3°C (RCP 2.6), 2.0–3.6°C (RCP 4.5), and 3.2–5.4°C (RCP 8.5) above the 1850–1900 levels.[30]

The medians for the Genoa sea-level increase (Figure 2) were obtained from Kopp *et al*.[(29)], and represent the medium forecasted SLR related to the mentioned RCP scenarios. The corresponding values were: 0.31 m (RCP 2.6), 0.43 m (RCP 4.5), and 0.57 m (RCP 8.5).

Wave run-up modeling

Water level scenarios were modeled using the XBeach model. XBeach is an open-source numerical model that solves coupled two-dimensional, depth-averaged equations for short-wave envelope propagation and flow with a spectral wave and flow boundary conditions.[31] XBeach was validated in Diaz *et al.*[32] for run-up prediction in moderate and rough sea conditions, considering a significant wave height range between 0.5 and 3.0 m and peak periods between 4.0 and 12.0 seconds. This is consistent with the findings by Mucerino *et al.*[33] in their study along the eastern Ligurian coast. XBeach bed level is based on the combined bathymetric and topographic data, which are re-interpolated among them to obtain a reliable description of morphological features. Subsequently, a cross-shore transect (see Figure 1) was extracted in order to obtain detailed 1D wave run-up simulations under several SLR scenarios.

To simulate these scenarios, we used a modeling technique known as "snap-shot."[34] This technique has been used successfully in other studies to investigate the effects of climate change on coastal environments,[34-36] and it allows for the simulation of future sea-level conditions without the need to run models over long timescales (e.g., 100 years). In this way, we eliminated computational costs and error accumulation in long-term simulations.[36] Due to the coastal morphology in our case, this approach was the best way to achieve the goals of this study. The rocky shore morphology impedes any adjustment of the cross-shore profile, and the wave-bottom interaction is negligible due to the rapidly increasing bathymetry of the cliff (Figure 1; *i.e.*, waves breaking directly on the cliff). As a result, we ignored the profile adjustment under SLR conditions.

A suite of 24 models was implemented to simulate all considered scenarios (6 wave conditions × 4 sea-level scenarios). Each model simulated 5 hours of incident waves to consider their complete development. For the assessment of wave run-up on the rocky coast, we analyzed the model output "zs" (water level).

Data of the on-land areas were obtained from LIDAR data (acquired in 2008 by the Italian Ministry of the Environmental and Safeguard of the Sea), whereas bathymetric data were provided by Regione Liguria (https://geoportal.regione.liguria.it/).Concerning the climate wave conditions considered, we simulated sea states that commonly occur in the study area (Figure 3).[37,38]

Field survey

Environmental data were acquired with a fortnightly cadence from July 2013 to September 2014. A multiparametric probe (YSI 30M/50 FT; 0.1°C and 0.1 resolution) was used to acquire water temperature (°C) and salinity (PSU) every sampling day at noon. Three (A, B, C) splashpools at different heights (ranging between 4 and 6 m, A to C) above the mean sea level were considered for this study, and were considered representative of the typical area conditions because of the narrowness of the supralittoral zone. The pools chosen had equal sunlight exposition, avoiding structural coverage, to avoid differences in both heating and flooding processes. It must be noted that the only water inputs in the selected splashpools were rainfall and marine spray as no other sources (leaks, creeks, tidal action) were able to interact with the water collections. More details on the sampling methodology can be found in Bonello *et al.*[17]

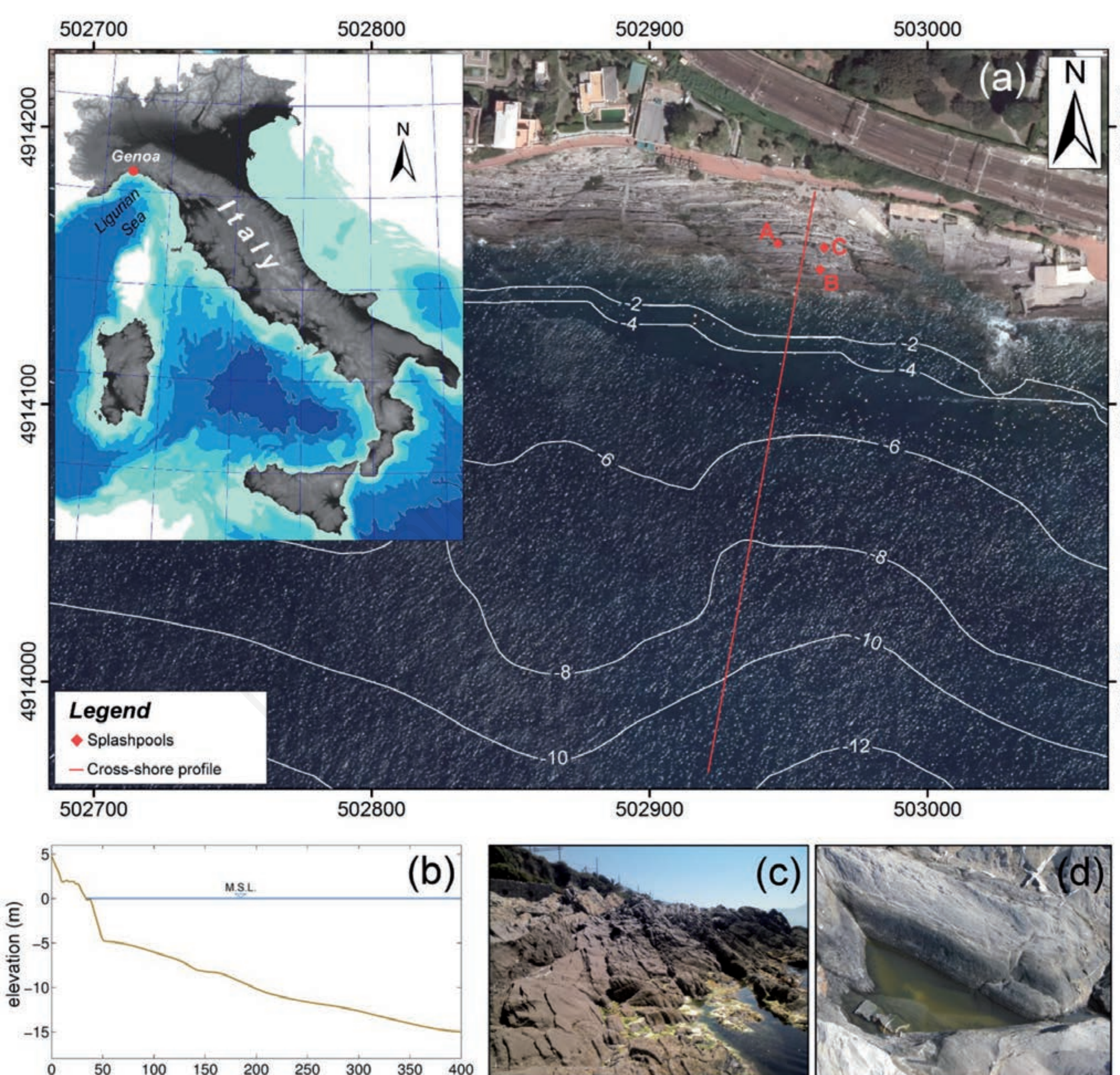

Figure 1. Description of the study area. Splashpools location (1.a), considered cross-shore profile (1.a, 1.b), view on the coastal morphology (1.c) and details of a splashpools (1.d).

Particular attention was given to the presence of larval stages of *A. mariae* (Diptera: Culicidae). Being the only culicid present in the splashpools of the study area,[20] identification was conducted via a non-invasive visual census of the juveniles (larvae and pupae), and data were recorded in terms of their presence or absence in the investigated pools.

Correlations between environmental variables and *A. mariae* presence were conducted in R Programming Language[39] and the figures were produced using the ggplot2 package.[40]

Results

Coastal modeling allowed the simulation of several SLR scenarios and the evaluation of potential impacts on splashpools water inputs and the subsequent changes in the internal environmental variables. Our model, run under several sea-level conditions, showed a generalized increase in the wave run-up (Figures 4 and 5). Figures 4.a, 4.b, 4.c, and 4.d depict the run-up values undersea conditions that occur more commonly in the study area. When SLR was factored into the models (2100 sea-level under RCP 2.6, 4.5, and 8.5), the wave run-up showed a clear increase. Model results were quite different in the case of stronger sea conditions; when higher incident waves (wave heights of 2.5 and 3.0 m) were factored into the sea-level change scenarios (Figures 4.e and 4.f), a run-up increase was observed; however, it exhibited a different trend from previous cases (Figures 4.a, 4.b, 4.c, and 4.d). Indeed, run-up oscillation in three SLR scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) shows a certain degree of overlapping. This feature is also highlighted in Figure 5, where run-up data of two borderline cases are compared.

Considering all the proposed scenarios (RCPs), we can identify a closure of the gap between the run-up oscillation values under the different RCPs' conditions, as illustrated in Figure 6.

Regarding the culicid observations, *A. mariae* larval stages, larvae, and pupae were found in all the considered splashpools (Figure 7). *A. mariae* was found in the range of 27.7±4.2°C and 23.7±4.5°C for water and atmospheric temperature, respectively (Figure 8). Regarding salinity, larval stages of *A. mariae* were found in the range of 46.5±13.5 PSU (Figure 8), highlighting a refined tolerance mechanism. During the months in which mosquito larvae were absent, salinity oscillated in the range of 42.7±5.3 PSU (Figure 8). The upper tolerance limit for the brood to develop was found to be 73.8 PSU (Figure 8).

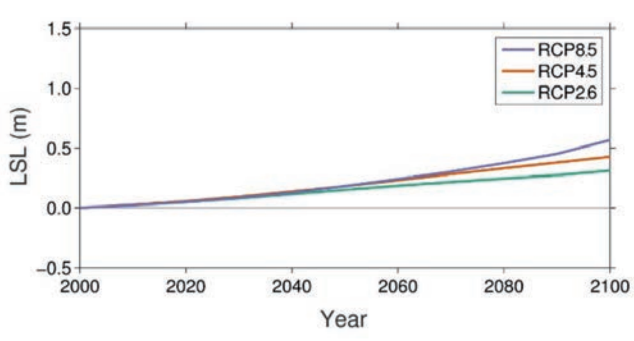

Figure 2. Local Sea-Level (LSL) projection in Genoa to the year 2100. Median for the Genoa tide gouge for each RCP scenario.[29]

Discussion

The results of our simulations revealed that the SLR's impact on wave run-up oscillation (Figure 4) is particularly pronounced at wave heights between 0.5 and 2 m; under such conditions, run-up peaks are well distinguished (Figure 4). Nonetheless, under extreme conditions (2.5 and 3 m), wave run-up peaks are confused into the "noise-floor" of oscillation values under different sea-level scenarios, resulting in significant overlapping (Figures 4 and 5). As a result, the findings show that lower wave heights have a significant impact (0.5–2 m). The latter are those that occur frequently in the study area,[37,38] and it is clear how changes are associated with ordinary wave conditions rather than extreme events. This is also demonstrated by the emphasized narrowing of the gap between the various mean run-up oscillations (Figure 6). This effect is caused by local coastal morphology, which is an important factor to consider when working at a small scale or in a highly fragmented environment like the one considered in this study.

One of the primary concerns about SLR scenarios is their role in the loss of coastal areas and habitats. When the dynamism of the littoral environment is affected and reduced by the presence of infrastructures, the presence of infrastructures can cause a coastal squeeze. The latter has the potential to significantly alter and limit the functioning and morphology of the coastal environment.[5] The previously mentioned gap reduction between mean wave run-up oscillation, mean SLR, and subsequent raising of the biological zero height may result in what is known as a "vertical coastal squeeze." Our findings support the findings of other authors who have previously investigated this phenomenon.[7-11]

The majority of the literature, however, is related to mesolittoral and intertidal zones, whereas we considered a supralittoral environment in which the factors involved in the hydric balance of splashpools can be summarized as freshwater inputs (rainfall, humidity, run-off), sun exposure (and subsequent evaporation), and seawater inputs (splash, spray).

Among these, only the latter is strictly dependent on the sea-level, while the others equally contribute whenever pools are close together with the same orientation.

If we analyze the salinity data collected and reported in Bonello *et al.,*[17] we can identify two different conditions. While

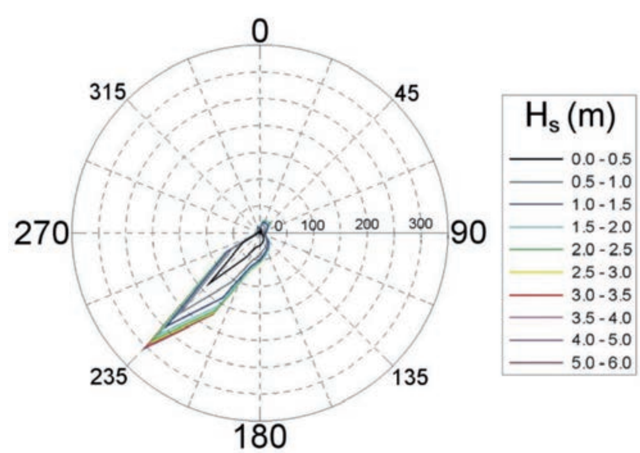

Figure 3. Wave rose diagram for the wave direction and the significant wave height in Ligurian Sea central sector.[37]

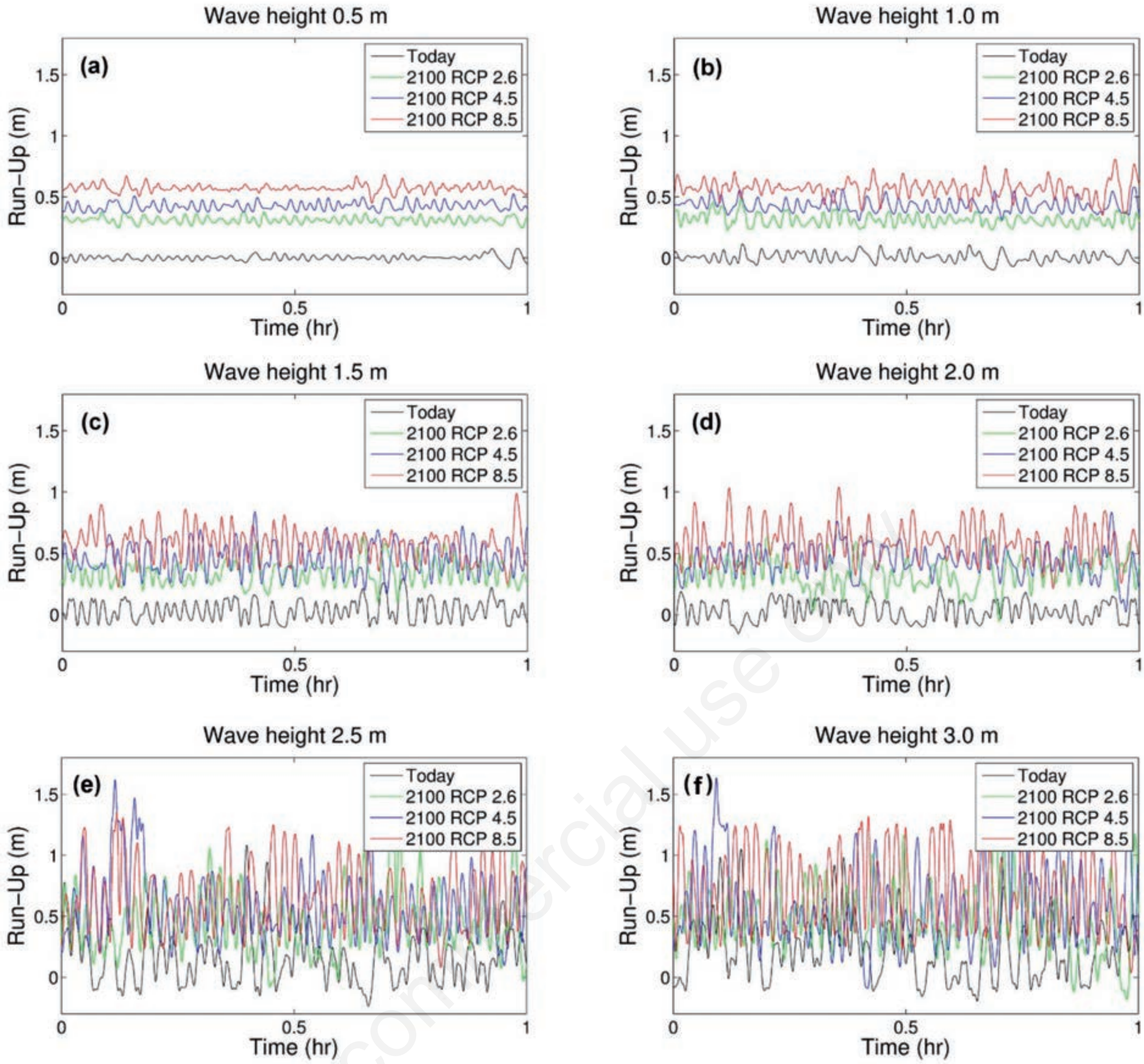

Figure 4. Wave run-up oscillation in sea-level change scenarios. 4.a: wave height of 0.5 m, 4.b: wave height of 1.0 m, 4.c: wave height of 1.5 m, 4.d: wave height of 2.0 m, 4.e wave height of 2.5 m, 4.f wave height of 3.0 m.

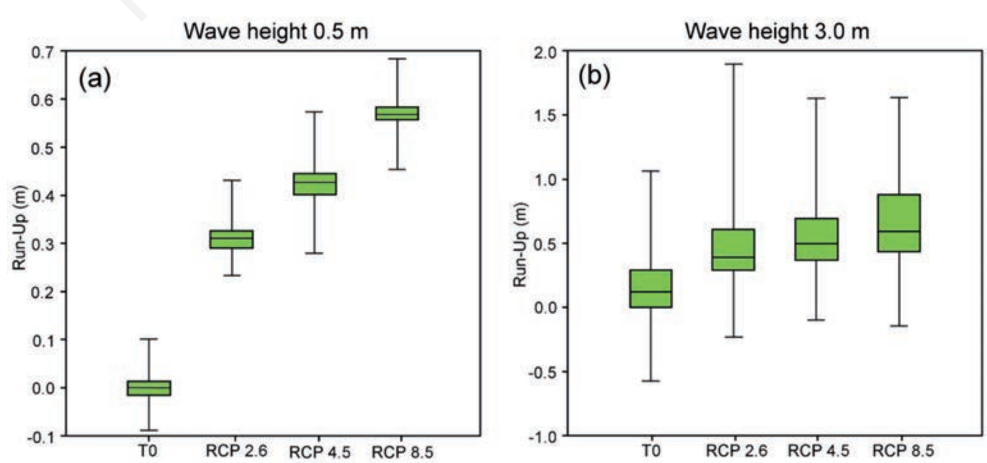

Figure 5. Data comparison between two borderline wave height considered cases. Overlapping between run-up values is evident in Figure 5.b.

pools A and B showed a mean salinity of 45.2±7.3 and 45.0±4.8 PSU, respectively, pool C, positioned higher than the others on the cliff, saw an increased variability in this variable, as confirmed by the obtained standard deviation (55.8±24.2 PSU). Even though we cannot ignore the pools' morphology as an influencing factor in evaporation and therefore water balance, we can consider an increased run-up as a substantial modifier in the higher located pools. It is likely that an increased seawater input driven by the augmented run-up can buffer by dilution the higher pools' salinity and generally modify the habitat characteristics.

The run-up increase highlighted in the various model scenarios can also cause an increase in saltwater inputs in previously unaffected coastal areas. As a result, we can identify the possibility of a "Dry Zone" reduction, which is defined as a cliff that is not affected by seawater inputs.

R-specialist species like *A. mariae* may be particularly favored due to the possibility of new niches occupancy, given the great spatial distribution they can reach as adults compared to other organisms confined to the aquatic environment, among which are the harpacticoid copepod *Tigriopus fulvus*, which mostly rely on pool water spillover forced by tides, sea storms, and rainfall to occupy new niches.[40]

As highlighted in our study, *A. mariae* larval stages can tolerate a wide salinity range due to their specialized physiological and behavioral mechanisms.[41]

Increased run-up, and thus spray-zone expansion, will result in increased seawater input in the splashpools area, which will buffer natural evaporation. This creates new opportunities for aquatic organisms to thrive and reproduce. Conversely, supralittoral zones that are currently dry or supported solely by fresh (rain or inland) water processes will change their mean conditions, becoming wet and marsh areas suitable for *A. mariae* egg deposition.[23] Even though salinity fluctuations had no effect on *A. mariae* larval presence, oviposition occurs exclusively in a transitional but marine-oriented environment. Nonetheless, preliminary observations showed that extremely high salinity values (70-80 PSU) can have a negative impact on *A. mariae* larval abundance;[23] thus, establishing the modeled conditions may favor their presence and breeding intensity by diluting the eventual high-salinity conditions via increased hydric input.

Finally, we must consider the rise in environmental temperatures caused by ongoing climatic changes, which are already affecting rocky shoreline environments around the world.[13,42,43] As highlighted in our study, such an increase can lengthen the reproduction period for *Acartomyia* sp., which is strictly correlated with environmental temperature (Figure 8). Because *Acartomyia* sp. juveniles are efficient predators, we must consider a possible

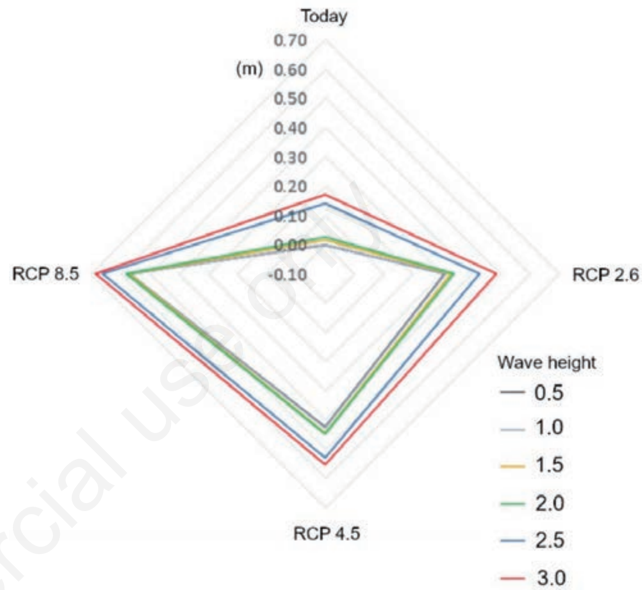

Figure 6. Graphic rendition of the closing gaps between different wave run-up oscillations under the investigated 2100 RCP scenarios. The gap reduction is reported clockwise, following the different SLR scenarios.

Figure 7. Example of *Acartomyia mariae* larval sampling in Nervi splashpools.

increase in their impact on splashpool species, as laboratory trials on *Tigriopus californicus* juveniles demonstrated.[44]

The emergence of these new conditions may have an impact on human health and population. An increased spatial distribution of *Acartomyia* sp. habitat and subsequent population growth could pose a sanitary risk, with implications for human activities and subsequent coastal management. Although there is no evidence of *A. mariae* vectoring human pathogens, its biting attitude[21] places this species in a relevant position when it comes to risk assessment and management. Furthermore, *A. mariae* is known as a vector for *Plasmodium relictum*, a parasitic organism responsible for avian malaria,[45] and may thus indirectly affect humans by necessitating control plans. Thus, *A. mariae* population control and subsequent management must be considered in the context of a dynamic environment that may undergo drastic changes.

Conclusions

This paper showed different possible scenarios and perspectives connected to sea-level rise and climate change's impacts on coastal communities.

As proposed in our study, when approaching a highly dynamic environment, such as the supralittoral zone, both descriptive and inferential perspectives must be considered in order to obtain substantial information on current and future scenarios. The ability of such environments to maintain their local equilibrium is dependent on their resistance, resilience, and adaptation capabilities, which we cannot quantify without additional precise research. Evidence of impact on rocky shore communities, on the other hand, has already been proposed, and the need for an applicable, scalable, and reliable model for the supralittoral zone is growing, in terms of both conservation activities and coastal management. Monitoring rocky shore communities can help evaluate local-scale climatic variation and contribute to the understanding of a manageable and consistent pool of biodiversity that must be protected and managed.

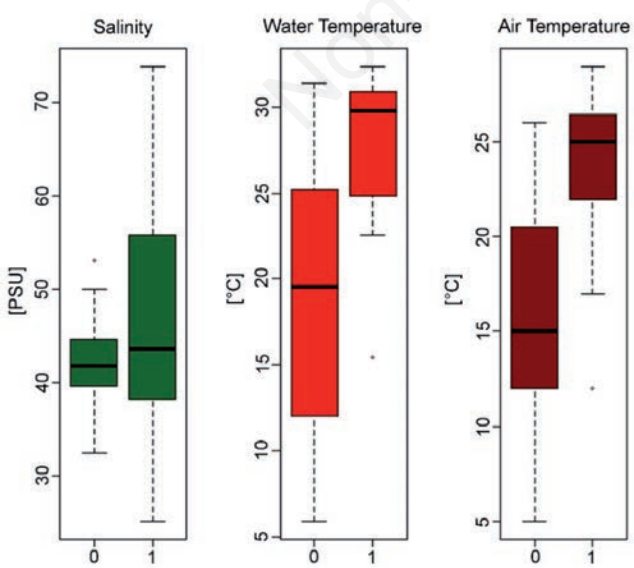

Figure 8. Environmental variables related with *Acartomyia mariae* absence (0) and presence (1) in the study area.

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