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Beyond the crest: quantifying coastal protection and risk mitigation services of submerged reefs in the Mexican Caribbean

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ABSTRACT

Introduction: Coral reefs function as natural coastal defenses by dissipating wave energy and reducing flooding and erosion. While the protective role of emergent reef crests is well documented, the contribution of submerged reefs remains poorly quantified. This study evaluates the coastal-protection function of two submerged reefs (Manchoncitos I and II) offshore Playa Paraíso, Quintana Roo, Mexico.

Objectives: (1) quantify wave height reductions associated with submerged reefs; (2) compare wave propagation under reef and no-reef scenarios; and (3) assess the sensitivity of wave attenuation to changes in reef roughness.

Methods: Numerical modeling (WAPO/REFDIF) was used to simulate wave transformation across the reef platform. A high-resolution bathymetric grid (4 × 3 km; 5 m) was developed using multibeam surveys, satellite-derived bathymetry, and in situ measurements. Simulations compared reef and no-reef scenarios and evaluated two Nikuradse roughness values ($k_s = 0.5$ and 1.5 m).

Results: The reefs generated local reductions in significant wave height ranging from 0.5 to 1.5 m. Manchoncitos I produced the greatest attenuation, whereas Manchoncitos II exhibited a more heterogeneous response, including localized wave-focusing effects. Increasing reef roughness enhanced wave-height reductions and expanded the spatial extent of wave dissipation. Wave attenuation varied according to reef geometry, roughness, and incident wave direction.

Conclusions: Submerged reefs provide measurable coastal-protection services by reducing wave energy reaching the shoreline. Reef morphology and roughness strongly influence attenuation patterns. These findings support reef conservation and restoration to reduce coastal risk.

Key words: Coral reefs; wave attenuation; numerical modeling; reef roughness; Nikuradse (k_s).

RESUMEN

Más allá de la cresta: cuantificación de los servicios de protección costera y mitigación del riesgo de arrecifes sumergidos en el Caribe mexicano

Introducción: Los arrecifes coralinos funcionan como defensas naturales costeras al disipar la energía del oleaje y reducir inundaciones y erosión. Aunque el papel protector de las crestas arrecifales emergidas está bien documentado, la contribución de arrecifes sumergidos permanece poco cuantificada. Este estudio evalúa la función



de protección costera de dos arrecifes sumergidos (Manchoncitos I y II) frente a Playa Paraíso, Quintana Roo, México.

Objetivos: (1) cuantificar las reducciones en la altura del oleaje asociadas a arrecifes sumergidos; (2) comparar la propagación del oleaje bajo escenarios con y sin arrecifes; y (3) evaluar la sensibilidad de la atenuación del oleaje ante cambios en la rugosidad arrecifal.

Métodos: Se utilizó modelación numérica (WAPO/REFDIF) para simular la transformación del oleaje sobre la plataforma arrecifal. Se desarrolló una malla batimétrica de alta resolución (4×3 km; 5 m) utilizando levantamientos multihaz, batimetría satelital y mediciones in situ. Las simulaciones compararon escenarios con y sin arrecifes y evaluaron dos valores de rugosidad de Nikuradse ($k_s = 0.5$ y 1.5 m).

Resultados: Los arrecifes generaron reducciones locales en la altura significativa del oleaje de entre 0.5 y 1.5 m. Manchoncitos I produjo la mayor atenuación, mientras que Manchoncitos II mostró una respuesta más heterogénea, incluyendo efectos localizados de concentración de energía del oleaje. El incremento de la rugosidad arrecifal aumentó la reducción de la altura del oleaje y amplió la extensión espacial de la disipación. La atenuación varió en función de la geometría arrecifal, la rugosidad y la dirección de incidencia del oleaje.

Conclusiones: Los arrecifes sumergidos proporcionan servicios medibles de protección costera al reducir la energía del oleaje que alcanza la costa. La morfología y la rugosidad arrecifal influyen fuertemente en los patrones de atenuación. Estos hallazgos respaldan la conservación y restauración arrecifal para reducir el riesgo costero.

Palabras clave: arrecifes de coral; atenuación del oleaje; modelación numérica; rugosidad arrecifal; Nikuradse (k_s).

INTRODUCTION

Coral reefs function as nature-based coastal defenses by dissipating incoming wave energy through friction, breaking, and flow obstruction, thereby reducing shoreline flooding and erosion. Barrier reefs can reduce wave energy by ~97 %, highlighting their importance for coastal hazard mitigation and climate adaptation (Ferrario et al., 2014). Beyond their physical attenuation capacity, global modeling shows that annual expected flood damage would double without coral reefs, with the largest expected benefits concentrated in low-lying, tourism-dependent countries (Beck et al., 2018; Ferrario et al., 2014).

Mexico is among the countries where coral reefs provide some of the highest coastal-protection benefits globally, due to the combination of extensive reef-lined shorelines, rapid coastal development, and high exposure of people and infrastructure. Quintana Roo is home to one of the largest tourism corridors in the Caribbean, where coastal assets depend heavily on the integrity of the Mesoamerican Reef. Spatial analyses show that coral reefs in Quintana Roo annually prevent \$4 billion USD per year in damage from storms, to hotel infrastructure

and buildings, avoiding an estimated USD 36 billion each 25 years in losses. Because much of the coastal development is directly located behind reef crests or submerged reef ridges, the protection service provided by reefs is particularly valuable: reefs prevent additional damage during Hurricanes and currently reduce annual risk for thousands of residents and major tourism infrastructure in the region. Together, these conditions create a strong dependence of Quintana Roo's economy and coastal communities on the health and persistence of coral reefs (Beck et al., 2018; Reguero et al., 2020).

While classical assessments emphasize the effects of emergent reef crests associated with barrier reefs, non-emergent (submerged) discontinuous reef structures and isolated reef mounds have not received the same attention, and their effects on wave propagation need to be better understood. Complex bathymetry associated with submerged reefs governs wave transformation through wave refraction, diffraction, reflection, frictional dissipation, and depth-limited breaking. Several field and theoretical studies show that fore-reef slopes and shallow reef flats can dissipate large portions of incident wave energy even when they do not break, with bottom roughness exerting

first-order control on attenuation (Lowe et al., 2005; Monismith et al., 2015; Rogers et al., 2015). In this context, architectural complexity refers to the three-dimensional structure of the reef framework (e.g., coral branches, mounds, cavities), which increases turbulence and friction, while roughness is a hydrodynamic parameter representing how this structure slows down waves and water flow. Both properties decline when reefs degrade.

Degradation poses a growing threat to these protective functions. Structural “reef flattening” reduces complexity, decreases roughness, and ultimately increases coastal exposure. Recent disturbance-recovery analyses combined with hydrodynamic modeling show that halving structural complexity can increase the frequency of extreme runup events, historically once per century, by up to 50-fold (Carlot et al., 2023). Regional risk assessments in Quintana Roo further demonstrate that reef degradation already increases flood risk for people, buildings, and hotel assets, and that targeted restoration can produce immediate, measurable reductions in wave impact (Reguero et al., 2020). Complementarily, Toth et al. (2023) show that restoring framework-building corals could mitigate future extreme flooding under sea-level-rise scenarios by increasing reef roughness and elevating reef crests.

Despite recent advances, the protective function of discontinuous submerged reef structures in Quintana Roo remains poorly quantified. Many reef ridges along this coastline—including Manchoncitos I and II do not emerge at low tide yet still have the potential to dissipate substantial wave energy. The lack of spatially explicit assessments of reef-based risk reduction has been identified as a key barrier to prioritizing restoration sites and evaluating the benefits of maintaining reef structural integrity. Regional analyses in Quintana Roo highlight that such quantitative evaluations have only recently begun to emerge and remain incomplete across most reef sectors (Reguero et al., 2020). Broader studies on submerged coral systems similarly emphasize that structural configuration critically shapes wave attenuation

but is often under-measured in management contexts (Carlot et al., 2023).

In this study, we assess the coastal-protection service provided by the discontinuous and non-emergent reefs (Manchoncitos I and II), located offshore Playa Paraíso, Quintana Roo, Mexico. We use high-resolution bathymetry and a validated wave-transformation model to compare wave propagation under reef and no-reef scenarios, and different degrees of reef roughness as a proxy for restoration effects. Our central research question is: To what extent do these submerged reefs reduce significant wave height and how sensitive are these protective functions to changes in reef roughness? By addressing this question, we provide hazard-focused evidence to support conservation and reef-restoration strategies that enhance natural coastal defenses for existing infrastructure.

MATERIALS AND METHODS

Study area: The study site is located along the northern sector of the Mesoamerican Barrier Reef System, offshore Playa Paraíso-Punta Maroma in the municipality of Solidaridad, Quintana Roo, Mexico. The region lies within UTM Zone 16Q (WGS84), between 20°43'00"-20°45'30" N and 86°54'30" – 86°48'00" W. The coastline is fronted by two submerged (discontinuous) patch-reef systems, Manchoncitos I and Manchoncitos II, positioned at approximately 5–13 m depth and separated from the Cozumel Channel by a continental shelf.

The regional geology is dominated by carbonate rocks, consisting of medium- to fine-grained calcarenites with abundant biogenic fragments. The continental shelf exhibits a steep slope towards the Cozumel channel, locally interrupted by reef outcrops that steepen the bathymetry (Carranza-Edwards et al., 1996; Ibarra Fernandez, 2008).

Nearshore hydrodynamics are influenced by the sheltering effect of Cozumel Island, which attenuates seasonal S-SE wave events and influences local wave conditions. A summary map of the study area, including reef polygons, coastline features, hotel frontages, and

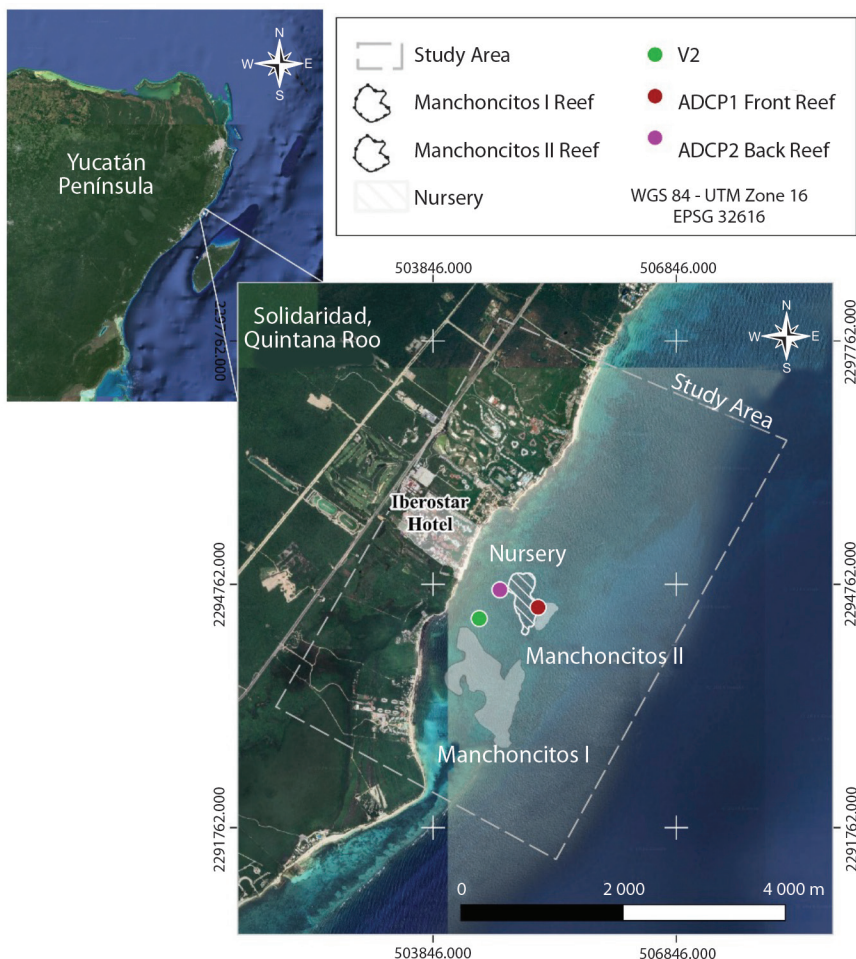


Fig. 1. Study area map with locations of the oceanographic instruments: A1 (front-reef ADCP), A2 (back-reef ADCP), and V2 (Vector velocimeter).

the locations of the oceanographic instruments (A1, A2, and V2), is provided in Fig. 1.

Meteo-Oceanographic setting: The study region has a warm sub-humid climate, with annual precipitation of 1 500–2 000 mm and lower rainfall during the boreal winter. Local wave conditions are dominated by short-period, wind-generated seas. Offshore significant wave height (H_s ; average height of the highest one-third of waves) typically ranges between 0.2 and 0.6 m for ~60 % of the year and rarely exceeds 2 m. The peak wave period (T_p ; the dominant oscillation period) commonly lies

between 5 and 6 s, with occasional long-period swell events (~10 s). In the Mexican Caribbean coast, wave approach is predominantly from the southeast, although at the site, this direction is influenced by coastal orientation and by the shadowing effect of Cozumel Island. Higher-energy events occur during April–May under strengthened S-SE winds (De la Lanza, 2006), and hurricanes are common from June to October, generating very extreme conditions.

Medium-term offshore wave statistics (2013–2023) were obtained from the ERA5 reanalysis, a global, observation-constrained dataset of atmospheric and oceanic conditions.

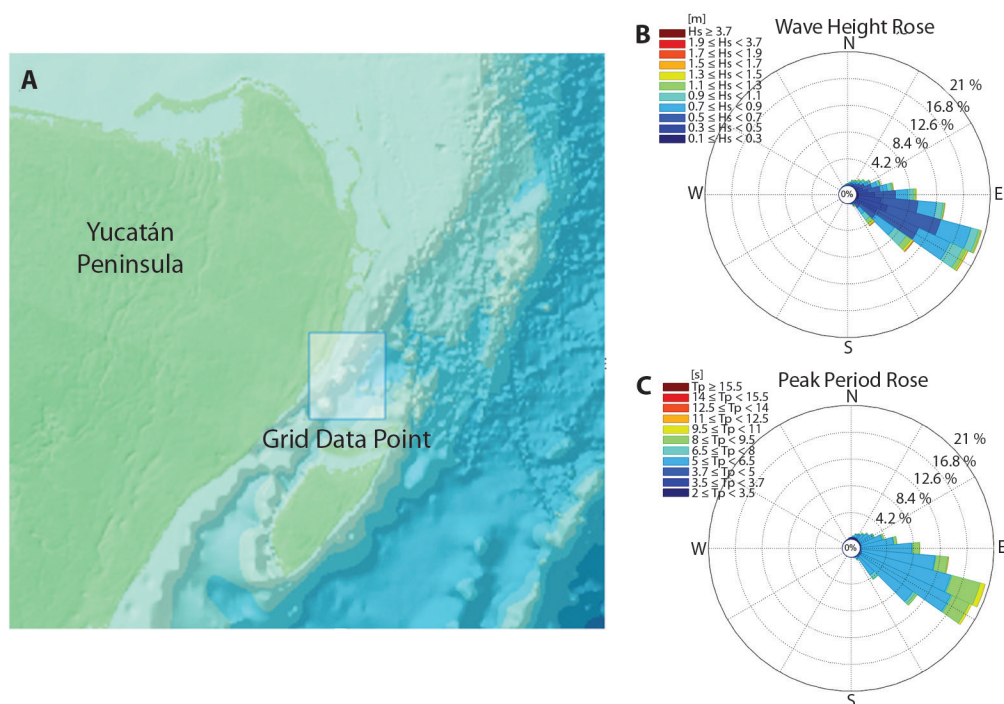


Fig. 2. ERA5 wave statistics (2013-2023) showing A. Spatial domain, B. Wave height rose, and C) Peak period rose.

Time series of H_s , T_p , and mean wave direction (Fig. 2) were used to characterize the local wave climate and to define the model forcing conditions (Hersbach et al., 2023). The ERA5 dataset provides a long, continuous, and spatially consistent record (2013–2023).

Bathymetric data acquisition and processing: Bathymetric data were compiled from three complementary sources that together captured deep-water morphology, the continental shelf, and reef-scale features.

i) Regional charts and a dedicated oceanographic cruise *Justo Sierra* (Universidad Nacional Autónoma de México, n. d.) around Cozumel Island provided multibeam large scale bathymetry using an EM302 system (30 kHz, ~20–5 000 m depth range) for deep waters. Multibeam echosounders map the seafloor using fan-shaped acoustic beams, with low-frequency systems optimized for deep water.

- ii) Satellite-derived bathymetry from CONABIO supplied continuous shallow-water coverage across the continental shelf, complementing the multibeam data in areas where ship-based measurements are limited. This data was calibrated with echosounder and radiometric measurements (Cerdeira-Estrada et al., 2012).
- iii) High-resolution nearshore bathymetry was also collected during an in-situ field campaign in December 2023 using a SonTek M9 ADCP (1 MHz, Fig. 3A; Fig. 3B) mounted on a small vessel. The ADCP (Acoustic Doppler Current Profiler) simultaneously records depth and water velocity based on acoustic backscatter. Positioning was corrected with RTK-GPS, achieving centimetric horizontal accuracy.

All xyz depth points were quality-filtered to remove outliers and then smoothed using a robust LOESS filter to reduce vessel-motion noise while preserving geomorphologically

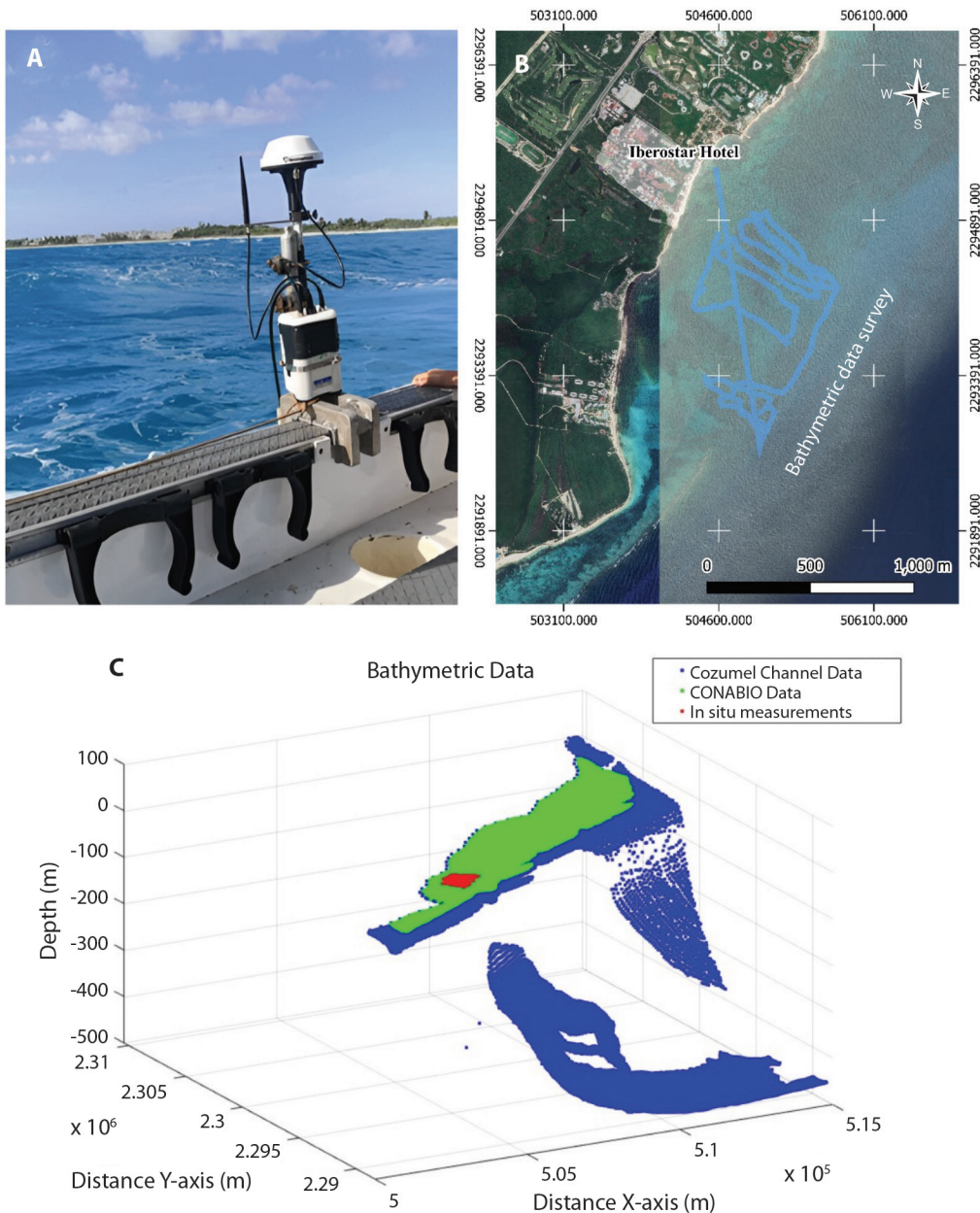


Fig. 3. A. Installation of an ADCP instrument with differential GPS on a boat for bathymetric measurements. B. Transect of in-situ bathymetric data collection. C. Sources of Bathymetric Data and Selected Study Area for Grid Generation.

meaningful features (Fig. 3C). The merged dataset was interpolated into a 5 m-resolution bathymetric grid using ordinary kriging. Small gaps were filled by trend-preserving interpolation to avoid unrealistic depressions or sharp

transitions that could destabilize the numerical wave model.

Wave and current measurements: During the field campaign, two bottom-mounted

Acoustic Doppler Current Profilers (ADCPs; Nortek Aquadopp Profiler, 2 Hz) and one-point velocimeter (Nortek Vector, 4 Hz) were deployed to obtain wave and current time series for model calibration and validation (Fig. 1).

A1 - Front-Reef ADCP: deployed seaward of the Manchoncitos II restoration site (“Nursery”) to measure incident waves before interacting with the reef.

A2 - Back-Reef ADCP: positioned landward of the same site to quantify transmitted and attenuated waves, capturing dissipation associated with reef rugosity and restoration structures.

V2 - Vector velocimeter: installed near Manchoncitos I to record near-bed orbital velocities and wave periods in a zone influenced by complex reef morphology.

The ADCPs measure pressure and velocity profiles using acoustic Doppler shifts, whereas the Vector instrument provides high-frequency, single-point velocity and pressure measurements near the seabed. From the pressure and velocity time series, significant wave height (H_s) and peak period (T_p) were computed using standard spectral methods (spectral density function, zero-moment definition for H_s , peak-period from the spectra). These observations were later used to compare modeled and measured wave heights at the same locations.

Numerical wave modeling: Wave transformation was simulated using the WAPO/REFDIF model, which solves the steady-state mild-slope equation. This formulation allows the calculation of wave propagation over variable and complex bathymetry, directly solving for shoaling, refraction, diffraction, and reflection. The model also includes different schemes for depth-limited breaking and bottom-friction dissipation. WAPO/REFDIF is well suited for coral-reef environments, where abrupt depth changes and high bottom roughness strongly modulate wave energy (Odériz et al., 2014). The most relevant background information for this derivation is based on previous work of

Berkhoff et al., (1973), Dalrymple et al., (1991), Losada et al., (1996), Dingemans et al., (1997), Silva et al., (2005), and validations of the model can be found in Silva et al., (2003) and Silva et al., (2006). A disadvantage of using this model is that wave propagation is made for monochromatic waves, an approach which is more valid if the wave spectrum is narrow-banded.

The computational domain was rotated 52.61° to align the offshore boundary with the dominant incident-wave directions, minimizing boundary reflections and enabling more realistic onshore propagation. The model grid used the 5 m resolution of the processed bathymetry, which is sufficient to resolve the width of reef flats, reef-crest morphology, and the local wavelengths associated with 6–10 s waves.

WAPO incorporates seabed roughness through the Nikuradse equivalent roughness height (k_s), allowing representation of the enhanced friction produced by coral structures. The simulations explored increasing k_s values to examine the sensitivity of wave attenuation to higher coral-colony relief and reef rugosity.

Bottom friction parameterization: In this contribution, bottom-friction is represented using the Nikuradse equivalent roughness height (k_s). Nikuradse relates roughness to a representative grain or structural element size, with a common definition being $k_s = 2.5D_{50}$ for sandy areas, taking values of $k_s = 0.002$ – 0.005 m, consistent with local sediment sizes. With regard to coral reefs, we are focusing our attention on the studies of frictional dissipation by Lowe et al., (2005), Monismith et al., (2015), and Rogers et al., (2015), in which the Nikuradse roughness can be effectively computed from the standard deviation (σ) of a cm scale bathymetric survey as 4σ (similar to the idea of calculating significant wave heights). This finding by Lowe et al., (2005) implies that k_s could be thought of as the statistical height of the reef colonies, which is a very convenient and easy approach to apply, the main advantage being that this value could serve as an objective for restoration projects. Using field data from a Pacific Atoll, Rogers et al. (2015) approximated



k_s using a least squares fit, and found values that varied from 1.1 to 2.5 m, very similar to the values we are suggesting in this paper. Reef areas were assigned $k_s = 0.5$ and 1.5 m, representing different degrees of restoration. These values reflect typical coral-colony heights and are within the range of structural complexity documented for Caribbean reefs, and are consistent with studies showing strong frictional dissipation over high-rugosity reef flats Monismith et al., (2015).

Experimental design (scenarios): Four monochromatic wave conditions were evaluated, spanning the dominant range of local sea states. Periods ($T_p = 6, 8,$ and 10 s) and heights ($H = 1$ and 2 m) were selected from the multiyear wave climatology, representing common short-period seas and the upper bound of normal conditions. Incident wave angles of 108° and 130° , measured clockwise from North, correspond to the primary wave approach directions from the ESE and SE-SSE sectors, respectively (Table 1). Although the regional wave climate is dominated by waves approaching from the SE sector (Fig. 2), these directions are largely shadowed by Cozumel Island and therefore were not considered in the present simulations. Instead, less frequent but dynamically relevant ESE and SE-SSE wave conditions were selected to ensure effective wave propagation toward the study area.

The selected scenarios allow for an independent assessment of the influence of reef ridge morphology and bottom roughness on wave transformation across the reef platform.

Table 1
Wave scenario matrix used in WAPO/REFDIE.

Case	Wave Period (s)	Wave Height (m)	Incident Wave Angle ($^\circ$)
			North = 0
Case 1	6	1	108 (ESE)
Case 2	10	1	108 (ESE)
Case 3	6	2	130 (SE-SSE)
Case 4	8	2	130 (SE-SSE)

Model calibration and validation.

To distinguish the relative contributions of geomorphology and roughness to wave attenuation, two complementary sets of numerical experiments were designed.

Geomorphic effect: Two bathymetric configurations were tested:

With-reefs (WR): the full observed bathymetry, including Manchoncitos I and II reef structures.

No-reef (NR): a counterfactual bathymetry in which reef-crest elevations were smoothed and lowered to match surrounding depths, removing the geomorphic obstruction while retaining the regional platform shape. This NR scenario isolates the alterations to wave propagation attributable solely to reef morphology.

Roughness effect - reef condition: WR simulations were repeated with different Nikuradse roughness heights (k_s) prescribed over the mapped reef polygons to represent gradients in coral relief achieved by hypothetical restoration. Following site-specific observations, we tested $k_s = 0.5$ m (low relief) and $k_s = 1.5$ m (high relief), which approximate typical colony heights and rugosity levels documented on Caribbean patch reefs.

Model calibration and validation: Model skill was assessed at the three instrument locations (A1, A2, and V2) by comparing simulated and observed significant wave height (H_s) and peak period (T_p). Performance metrics included root-mean-square error (RMSE), normalized RMSE (NRMSE), bias, and the coefficient of correlation (R), reported for each family of scenarios (Fig. 4; Table 2). These metrics quantify the average model-data misfits, its magnitude relative to observations, systematic over- or under-prediction, and overall agreement strength.

For nearshore wave propagation models, we considered NRMSE values ≤ 20 -30% indicative of acceptable skill. Because WAPO simulates monochromatic waves, model forcing was

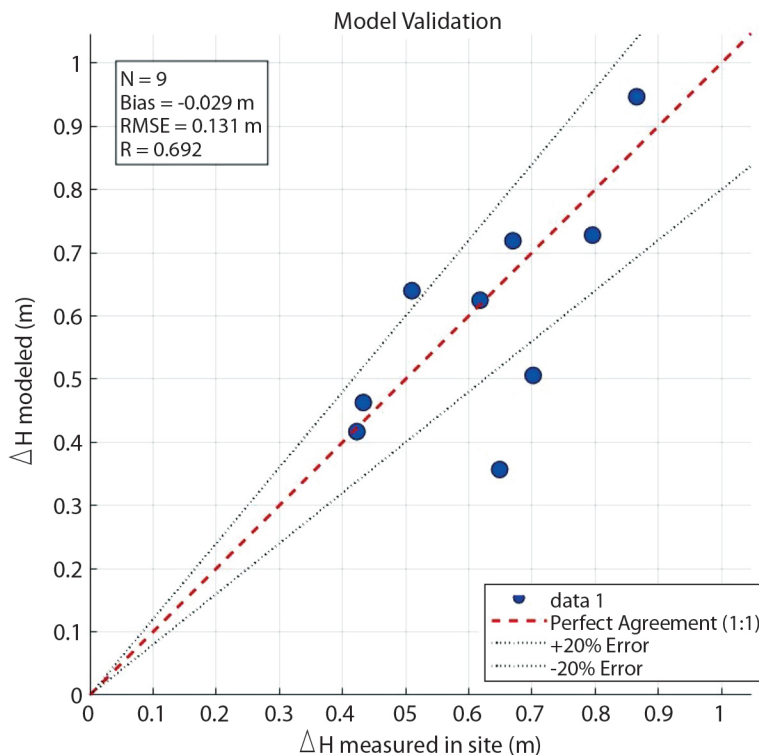


Fig. 4. Model validation. Modeled versus observed ΔH at A1, A2 and V2 with 1:1 line and skill metrics.

Table 2
Calibration/validation statistics (RMSE, NRMSE, bias, R).

Metric	Value	Interpretation
Number of points (N)	9	
bias	-0.029m	Slight underestimation
mean absolute error (MAE)	0.095m	
Root mean square error (RMSE)	0.131m	
percent rmse	20.85%	
Correlation coefficient [R]	0.692	Moderately strong correlation
Willmott's index of agreement (d)	0.816	Good agreement

matched to the observed T_p at each deployment, selecting the sea-state mode corresponding to the dominant spectral peak. Directional agreement was evaluated using polar scatter plots, which enabled inspection of systematic directional shifts or misalignment between modeled and observed wave approach angles.

The comparison between modeled and observed wave conditions showed good agreement across instrument locations (Fig. 4). Simulated significant wave heights closely reproduced field observations, with a low bias (-0.029 m), RMSE of 0.131 m, and a Willmott's index of agreement of 0.816 (Table 2). Although some scatter was observed, the model

adequately captured the magnitude of wave attenuation across the reef system and was therefore considered suitable for evaluating the influence of reef morphology and roughness on wave transformation.

A direct comparison between backreef and front reef wave heights for two wave periods (6 and 8 seconds) is shown in Fig. 5. At the measurement sites, front reef wave heights were consistently larger than those observed on the back reef in both the modeled and measured datasets. This observation is consistent with the time series measured during the field campaign (not shown). Nevertheless, as will be shown on the results, isolated reef mounds like Manchoncitos II can induce wave focusing in certain back reef areas.

RESULTS

Bathymetry and wave field overview: The high-resolution bathymetric grid (5 m; 994 x 780 nodes) spans approximately 4 km (N-S) by 3 km (E-W) and resolves the wavelengths

associated with the dominant short period components of the local sea state ($T_p \approx 6$ s). The bathymetry reveals two submerged patch-reef structures: Manchoncitos I, the larger reef, occurs at depths of 5–10 m and extends approximately 1 km in length, whereas Manchoncitos II is a narrower isolated reef mound located at depths of 5–9 m and extending approximately 500 m (Fig. 6A). Both reefs rise abruptly (~ 4 m) above the surrounding carbonate platform, whose base lies near 9 m depth. The modified bathymetry without reef structures is shown in Fig. 6B.

A shallow back-reef area west of Manchoncitos II hosts an active coral-restoration nursery managed by the Iberostar team, underscoring the ecological and conservation relevance of the site within the broader hydrodynamic context.

Effect of reef presence on wave attenuation: Across the scenarios tested, the Manchoncitos I reefs are the most efficient to block and attenuate offshore wave heights, especially under conditions from NE (Cases 1 and 2, Fig. 7A-D), where energy blocking becomes very evident.

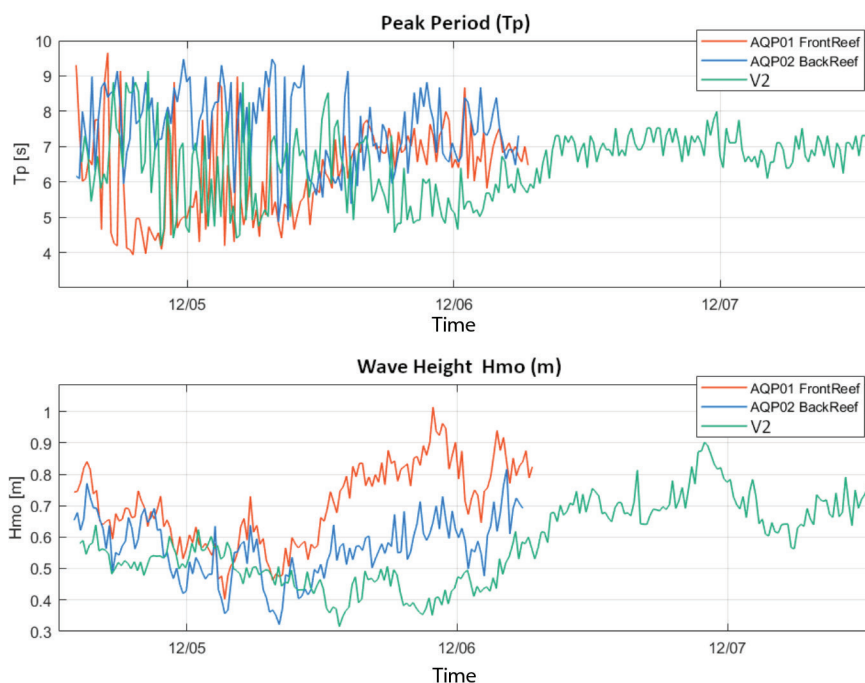


Fig. 5. Time series of A. peak period (T_p) and B. significant wave height (H_{m0}) measured at A1, A2 and V2.

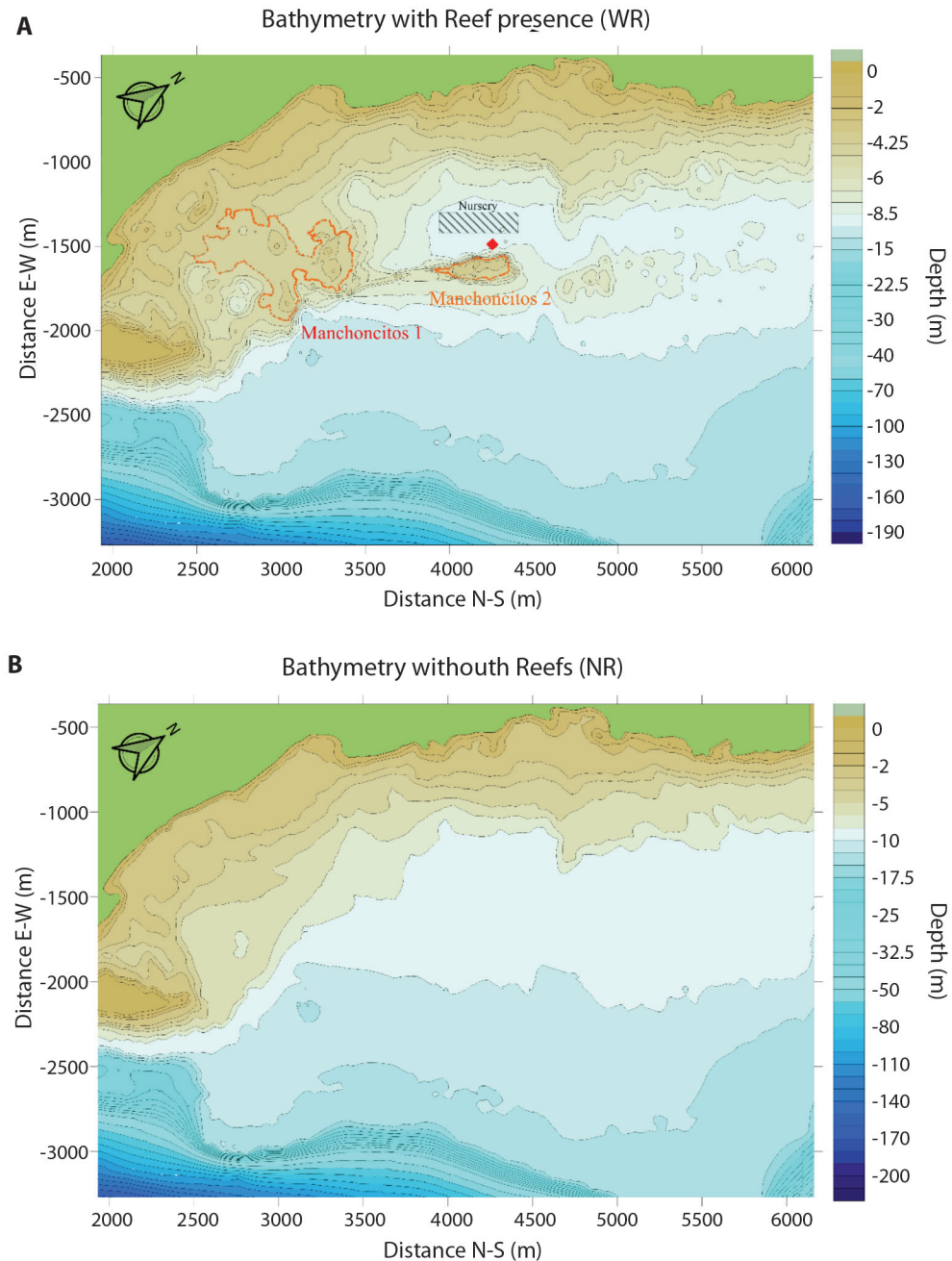


Fig. 6. High-resolution bathymetric maps of the study area showing (A) the observed reef configuration and (B) the no-reef bathymetric scenario used in the numerical simulations.

This effect is due to the large extension of Manchoncitos I reef. For SE-SSE waves (Cases 3 and 4, Fig. 7E-H), the blocking effect is less evident

as energy seeps through the reef openings, but wave dissipation is still clearly achieved.

Wave Height Dissipation Results

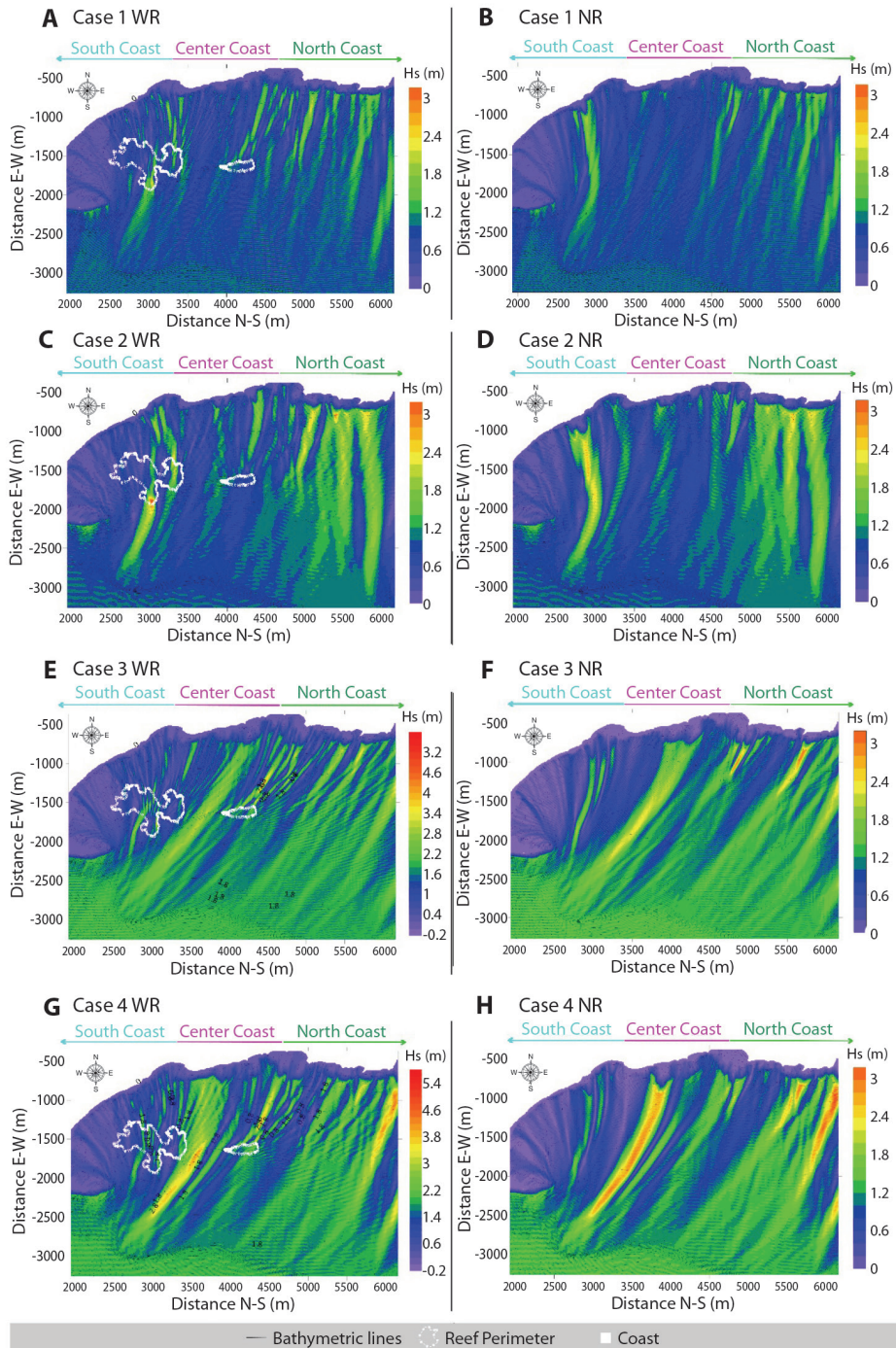


Fig. 7. Spatial distribution of wave height dissipation induced by the presence of reef structures, comparing the with-reef (WR) and no-reef (NR) configurations: **A.** Case 1 WR, **B.** Case 1 NR, **C.** Case 2 WR, **D.** Case 2 NR, **E.** Case 3 WR, **F.** Case 3 NR, **G.** Case 4 WR, and **H.** Case 4 NR. Blue areas indicate wave height reduction, green areas represent moderate conditions, and red areas denote wave height increase.

For the case of Manchoncitos II, there are also reductions in significant wave height on the back reef, although the attenuation pattern is spatially more heterogeneous and areas of dissipation alternate with localized back-reef zones where wave heights remain comparatively elevated. These spatial variations coincided with gaps and low-relief sections of the reef crest. This wave-focusing effect redistributes wave energy across the back-reef area and concentrates more energy in localized zones. Smaller and isolated reef mounds such as Manchoncitos II are capable of scattering incoming waves.

Across all wave scenarios, reef-induced wave height reductions exhibited a strong dependence on incident wave direction and offshore wave conditions. For ESE wave conditions (Cases 1 and 2, Fig. 7A-D), Manchoncitos I produced substantial attenuation along the southern sector of the coast, with local wave height reductions ranging from approximately 70 to 90 % under moderate wave forcing (Case 1, Fig. 7A-B), and decreasing to about 35–55 % under the longer-period Case 2 conditions (Fig. 7C-D). In contrast, Manchoncitos II displayed a weaker and more spatially heterogeneous influence, locally enhancing wave focusing and generating areas of amplified wave energy rather than uniform dissipation.

Under more energetic SE-SSE wave conditions (Cases 3 and 4, Fig. 7E-H), overall wave attenuation was reduced but remained significant, with Manchoncitos I consistently dissipating 20–45 % of the incoming wave height and providing localized protection to adjacent coastal segments. In these cases, Manchoncitos II continued to induce smaller-scale focusing effects, resulting in a patchier attenuation pattern. Together, these results demonstrate that reef-induced wave dissipation is highly non-uniform, controlled by the combined effects of reef geometry, roughness, and incident wave direction, with Manchoncitos I acting as the dominant physical barrier to wave energy across the platform.

Influence of reef roughness and energetic wave conditions: The roughness sensitivity experiments showed that modifying the Nikuradse roughness (k_s) produced systematic wave-height reductions (ΔH) in the regions associated with both reef structures (backreefs). Fig. 8 shows the differences in wave height between simulations with enhanced reef roughness and the baseline roughness scenario, therefore, negative values indicate reductions in wave height. For all cases and in both reefs, increasing k_s resulted in larger attenuation values in the back-reef region and altered the extent of the areas with reduced wave energy.

For ESE wave conditions (Cases 1 and 2, Fig. 8A-D), increasing roughness from $= 0.5$ m resulted in relatively small additional reductions in wave height, generally on the order of ~ 0.1 m, localized in the lee of both reef structures. When roughness was increased further to $= 1.5$ m, wave height reductions became markedly larger, reaching values of up to ~ 1.3 m and extending across broader back-reef areas. In Case 2, localized reductions of up to ~ 0.5 m were observed behind Manchoncitos I, while reductions associated with Manchoncitos II remained limited and became evident primarily under the highest roughness configuration, with values approaching ~ 0.3 m.

Under SE-SSE wave conditions (Cases 3 and 4, Fig. 8E-H), the magnitude of incremental wave height reduction associated with increased roughness was generally smaller, although similar spatial patterns were observed. In these cases, increases in roughness led to localized zones of enhanced wave height reduction without producing extensive areas of attenuation.

Across all wave scenarios, progressive increases in Nikuradse roughness were associated with increases in both the magnitude and spatial extent of wave height reduction. Larger reductions were consistently observed in the vicinity of Manchoncitos I, while changes associated with Manchoncitos II were more limited and primarily apparent under the highest roughness level.

Wave Height Dissipation Results with Nikuradse Roughness

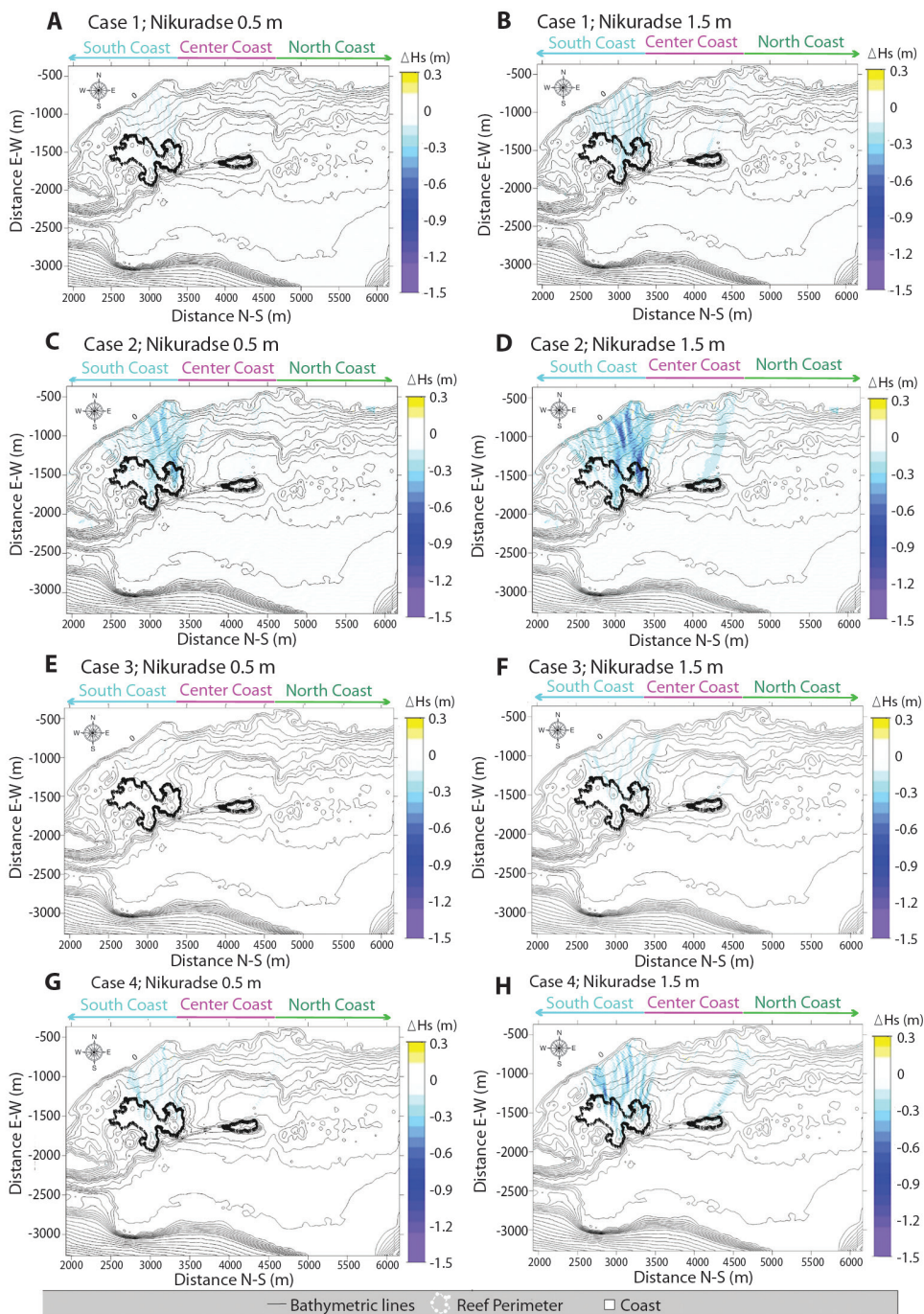


Fig. 8. Spatial distribution of wave height dissipation resulting from an increase in Nikuradse roughness, expressed as coral colony height (CH). Results are shown for: (A) Case 1, CH = 0.5 m; (B) Case 1, CH = 1.5 m; (C) Case 2, CH = 0.5 m; (D) Case 2, CH = 1.5 m; (E) Case 3, CH = 0.5 m; and (F) Case 3, CH = 1.5 m. (G) Case 4, CH = 0.5 m; and (H) Case 4, CH = 1.5 m. Blue areas indicate wave height reductions, while yellow areas denote increases.

DISCUSSION

Reef-mediated wave attenuation as a natural defense: Our results show that the Manchoncitos reef system provides substantial attenuation of incident wave energy, with maximum local reductions of 50–80 %. Although both reef crests remain fully submerged, Manchoncitos I generated a pronounced wave-shadow zone comparable to that reported for emergent Caribbean reef crests. This behavior is explained by a combination of geomorphological features: Manchoncitos I exhibits a larger cross-shore width, a more continuous crestline, and a steeper relief from the surrounding platform. These characteristics increase refraction and shoaling prior to the reef flat and promote significant energy dissipation despite the absence of an emergent barrier.

Manchoncitos II is a much smaller reef, with an isolated mound morphology that generated a more spatially variable pattern. Together, both reefs function as a discontinuous but hydrodynamically effective natural breakwater system. Importantly, the attenuation was not spatially uniform. The model revealed localized back-reef areas of elevated wave height associated with deeper passages and small-scale gaps in the reef. This spatial heterogeneity is consistent with observations from other submerged reef systems and underscores that reef-mediated protection depends strongly on fine-scale geomorphology.

This illustrates that the presence of reefs themselves is not a guarantee of widespread wave dissipation, it depends strongly on reef geometry and bathymetric configuration. Barrier reefs will always attenuate wave height as their geomorphology blocks wave energy inducing dissipation; but discontinuous reef ridges and isolated reef mounds could generate wave focusing, locally increasing wave heights on the lee of the reefs. This is a well-known effect applicable to many other similar physical processes (Torres et al., 2022).

Overall, these findings highlight that submerged reef ridges—despite lacking emergent crests can play a critical role in modulating

wave energy and provide measurable natural protection to adjacent coastlines. These results confirm that submerged patch reefs can function as effective natural barriers even within highly developed coastal corridors.

Importance of structural complexity and rugosity: Wave-modeling experiments showed that increased rugosity, expressed through Nikuradse roughness (k_s), enhanced wave-height reductions and expanded attenuation zones. The response was progressive for Manchoncitos I and threshold-like for Manchoncitos II, underscoring that the influence of structural complexity depends on each reef's geometry, relief, and crest continuity.

Implications for coastal-risk management and hybrid solutions: The Manchoncitos reefs can function as natural coastal-protection infrastructure, reducing nearshore wave energy across a range of sea states and thereby stabilizing the adjacent shoreline, especially if coral restoration is successful (high roughness scenarios). Unlike gray-engineered structures such as breakwaters or seawalls, coral reefs provide wave attenuation while simultaneously supporting ecological connectivity, habitat complexity, and carbon sequestration capacity (Beck et al., 2018; Spalding et al., 2001). These multifunctional benefits underscore the value of reef systems as nature-based solutions that deliver both physical and ecological services.

Restoration-oriented roughness scenarios demonstrated that increasing reef roughness leads to stronger wave dissipation, with high-roughness conditions producing reductions of up to ~1.0–1.2 m at Manchoncitos I and ~0.3–0.4 m at Manchoncitos II. These findings indicate that recovery of coral framework not only supports ecosystem functions but also enhances the hydrodynamic role of reefs as wave-attenuating features.

However, recovery of framework-building corals such as *Acropora palmata* typically occurs over decadal timescales. Therefore, hybrid approaches that combine reef restoration with engineered modules or artificial reef bases can provide immediate physical protection while



facilitating biological regrowth (Cheong et al., 2013; Hong et al., 2019; Hong et al., 2020). Our modeling results support this strategy: the addition of artificial structures produced dissipation levels comparable to an increase of approximately 0.5 m in effective roughness height (k_s), indicating that such interventions can enhance wave attenuation during early restoration stages.

These findings highlight the potential of hybrid reef-engineering strategies to bridge the temporal gap between reef degradation and ecological recovery. By enhancing wave dissipation during the early stages of restoration, such approaches may help maintain shoreline stability, reduce erosion pressures, and strengthen the resilience of reef-backed coastlines under future climate-driven increases in wave energy.

Limitations and future applications:

Although the monochromatic WAPO framework simplifies the full ocean-wave spectrum, previous studies have shown that mild-slope solvers reliably reproduce the dominant physical processes governing wave transformation on coral reefs, including refraction, diffraction, and reflection, with inclusion of depth-limited breaking, and frictional energy loss (Buckley, 2016; Lowe et al., 2005). As a result, while absolute wave height patterns may differ from those generated by spectral wave models (i.e. SWAN), the WAPO approach provides a theoretically sound option as it includes the most important wave processes relevant for complex bathymetries such as the one of this study, including coastal-management applications.

Several limitations point to opportunities for future research. First, the representation of reef roughness through a single Nikuradse parameter (k_s) captures the first-order influence of structural complexity but does not resolve spatial variability in coral morphology, colony size distributions, or patch-scale porosity. Future modeling efforts could incorporate spatially explicit rugosity maps derived from photogrammetry or LiDAR to improve accuracy. Second, the model does not account for wave-driven currents, sediment transport,

or feedback between reef accretion, erosion, and hydrodynamic forcing. Coupled morpho-dynamic-ecological frameworks would allow evaluation of how changes in coral growth, sediment budgets, and storm impacts influence long-term shoreline stability. Finally, integrating these models with socio-economic assessments could help quantify the avoided-damage value of reef protection, such as reduced beach-nourishment needs, maintenance costs for coastal infrastructure, and tourism-related benefits—thereby strengthening the role of reef conservation and restoration within climate-adaptation planning.

Broader significance: This study provides one of the few quantitative evaluations of the coastal-protection services delivered by submerged reef systems within an intensively developed tourism corridor. By integrating hydrodynamic modeling with high-resolution reef morphology and experimentally derived roughness scenarios, our results establish a clear scientific foundation for recognizing submerged patch reefs as functional natural-defense infrastructure. In doing so, the study demonstrates how wave-modulating services, often overlooked in submerged reefs, can be measured, compared across reef units, and explicitly linked to restoration potential.

Beyond its biophysical insights, this work aligns with emerging regional frameworks on Nature-based Solutions (NbS) and Caribbean Blue Economy initiatives. These frameworks emphasize the dual ecological and socio-economic value of healthy reef systems, particularly in regions where tourism, coastal development, and hazard exposure intersect. The Manchoncitos system exemplifies how private-sector participation in reef restoration can translate into measurable gains in coastal resilience, directly benefiting infrastructure protection, beach stability, and long-term adaptation planning.

More broadly, the study contributes to the growing recognition that conserving and restoring coral-reef structure is not only a matter of ecological stewardship, but also an investment in nature-based coastal protection.

As climate change intensifies wave energy, sea levels, and storm impacts across tropical coastlines, quantitative assessments such as this one will be essential for guiding policy, prioritizing restoration targets, and developing hybrid reef-engineering solutions that sustain both biodiversity and coastal safety.

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