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RESEARCH

Effect of Coral Reefs on Wave Height Observed by Satellite Altimetry

Mariia Usoltseva[1,2] · Marcello Passaro[2] · Denise Dettmering[2]

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Abstract

Coral reefs, among other benefits, offer a natural sheltering effect for coastal communities by attenuation of incoming waves. Despite the long-standing scientific interest in this subject, there remains a lack of comprehensive studies that assess wave behavior on coral reefs through satellite altimetry. This study investigates the influence of coral reefs on wave heights using a multi-mission along-track satellite altimetry dataset. Significant wave height statistics for different sea states derived from altimetry are compared with those from the ERA5 reanalysis dataset. Additionally, the role of coral reef structural complexity in wave attenuation is analyzed through regional assessments of altimetry data during calm periods and following destructive storms. The results show a strong agreement between the wave height attenuation observed from satellite altimetry and ERA5 datasets, with a correlation coefficient of 0.724. In 80% of the observations, a significant reduction in wave height was observed after waves passed over coral reefs. Statistical evaluation indicates that wave height attenuation increases as offshore wave conditions intensify, with an average 50% reduction for higher sea states. Furthermore, regional analysis after extreme events demonstrates decreased wave attenuation in areas with reduced hard coral cover. The study highlights the potential of satellite altimetry in observing wave height changes across coral reefs. Additionally, this study contributes to knowledge of wave behavior in coral reefs, showing the dependency of the attenuation degree on various sea states.

Keywords Satellite altimetry · Coral reefs · Wave attenuation · Applied remote sensing

1 Introduction

Coral reefs, occupying only a fraction of the ocean floor, are highly diverse and valuable ecosystems. They provide habitats for more than 25% of marine species and support coastal communities by supplying resources and jobs. In addition to their biodiversity and other benefits, coral reefs act as physical barriers, influencing wave behavior and offering natural coastal protection [7].

✉ Mariia Usoltseva
mariia.usoltseva@tum.de

Marcello Passaro
marcello.passaro@tum.de

Denise Dettmering
denise.dettmering@tum.de

1 Institute for Astronomical and Physical Geodesy, Technical University of Munich, Arcisstr 21, Munich 80333, Germany

2 Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Arcisstr 21, Munich 80333, Germany

As climate change strengthens the frequency and intensity of extreme weather events such as tsunamis, storms, and storm surges [18], coastal areas with high population densities are becoming more vulnerable. At the same time, climate change also impacts coral reefs [14], leading to a loss of their structural complexity and changes in their ability to reduce waves [3]. Consequently, the examination of the influence of coral reefs on wave attenuation has gained paramount significance in the last decades.

Several field experiments were conducted at the Great Barrier Reef [10, 26, 28], Hawaiian islands [9, 16], Caribbean reef [15, 17], and other reefs to examine the wave attenuation on reefs. The main goal of those experiments was to acquire time series of several parameters related to wave behavior, such as significant wave height (SWH), wind speed, and tide data. The methodology remained similar among those experiments: deployment of several measuring devices, such as buoys and wave staffs, offshore, on a line towards the reef front, and in the middle of the reef's lagoon. The experiments showed the general wave height attenuation and energy dissipation caused by the bottom friction and wave breaking [10, 16, 17, 28] and dependency of wave heights on the reef flat and its lagoon on the depth of water over the seawards reef slope [10, 28].

The investigation of wave attenuation in the presence of coral reefs can be conducted not solely by direct field measurements but also by utilizing remote sensing techniques. [8] investigates the dependency of wave attenuation on the porosity of the reef matrix, the reef submergence depth, and local wind speed employing SWH measurements from satellite altimeters over the Great Barrier Reef from September 1992 to 2008. To estimate wave attenuation, the SWH estimates from satellite altimetry were extracted at three locations: offshore, on the reef matrix, and between the reef and the mainland. The collected data, in combination with the porosity index of the reef matrix, water level, and bathymetry, showed a clear influence of reef submergence of less than 7 m on wave energy but no functional dependency on reef matrix porosity.

Despite the extensive body of research on wave attenuation on coral reefs, there is still an absence of a comprehensive global study performed with remote sensing observations assessing the change in wave height on a global scale under various initial conditions. Using satellite altimetry instead of field measurements or numerical models might be beneficial for studying these changes since there is a direct comparison of two measurements of the same wave field before the coral reef and on the coral reef. The objective of this study is to assess the ability of satellite altimetry to observe the change in SWH on coral reefs and quantify the effect of coral reefs on SWH for different sea states and post-destructive storms.

Such research was unfeasible until recent years due to the absence of reliable altimetry measurements in coastal regions. Over the last two decades, numerous international studies have been conducted to improve the understanding and quality of satellite altimetry observations in coastal regions. These works have mainly focused on refining geophysical and propagation corrections applied to the range measurements and developing specialized retracking algorithms designed to accommodate nonstandard waveforms caused by shallow waters and proximity to the land [4].

This study uses along-track satellite altimetry observations sourced from the Sea State Climate Change Initiative (CCI) v3 dataset [22]. The dataset has been extensively quality-controlled and validated also in comparison with buoys and model data [6, 27]. It uses advanced retrieval algorithms that have shown notably enhanced performances in coastal regions compared to the previous standard [24]. These data have already been validated and used globally in the coastal zone to quantify the change of the SWH from offshore to the last 3 km from the coastline [20]. Spanning from January 2002 to December 2020, the dataset contains global, quality-controlled measurements from various cross-calibrated altimetry missions, including Cryosat-2, Jason-1, Jason-2, Jason-3, Saral, Sentinel-3A, and Envisat. By applying the methodologies described in subsequent sections, we aim to investigate the detection of changes in SWH as waves propagate over coral reefs and enhance our understanding of coral reef-wave interactions.

2 Data and Methods

2.1 Data

Satellite altimetry In this study, we analyzed multi-mission cross-calibrated satellite altimetry data from the Sea State CCI dataset [22]. The Sea State CCI dataset offers spatial coverage from −80° S to 80° N and spans an extensive temporal period starting on January 2002 and ending on January 2020, making it ideal for investigating long-term trends and variations in sea state conditions connected with the variability of coral cover. The data is collected from multiple cross-calibrated satellite altimetry missions, including Cryosat-2, Jason-1, Jason-2, Jason-3, Saral, Sentinel-3A, and Envisat. The detailed information on the retracking and quality control methodology employed in the Sea State CCI dataset is described by [21].

In this study, the observations from Cryosat-2 are excluded from the dataset due to its orbit characteristics designed for polar observations with high spatial resolution, which result in a very long repeat cycle — 369 days. For other satellites only the observations taken during the core orbit phases are taken into consideration. After this period, most of the satellites moved from the original science orbit with repeating ground tracks to another orbit with different orbital characteristics. Subsequently, data processing with the use of nominal ground tracks becomes unfeasible. Thus, the time range of valid ground tracks differs from the temporal coverage of satellite missions.

ERA5 To investigate the capability of along-track satellite altimetry to observe changes in wave heights across the reefs, the SWH estimates from the altimetry dataset are compared to the SWH variable from the ERA5 dataset [13]. The choice of the ERA5 reanalysis stems from its high temporal resolution and grided data structure. In contrast to the altimetry dataset under examination, which exclusively provides along-track data with long intervals of 10 to 35 days between revisiting the same geographic location, ERA5 offers global coverage at hourly intervals.

The model dataset is created with the data assimilation principle, combining historical observations from various sources, such as weather stations, satellites, and buoys, with sophisticated numerical weather models. The process involves fitting a weather forecast model with new observations of the variables to calculate a better estimate, improve the forecast, and generate a comprehensive and consistent representation of the Earth's global atmosphere, land surface, and ocean waves [12].

This study utilizes the parameter *Significant height of combined wind waves and swell*, compared to SWH derived from satellite altimetry. The parameters are provided with a temporal resolution of 1 h on a regular latitude-longitude grid with 0.5° spatial resolution.

Coral atlas To observe the change in height of ocean waves on coral reefs, information on reef locations and boundaries is needed to separate altimetry and reanalysis data on wave parameters measured on the reef and offshore. This data is provided by the Allen Coral Atlas [1] as reef extent product.

The reef extent product is a 5 m pixel resolution raster derived from Planet's PlanetScope satellite imagery between the years 2018 and 2020.

2.2 Data Selection Criteria

During the data preprocessing phase, several key considerations on geographical extent, time frame, and wave parameters were developed. The geographical extent of the study area is mainly limited by the specifications of the Coral Atlas dataset, which includes coral reefs located only within the latitudinal range from −30° to 30°. This geographical constraint aligns with the typical distribution of coral reefs mainly located in tropical and subtropical waters. Consequently, this limitation has a relatively small impact on the study results.

Additionally, it is important to mention the temporal window within which the satellite images of reef extent were taken, spanning the years 2018 to 2020. Therefore, the results of the study are more accurate in this time span due to the variability of reef extent and hard coral cover over different years.

Another consideration imposed on the satellite altimetry dataset involved the implementation of a filter based on the distance to the coast. Application of this filter to the altimetry data preserved only observation points located between 3 and 500 km to the coastline. The lower bound of the filter aimed to eliminate potential outliers [20]. The upper bound of the filter to optimize processing time without sacrificing data quality. This decision was justified by the fact that most coral reefs are situated in proximity to coastlines.

In addition to the discussed earlier limitations, it is necessary to address a further constraint related to the minimum SWH observed along the reef borders. This study considers pairs of observations over the reefs and their adjacent border areas only when the wave height along the reef border equals or exceeds 0.5 m. This threshold is imposed due to several important considerations. Firstly, smaller wave heights exhibit relatively minimal attenuation effects, making their inclusion into the analysis of limited significance. Secondly, satellite altimetry, as the primary data source, encounters limited accuracy for smaller wave heights due to suboptimal signal-to-noise ratios associated with smaller signals [24]. Consequently, the study focuses on observing the attenuation of SWH meeting or surpassing this 0.5 m threshold along the reef borders.

2.3 Processing of Altimetry Data

The SWH observations within the SeaState CCI dataset are provided in a ready-to-use state after preprocessing, cross-calibration between satellites, and quality control. These datasets are organized into daily files, each containing observations from all the satellites operating on that specific date.

Location flags SWH observations were categorized into reef observations, border observations (first observation before the reef), and open ocean observations (excluded from this study) to analyze changes in wave heights from open water to coral reefs. This categorization was determined by measuring the distance of each observation to the reef polygon using the following criteria:

1. If the measured distance equals zero, the observation is categorized as a reef observation, signifying its proximity to the reef structure.
2. The closest observation to the reef is considered a border observation if it is further than 3.5 km. The threshold of 3.5 km was selected to exclude the possibility of a reef matrix presence within the altimeter footprint.

To enhance processing efficiency, the distance calculations are executed not for each individual observation but singularly for each nominal track of every satellite, given the fact that satellite ground tracks repeat very closely every cycle. An example of location flags calculated for nominal tracks of the Jason-1 satellite is shown in Fig. 1. Subsequently, these flags are applied to each observation through a linear one-dimensional interpolation. Notably, any variability introduced by an individual passes along the same ground track due to orbit deviations is disregarded in this analysis.

Following the data reorganization, implementation of all specified constraints, and the interpolation of location flags, the changes in SWH values can be computed and analyzed. To accomplish this, the SWH value closest to the land on a reef is subtracted from the SWH value on the reef border. This approach allows direct comparison of measurements of the same wave field taken before and after the coral reef. Subsequently, an averaged SWH attenuation value is computed for each reef within every satellite ground track.

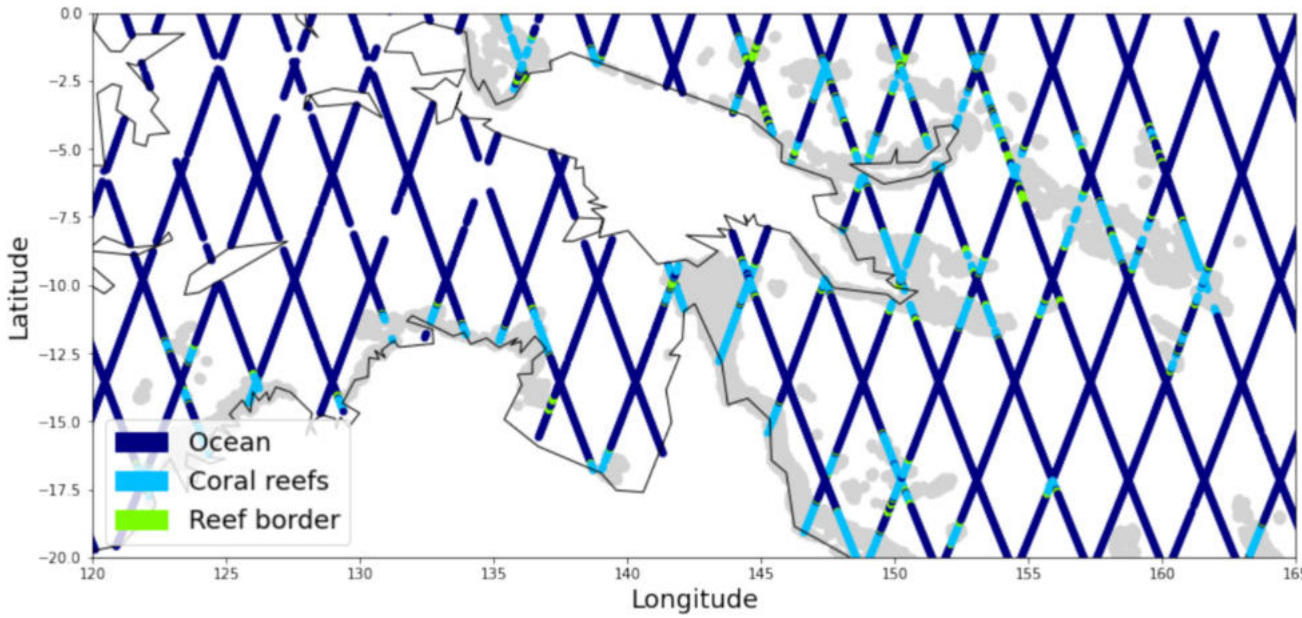

Fig. 1 Jason-1 location flags

Different sea states To assess the influence of coral reefs on SWH for different sea states, we employed the sea state classification defined by the World Meteorological Organization (WMO) as the Douglas Sea Scale, using the first observation before the reef as a reference point. This classification system categorizes sea states from 0 m, representing calm seas, to over 14 m for phenomenally high waves. Following the classification of observations on different sea states, the developed algorithm calculates the differences between this first observation before reaching the reef and the observation over the reef.

Influence of structural complexity To evaluate the impact of structural complexity on coral reefs' ability to attenuate waves, we categorized all reefs into distinct regions. These regions were defined based on the UN Environment Programme report on the status of coral reefs [25]. The regions include East Asian Seas, Pacific, Australia, Caribbean, West Indian Ocean, Red Sea and Gulf of Aden, South Asia, East Tropical Pacific, Gulf of Oman, and Brazil.

The years 2002, 2009, and 2018 were chosen for regional statistical evaluation, representing opposite states of the overall coral cover. This selection is explained by the change of coral reef structural complexity time-series provided in the UN report [25]. In summary, in 1997–98 one of the most powerful El Niño events caused a significant reduction in global average hard coral cover, regressing from 32.5 to 30% between 1997 and 2002. Between 2002 and 2009, global average hard coral cover exhibited a remarkable recovery, returning to pre-1998 levels and reaching a peak of 33.3% in 2009. Following 2009, there was a sustained decline in global hard coral cover, particularly exacerbated by the severe impact of the strongest El Niño event in 2015–16, which induced the most pronounced heat stress ever documented during such occurrences [5]. This period witnessed a marked reduction in hard coral cover to 28.8%, equivalent to a substantial loss comprising 13.5% of the world's hard coral coverage.

2.4 Processing of ERA5 Data

An alternative methodology was employed to categorize gridded reanalysis data on reef and reef border points. Since the model provides parameter values on a regular grid, flags are generated only once for the entire model grid. For each grid point, the location flags are determined through distance calculations from the point to the closest reef polygon. Subsequently, these computed flags are applied to every individual timestamp within the dataset. This methodology was chosen to ensure consistent data categorization and efficient processing of large datasets.

To compare the performance of the satellite altimetry and ERA5 datasets, we projected the gridded model data on the altimetry tracks utilizing a three-dimensional linear interpolation. This involves interpolating data points across the latitude, longitude, and time dimensions to match the spatial and temporal resolution of the altimetry measurements. Following interpolation, the ERA5 data along the satellite tracks were processed using the same algorithm applied to the altimetry data. This includes the classification of modelled observations on different sea states and the utilization of location flags derived from the satellite altimetry dataset.

3 Results

To assess the global influence of coral reefs on wave heights, the SWH attenuation was computed on a global scale, encompassing an 18-year period from 2002 to 2020. To evaluate SWH changes on coral reefs, we separated along-track altimetry observations into two categories: first measurements before the coral reef from the ocean side and measurements over the coral reef. Subsequently, the closest to the land SWH observation flagged as the coral reef is subtracted from the first measurements before the reef.

3.1 Global SWH Attenuation

Figure 2 provides a global overview of the average SWH values on coral reefs, SWH values on the reef border, and the differences between these values along the same satellite track. Each point on these plots corresponds to the mean

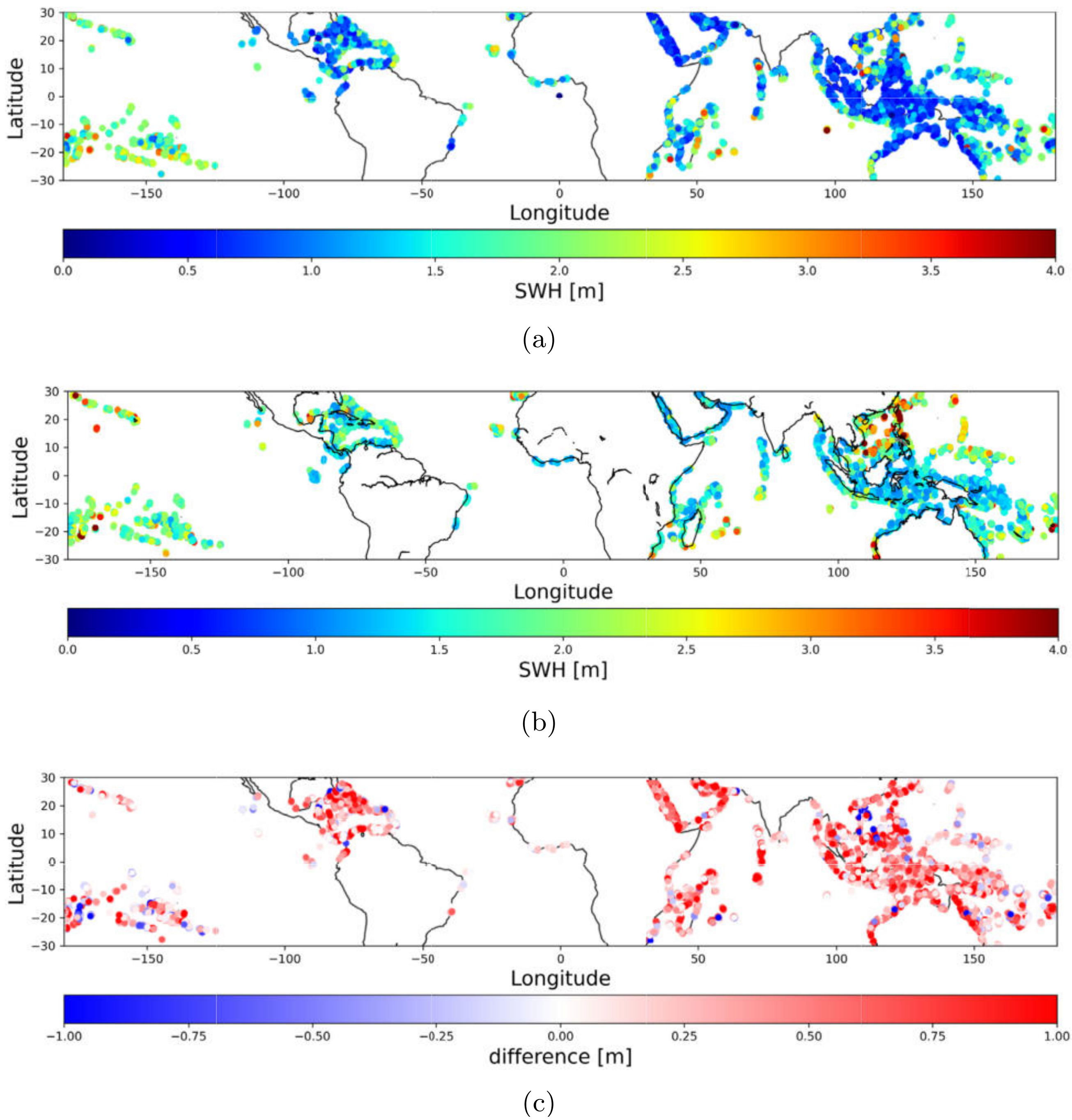

Fig. 2 Mean SWH observed by along-track satellite altimetry over coral reefs (**a**), on the reef border (**b**), and differences between them (**c**)

SWH value for a segment of the coral reef within one satellite ground track. In total, the analysis includes 350,260 attenuation observations, providing robust statistical support for the observed trends. From Figure 2a and b, the global picture expected from the meta-analyses of other works [7] emerges: average wave heights within reef polygons are notably smaller than wave heights right before reefs. This phenomenon is accentuated when the differences between reef and border SWH values are calculated. As illustrated in Fig. 2c, in most instances, the SWH over a coral reef is smaller than before the reef. The percentage of all positive SWH differences was calculated and equalled 78.8%. This underscores that, for 78.8% of observation, the SWH of the wave field approaching the reef is higher than within the reef, thus confirming the ability of satellite altimetry to detect changes in SWH travels across the reef.

The 21.2% of negative differences observed in this study can largely be attributed to several factors influencing wave attenuation, such as variability in coral reef health and extent over time, the geometry of individual reefs [23], and the local offshore wave climate. One contributing factor is the temporal mismatch between the altimetry observations and the reef extent data. The reef polygons used to classify reef and reef-border observations were derived from satellite imagery captured between 2018 and 2020 [1]. As reef structures can change significantly over time, the classification of altimetry data acquired outside this period is subject to increased uncertainty. This mismatch may result in some locations with reduced wave heights being misclassified as reef-border points. Besides, this study does not account for wind direction, which plays a crucial role in determining the angle at which waves approach a coral reef and, consequently, influences the process of wave attenuation.

To compare the performance of along-track satellite altimetry with the ERA5 dataset the SWH estimates from the ERA5 dataset are interpolated at the precise geographic coordinates of the satellite tracks. This method ensures a point-to-point alignment between the model-derived data and the satellite altimetry observations.

Figure 3 shows the maps of mean SWH values computed from ERA5 interpolated on satellite ground tracks for coral reefs (a), closest SWH values to the reef border (b), and the differences between them along the same track (c). The average SWH values and their differences extracted from the ERA5 dataset show consistency with the results observed in along-track altimetry data. A reduction in SWH values is visible as the waves travel from the open water across coral reefs. This major attenuation in wave heights is particularly notable in Fig. 3c illustrating calculated SWH differences.

The spatial patterns of high and low average SWH show strong agreement between the two datasets. When analyzing the difference maps in Figs. 2c and 3c, areas with significant positive change, such as the East Asian Seas and Australian regions, are consistent across both datasets. Similarly, regions with smaller or negative changes, such as the Tropical Pacific and West Indian Ocean, also show a comparable pattern. However, the difference maps generated from ERA5 data interpolated on altimetry tracks appear more homogeneous and faint, indicating lower average SWH attenuation derived from the model.

A comparison of a number of locations exhibiting negative SWH attenuation between Figs. 2c and 3c reveals a high degree of consistency. Specifically, 14.7% and 15.9% of locations, respectively, show persistent negative attenuation over the years. Despite this consistency, a large percentage of points displaying negative attenuation requires further analysis.

Figure 4 presents the spatial distribution of points exhibiting negative attenuation relative to coral reef structures in the Tropical Pacific. This data is derived from both along-track altimetry observations (a) and ERA5 interpolated on altimetry tracks (b). The locations of negative attenuation points align for both datasets in most cases, suggesting that the source of negative attenuation is likely physical rather than an artefact of observation or modelling techniques.

The location of observation points significantly affects the calculated attenuation values. As shown in Fig. 4, many of these negative points are located within the reef structure itself or in narrow regions of open water between sections of the reef, where the wave heights are already reduced. The geometry of the reef border can also influence the percentage of points with constant negative attenuation. For instance, the border observation may occur within a small bay between reef edges, where the sea state is comparable to or even lower than the reef edge, resulting in apparent SWH attenuation below zero. These cases highlight the potential for further algorithm refinement to account for such points. Improvements could include filtering out or adjusting data points in these complex areas to provide more accurate attenuation estimates and avoid erroneous results caused by spatial proximity rather than wave dynamics.

The summary of the comparison between the altimetry and ERA5 in its gridded format and interpolated on satellite tracks is presented in Table 1, showing SWH attenuation statistics. Overall, the statistical comparison of datasets for global SWH attenuation reveals alignment in central tendencies and shows a high degree of agreement between along-track satellite altimetry and ERA5 interpolated on satellite tracks, with a correlation coefficient equal to 0.724.

While the percentage of observed positive differences is very similar among all three datasets, the mean attenuation value computed from the ERA5 on satellite tracks is smaller than that from satellite altimetry. This results from the coarser spatial resolution of the model and generally smother representation of a wave field in different reef regions stemming from the interpolation process.

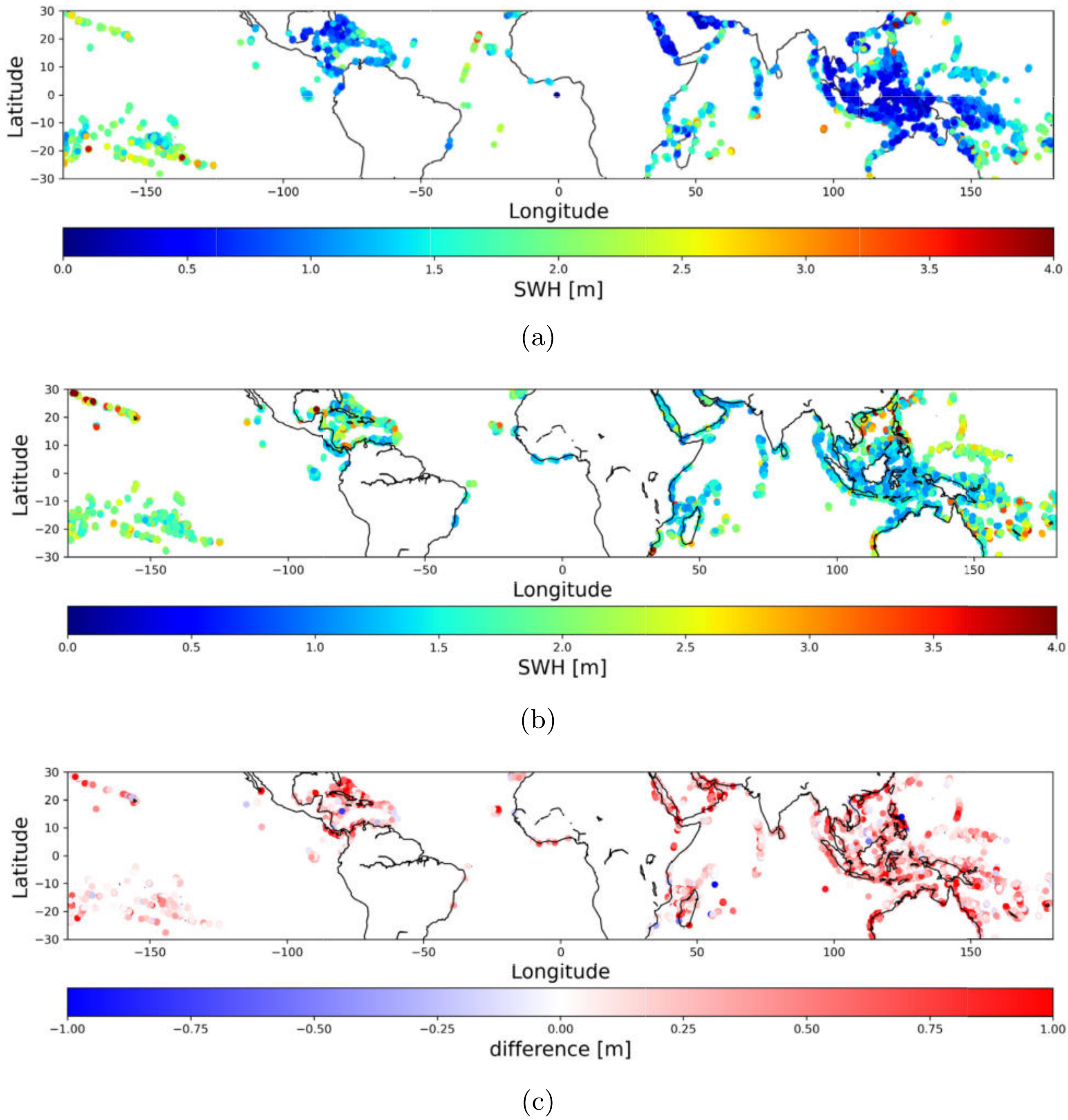

Fig. 3 Mean SWH produced from ERA5 data interpolated on altimetry tracks over coral reefs (**a**), on the reef border (**b**), and differences between them (**c**)

The reanalysis grid resolution highly influences the inclusion of coral reefs and their parts into the SWH attenuation analysis with ERA5 data. In the context of ERA5, the spatial resolution of oceanic variables stands at 0.5° by 0.5°. Consequently, the notable implication is that the fine structures of coral reefs and some smaller reefs remain entirely excluded from the analysis of SWH changes. An additional complication stemming from the spatial resolution of the ERA5 dataset, obvious even for larger coral reefs, is that an entire reef can be represented only by a single data point. The location of this singular point within the reef structure exerts a substantial influence over the observed degree of SWH attenuation in the analytical results, considering the nuanced interactions of waves with various segments of coral reef structures [2].

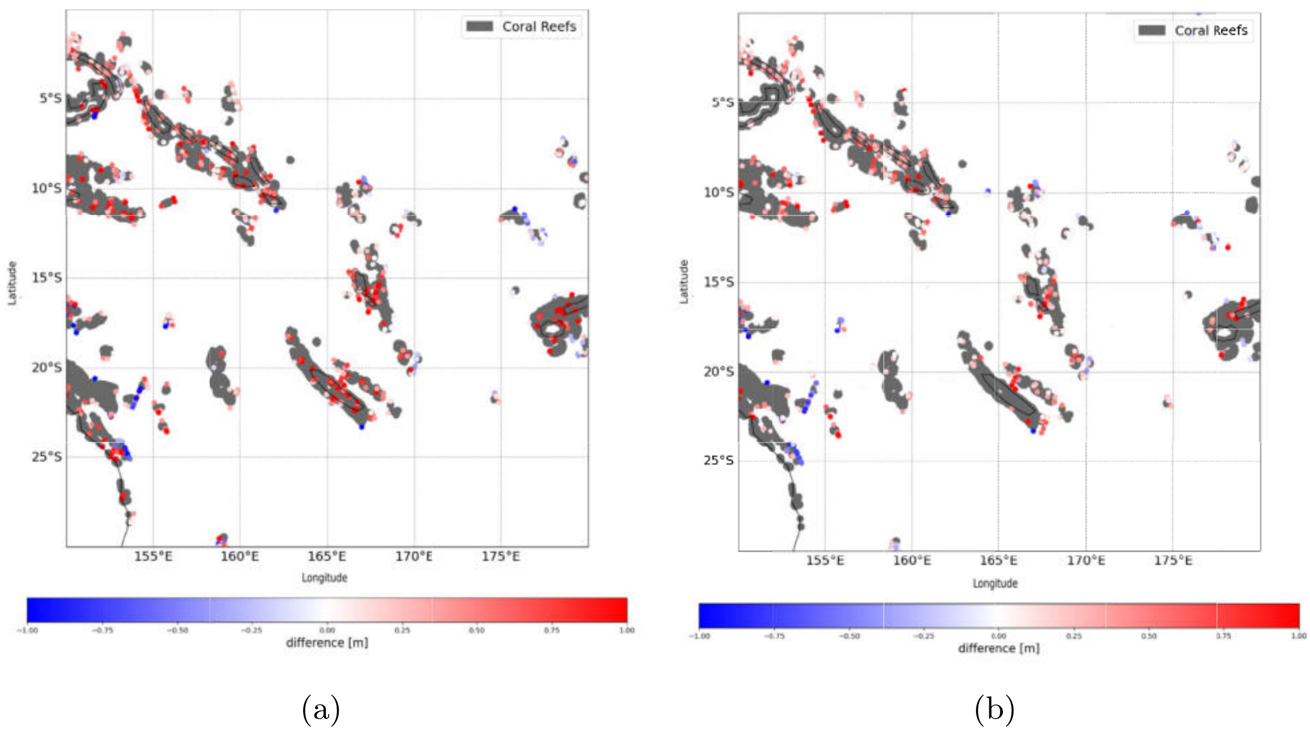

Fig. 4 Zoomed-in average SWH differences in the Pacific region derived from along-track altimetry observations (**a**) and ERA5 interpolated on altimetry tracks (**b**)

An additional assessment of SWH attenuation trends and distributions is illustrated in the histogram presented in Fig. 5. The histogram highlights the similarities in central tendencies between the two datasets, exhibiting peaks at the right side of zero. This indicates that SWH attenuation values derived from satellite altimetry and ERA5 reanalysis are generally positive but close to zero.

However, a notable difference is observed in the distribution of SWH attenuation values. The ERA5 data interpolated on altimetry tracks displays a narrower distribution with a sharper peak, suggesting that ERA5 tends to detect lower overall SWH attenuation compared to satellite altimetry. This can be attributed to its coarser spatial resolution and the inherently smoother representation of wave fields in reanalysis data.

Table 1 Mean and standard deviation of SWH attenuation recorded by satellite altimetry and ERA5

Calculation	Altimetry	ERA5 on satellite tracks	ERA5 on a grid
Mean SWH attenuation [m]	0.48	0.31	0.34
Standard deviation [m]	0.46	0.44	0.26
Positive attenuation [%]	78.8	81.7	89.6

3.2 Dependency on Sea State

Subsequently, a detailed analysis was conducted to examine SWH attenuation across sea states ranging from 0.5 to 9 m. The objective was to assess the capability of along-track satellite altimetry in capturing variations in wave height under different offshore conditions and to derive statistical

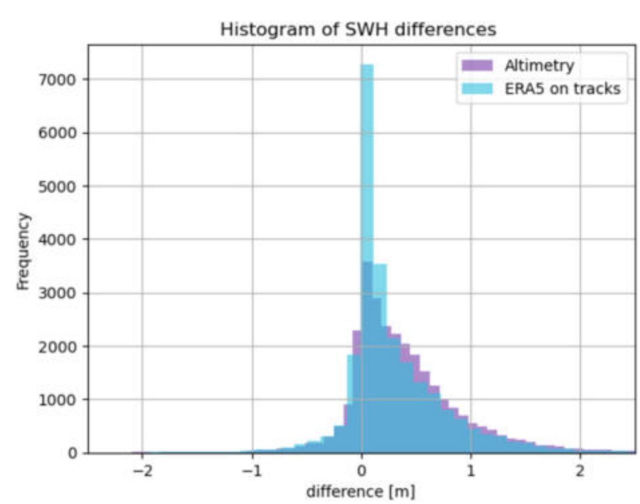

Fig. 5 Histogram of SWH differences derived from along-track altimetry observations and ERA5 on satellite tracks

Table 2 Number of altimetry and interpolated ERA5 points used for the analysis of each sea state

Sea state	Altimetry observations	ERA5 on satellite tracks estimates
Sea state 3 (0.5–1.25 m)	63,044	69,492
Sea state 4 (1.25–2.5 m)	76,921	66,454
Sea state 5 (2.5–4 m)	15,056	9960
Sea state 6 (4–6 m)	1141	873
Sea state 7 (6–9 m)	44	18

data on SWH attenuation for various sea states. Table 2 presents the total number of valid altimetry observations and estimates from interpolated ERA5 used in the analysis of each sea state. The number of points differs between the data sources due to the filtering of NaN values. The interpolated ERA5 dataset contains a higher number of NaNs, primarily due to the presence of invalid fill values in the original gridded ERA5 data and the propagation of NaN values during the interpolation process.

Figure 6 shows the histograms comparing SWH attenuation for different sea states observed by satellite altimetry and interpolated from the ERA5 data on the satellite track. For lower sea states, where wave heights are relatively small, the attenuation is minimal. This is illustrated in the first histogram, corresponding to SWH values at the reef border ranging from 0.5 to 1.25 m. The attenuation values for this sea state are predominantly clustered between −1.5 and 1.5 m, with most values centered around zero. This symmetrical distribution suggests little to no difference in SWH before and after the coral reef at the lowest sea states.

However, as offshore sea states increase in intensity, the histograms show a progressively right-skewed distribution, indicating increased attenuation. For the highest sea states, ranging from 4 to 9 m, there are nearly no instances of negative attenuation, implying that larger waves are more likely to experience a significant reduction in height as they interact with coral reefs. The wider distribution of attenuation values across all sea states reflects the substantial variability in the wave attenuation process.

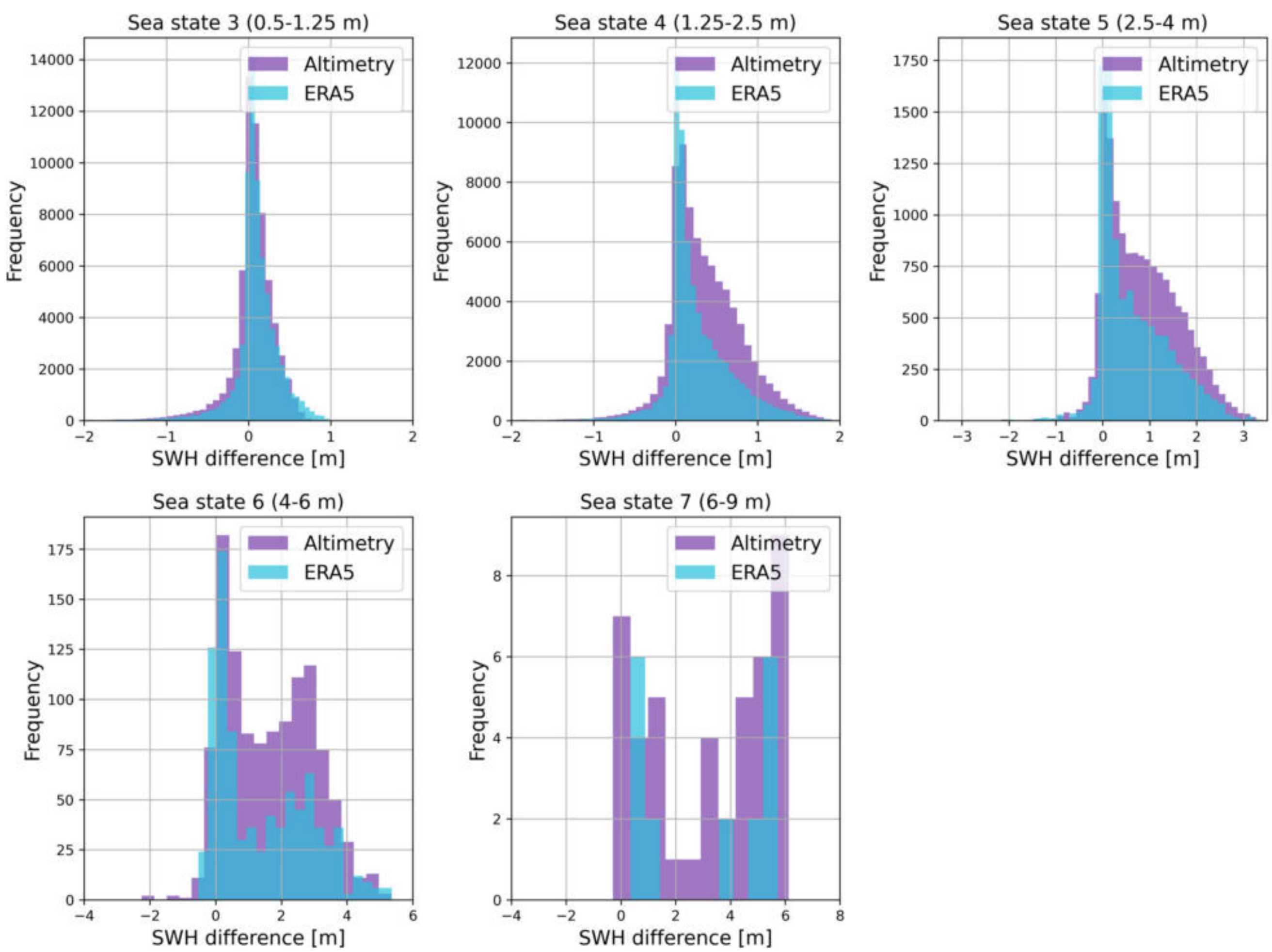

Fig. 6 Histograms of SWH attenuation observed by along-track satellite altimetry and ERA5 interpolated on satellite tracks for different sea states

In addition to the right-skewed distribution observed for higher sea states, a distinct plateau is evident for sea states 4 and 5, corresponding to wave heights between 1.25 to 2.5 m and 2.5 to 4 m, respectively. This plateau begins just at the right side of zero and extends up to a value slightly below the lower boundary of the respective sea state. It indicates a high occurrence of attenuation values between 0 and the lower bound of each sea state.

For the highest sea states 6 and 7, spanning from 4 to 6 m and from 6 to 9 m, a secondary peak emerges just before the lower boundary of the sea state, particularly noticeable in the histograms derived from the altimetry dataset. This suggests that, in many observed cases, wave heights are reduced by up to 3 m for sea state 6 and up to 5 m for sea state 7, effectively resulting in nearly full attenuation or wave breaking due to the reef's influence. The presence of this secondary peak for the highest sea states emphasizes the significant role coral reefs play in attenuating larger waves. This observation is consistent with the meta-study findings by [7], which showed that, on average, coral reefs can attenuate up to 89% of the initial wave height.

Notably, the analysis of datasets exhibits fewer observations for higher sea states from 4 to 6 m and from 6 to 9 m. This is due to the infrequency of high sea states in coastal zones, where coral reefs are predominantly located.

Overall, the histograms reveal consistent patterns in terms of central tendencies and skewness, regardless of whether SWH attenuation is derived from satellite altimetry or interpolated ERA5 data along satellite tracks. However, a key difference between the CCI and ERA5 datasets is that, for all sea states, ERA5-derived attenuation exhibits less variability, sharper peak around zero, and less prominent secondary peak for higher sea states. This reduced variability can be attributed to the smaller set of spatial points in ERA5, resulting from coarse grid resolution. While the interpolation process improves the coverage, it fails to fully capture the influence of coral reefs located between model grid points. Moreover, ERA5 appears to underestimate attenuation, as the majority of its sea state histograms display a narrow, pronounced peak just to the right of zero. In contrast, this peak is less prominent in the satellite altimetry data. These findings suggest that satellite altimetry may provide a more detailed and accurate representation of wave behavior over coral reefs under varying offshore conditions.

The correlation between increased attenuation and higher initial sea states is further illustrated in Figs. 7 and 8. Figure 7 presents mean wave attenuation as a percentage of the original SWH and the percentage of positive differences, while Fig. 8 highlights the mean attenuation in meters along with the associated standard deviation for each sea state.

ERA5 computed on altimetry tracks exhibits a notably high degree of similarity with altimetry data. This solid agreement is evident when inspecting the percentage of positive attenuation in Fig. 7 for sea states ranging from 1.25 to 6 m, which differ only by a few percent between the two datasets. Regarding the lowest and highest analyzed sea states, it is important to interpret statistics derived from satellite altimetry for very low and very high sea states with caution. The relatively small number of samples for the highest sea state, as seen from the last histogram in Fig. 6, does not allow for statistical evaluation. Conversely, even though the altimetry dataset provides enough data for low sea state (0.5–1.25 m) it is important to consider the limited accuracy of satellite altimetry in detecting very low SWH [24].

The analysis highlights large percentages of positive differences, reaching approximately 80% for wave heights between 1.25 and 6 m and 100% for SWH values ranging from 6 to 9 m. This indicates that, in most cases, satellite altimetry successfully captures the expected decrease in wave height as waves pass over coral reef environments.

The mean attenuation data in Fig. 8 highlights slight differences between altimetry and ERA5 along satellite tracks,

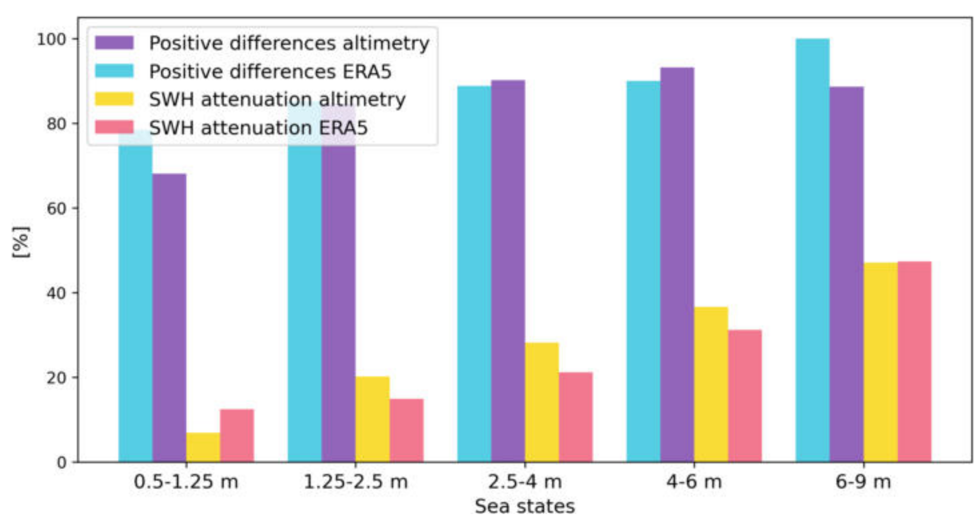

Fig. 7 Positive attenuation percentage and mean attenuation for different sea states computed for satellite altimetry and compared to ERA5 interpolated on satellite tracks

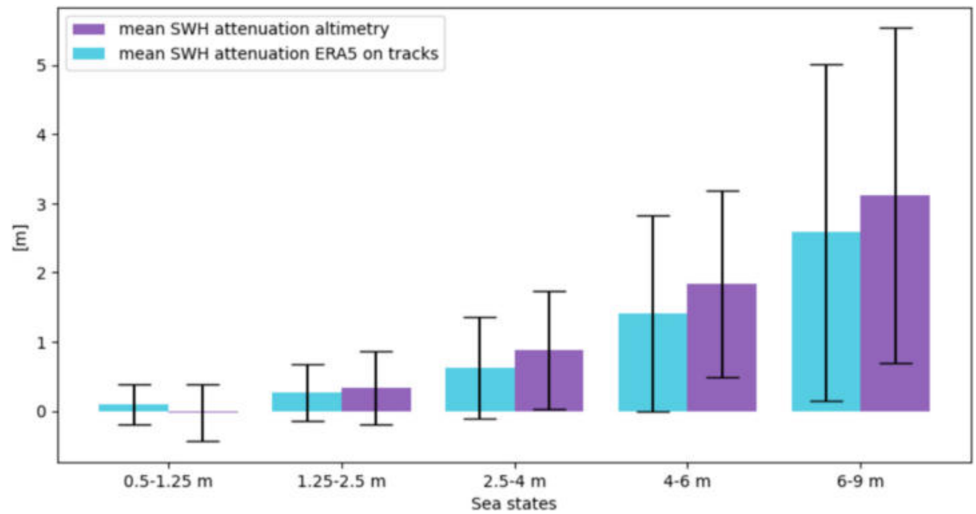

Fig. 8 Mean attenuation for different sea states computed for satellite altimetry and compared to ERA5 on satellite tracks. The bars represent the standard deviation of computed SWH attenuation

with ERA5 consistently reporting lower attenuation values across all sea states. However, drawing firm conclusions about the relative performance of these datasets or the mean attenuation for each sea state is challenging. This difficulty arises primarily from the substantial variability in SWH attenuation, as reflected in the standard deviation bars in the figure. Such variability is driven by the varying initial physical characteristics of the incoming waves and the differing health and structural complexity of coral reefs during the observed years.

3.3 Dependency on Reefs' Structural Complexity

The ability of coral reefs to attenuate wave heights significantly depends on the structural complexity of reefs, which is in turn dependent on reefs' health [3, 11]. The complex and rough formations on the seafloor cause wave energy loss through friction, turbulence, and resistance, while the reef structures as a whole can cause wave reflection and refraction, processes changing the direction of waves and reducing their height. Factors such as coral bleaching, ocean acidification, pollution, and physical damage from storms or human activities can all contribute to reef health degradation, resulting in decreased wave attenuation capacity. Therefore, the effect of coral reefs on wave energy and wave height is highly variable over the years and in reef groups.

Table 3 presents the mean positive SWH attenuation on coral reefs calculated using altimetry data across eight significant regions for the years 2002, 2009, and 2018, each characterized by differing levels of structural complexity. The reasoning behind the choice of these specific years is described in the Section 2.3. The calculated mean SWH attenuation analysis reveals an overall consistency over the years, with a slight tendency for lower attenuation values in the years following the El Nino events. This effect is the most evident for the year 2018, the year with the lowest global hard coral cover percentage according to [25].

Regions significantly impacted by the 2015–2016 El Niño event, such as Australia, the East Asian Seas, and the East Tropical Pacific, experienced over a 20% reduction in their wave attenuation capabilities between 2002 and 2018. For instance, in the East Asian Seas region, coral reefs exhibited a mean reduction in incoming wave heights of 34% in 2002, which rose to 38% in 2009 before dramatically dropping to

Table 3 Regional mean SWH attenuation with confidence intervals

Location	Mean attenuation 2018 [%]	Mean attenuation 2009 [%]	Mean attenuation 2002 [%]
East Asian Seas	31.6 (34.4–35.5 %)	38.1 (37.5–38.7 %)	34.8 (34.6–35.7 %)
Pacific region	29.7 (29.1–30.3 %)	27.2 (26.6–27.8%)	27.1 (26.5–27.6 %)
Australian region	30.2 (29.5–32.2 %)	33.7 (32.8–34.8 %)	31.1 (30.2–31.9 %)
Caribbean region	28.9 (28.3–29.5 %)	31.1 (30.3–31.8 %)	29.1 (28.3–29.8 %)
West Indian Ocean	26.3 (25.4–27.1 %)	26.9 (26.0–27.7 %)	27.3 (26.3–28.1 %)
Red Sea	34.1 (32.5–35.7 %)	38.2 (36.3–39.9 %)	37.4 (35.7–39.0 %)
South Asia	26.3 (24.9–27.6 %)	23.7 (22.3–25.1 %)	25.8 (24.4–27.2 %)
East TropicalPacific	27.5 (26.6–28.1 %)	31.6 (30.6–32.5 %)	28.2 (27.6–29.3 %)

31% in 2018, following the intense 2015–2016 El Niño event. The increase in mean SWH reduction in 2009 likely reflects a recovery in the attenuation ability of coral reefs as hard coral cover rebounded during calmer periods.

Despite the relatively small scale of differences in SWH reduction between years in a few regions, including the East Asian Seas, Australian Region, Red Sea, and East Tropical Pacific, these differences are statistically significant. These findings suggest that our satellite altimetry-based analysis may be capable of detecting changes in coral reef structure and their influence on wave attenuation.

4 Conclusions

Comparative analysis was conducted between SWH attenuations derived from along-track satellite altimetry and those computed with ERA5 data, both in its gridded form and interpolated on the satellite tracks, covering an 18-year period from 2002 to 2020. The results demonstrated a strong correlation between satellite altimetry and ERA5 data interpolated on satellite tracks, with a correlation coefficient of 0.724. Both datasets exhibited similar percentages of positive attenuation, with 78.8% of observations showing attenuation for altimetry and 81.7% for ERA5 on satellite tracks. However, the global mean attenuation differed, with altimetry showing an average attenuation of 0.48 m, while ERA5 interpolated on altimetry tracks indicated a lower mean attenuation of 0.31 m. This discrepancy suggests that although the global attenuation patterns are broadly similar between the datasets, ERA5 tends to underestimate attenuation due to the smoothing effects of coarse spatial resolution and the interpolation process, which limits its ability to capture the detailed wave behavior over coral reefs.

The analysis of SWH attenuation across different sea states yielded results consistent with the global findings. Altimetry data consistently exhibited higher attenuation values and greater variability across all sea states compared to ERA5 data interpolated on satellite tracks.

In addition to comparing the two datasets, this study provides new statistical insights into changes in SWH as waves pass over coral reefs, a phenomenon not widely explored in previous studies. As the sea state increases, the percentage of positive attenuation observations and mean attenuation both rise correspondingly. As the sea state increases, there is a corresponding increase in the percentage of observed positive attenuations and mean attenuation. For instance, for the SWH between 4 and 6 m, corresponding to very rough sea conditions, mean attenuation stands at 2 m. Both datasets consistently show a substantial decrease of SWH over coral reefs for higher sea states, highlighting reefs' ability to attenuate wave height and their potential as natural barriers for coastal protection.

Furthermore, the influence of varying coral reefs' structural complexity on their ability to attenuate waves was examined. The regional analysis was conducted in years characterized by low hard coral cover following severe El Niño and in years with high structural complexity, observed a few years after these destructive events. The findings revealed a slight decrease in mean SWH attenuation in the years following the decrease in hard coral cover. This phenomenon is especially evident for Australian, Pacific, and East Asian regions, showing about a 20% reduction in mean attenuations.

In conclusion, along-track satellite altimetry demonstrates great potential as a tool for contributing to the coral reef observation system. Its global coverage and high spatial resolution provide the capacity for a global examination of SWH variations across coral reefs, enabling the detailed analysis of changes on smaller reefs and in different parts of the reefs' profile. The accuracy of altimetry data in coastal regions has been substantially improved in recent years by developments in coastal pre-processing techniques, enabling more accurate observations in these challenging conditions. While the effectiveness of satellite altimetry is slightly compromised when coral reefs are situated between satellite tracks, the integration of multi-mission cross-calibrated altimetry effectively addresses this limitation. The primary challenge remains the revisit times for the same locations dictated by relatively long repeat cycles of satellite altimetry. This limitation impacts the observation of fast-changing or rarely occurring events, such as very high sea states.

Numerous applications, including coastal protection, natural hazards management, and the wave energy industry, are deeply concerned with changes in coral reef health, particularly regarding their capacity to attenuate wave heights. This study shows that satellite altimetry can be applied to this task by implementing a more rigorous data selection process to reduce variability caused by wind direction and the alignment of satellite tracks relative to reef topography. By analyzing changes in wave attenuation patterns along consistent satellite ground tracks over time, we can draw meaningful conclusions about shifts in reef structural complexity and, consequently, reef health.

As satellite altimetry technologies continue to advance, the prospects for studying wave height changes over coral reefs are poised to significantly improve. The concurrent operation of multiple satellite missions offers the advantage of reduced revisit times for the same reef structure. The resulting enhanced temporal coverage increases the probability of capturing of rare events and affords more detailed insights into the changes of SWH on coral reefs during and after destructive storms and anthropogenic hazards. Moreover, the deployment of new satellite missions, such as SWOT [19], featuring exceptionally high spatial resolution and accuracy along the coast holds substantial potential for investigating

SWH variations in different reef zones, such as lagoon, back reef, reef flat, reef crest, and fore reef. These advancements further facilitate the examination of changes in wave climate in coastal regions shielded by coral reefs, in correlation with changes in the structural complexity of these reefs.

Author Contributions M.P. conceived the main idea of the study. M.U. developed the computational framework and conducted the data analysis. M.P. and D.D. verified the analytical methods and supervised the research findings. M.U. drafted the manuscript with input and support from M.P. and D.D. All authors provided critical feedback and contributed to shaping the research, analysis, and final manuscript.

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Data Availability Merged multi-sensor time-series of along-track satellite altimeter significant wave height data were downloaded from the ESA Sea State Climate Change Initiative (CCI) at https://catalogue.ceda.ac.uk/uuid/e6af67fca81c40b7bb3eddaadde06909/. Significant wave height of combined wind waves and swell from the ECMWF ERA5 reanalysis was obtained from https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview. Coral reef outlines were taken from the Allen Coral Atlas at https://allencoralatlas.org/atlas/.

Declarations

Competing Interests The authors declare no competing interests.

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