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RESEARCH ARTICLE

Thresholds and trends in wave steepness: A data-driven study of coastal wave breaking risk

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ABSTRACT

Wave steepness plays a crucial role in coastal engineering, sediment transport, and maritime safety, as steeper waves exert stronger forces on coastal structures, enhance sediment mobilization, and increase risks for vessels and swimmers. Despite its importance, previous studies have often treated wave steepness in generalized contexts, lacking region-specific evaluations or failing to account for temporal variability and localized wave dynamics. Moreover, many analyses have not sufficiently linked wave steepness to practical risk indicators such as wave breaking potential. To address these gaps, this study presents a comprehensive analysis of wave steepness and its association with breaking risk on the Gold Coast, Australia, using data collected throughout 2023. Wave steepness, a dimensionless parameter defined as the ratio of wave height to wavelength, serves as a critical indicator for assessing wave stability and potential for breaking in coastal environments. Using the formula $S \approx \frac{2\pi H_s}{g T_p^2}$, we analyzed 17,520 observations of significant wave height (H_s) and peak period (T_p) to categorize waves into four distinct stability classes: gentle, moderate, steep, and breaking risk. Results indicate that only 0.34% of observations exceeded the critical breaking threshold of $S > 0.04$, with the maximum steepness of 0.0564 recorded on December 1, 2023. Significant seasonal variations were observed, with October exhibiting the highest mean steepness (0.0127) and June the lowest (0.0052). A strong negative correlation ($r = -0.78$) between peak period and wave steepness confirms the theoretical relationship between these parameters. The study also revealed that 69% of waves were classified as gentle ($S < 0.01$), 28% as moderate ($0.01 \leq S < 0.025$), 2.3% as steep ($0.025 \leq S < 0.04$), and only 0.3% posed a breaking risk. These findings provide valuable insights for coastal management, maritime safety, and engineering applications by establishing quantitative thresholds for wave breaking risk assessment in similar coastal environments.

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Introduction

Wave steepness, a dimensionless ratio of wave height to wavelength, serves as a critical parameter in coastal engineering and oceanography (Zhongbiao Chen et al., 2014). It is essential for evaluating wave stability and the potential for wave breaking, influencing coastal processes such as sediment transport (Balas et al., 2024a) and shoreline erosion (Xie et al., 2024). Understanding wave behavior is also crucial for maritime safety and recreational activities in coastal areas (Petropoulos et al., 2022).

In coastal engineering, wave steepness is pivotal for designing and maintaining coastal structures (Chondros et al., 2024). Breakwaters, seawalls, and other protective measures must be engineered to withstand the forces exerted by waves, and wave steepness directly affects these forces (Al-Towayti et al., 2025). For instance, steeper waves exert greater pressure on coastal defenses, increasing the risk of structural damage or failure (Tang et al., 2020). Understanding wave steepness helps engineers optimize the design of these structures to ensure they can effectively mitigate coastal erosion and protect coastal communities.

Wave steepness plays a significant role in sediment transport, which in turn affects shoreline erosion (Yu et al., 2024). Steeper waves possess more energy and can mobilize larger volumes of sediment, leading to increased erosion rates (Schmelz et al., 2025). The direction and intensity of sediment transport (Uğurlu & Balas, 2024) are also influenced by wave steepness, with steeper waves often causing more significant alongshore and cross-shore sediment movement (Dionísio António et al., 2023). This understanding is critical for developing effective beach nourishment strategies and managing coastal sediment budgets.

Maritime safety is directly influenced by wave steepness, as steeper waves pose greater risks to vessels and offshore structures (Kwon et al., 2025). High wave steepness can lead to increased instability and potential capsizing of smaller boats, while larger ships may experience structural stress and reduced manoeuvrability (Tian et al., 2023). For recreational activities such as surfing and swimming, wave steepness determines the size and intensity of breaking waves, affecting the safety and enjoyment of these activities (Leatherman et al., 2024).

Wave steepness data can inform beach nourishment strategies by providing insights into sediment transport patterns (Husemann et al., 2024). Understanding how wave steepness affects sediment mobilization and deposition can help coastal managers develop more effective strategies for maintaining beach width and protecting shorelines from erosion.

Understanding wave energy dissipation is crucial for predicting wave behavior in coastal regions (De Vita et al., 2018). Wave breaking is a primary mechanism of energy dissipation, but other factors such as bottom friction and turbulence also play a role. The rate of energy dissipation affects wave height (Durap, 2024a), period, and steepness, influencing sediment transport and shoreline erosion.

Coastal protection structures, such as breakwaters and seawalls, are designed to mitigate the impacts of waves on shorelines (Vieira et al., 2024). The effectiveness of these structures depends on their ability to dissipate wave energy, reduce wave height, and alter wave direction. The design and placement of coastal protection structures require a thorough understanding of wave dynamics, sediment transport, and coastal morphology.

The classification of waves into stability categories based on steepness thresholds is a valuable tool for coastal management and safety assessments (Chondros et al., 2024; Durap & Balas, 2024). The identification of correlations between wave parameters, such as the negative correlation between peak period and wave steepness, can improve predictive models for wave breaking risk (Trizna, 2001).

The Gold Coast of Australia, a region celebrated for its extensive beaches and vibrant surf culture, experiences a diverse wave climate shaped by its exposure to the Pacific Ocean. This makes it an ideal location for investigating wave dynamics, yet detailed studies on wave steepness and its implications for breaking risk in this area remain scarce in terms of risk categorization and coastal management strategies.

(i) This study fills this research gap by conducting a comprehensive analysis of wave steepness and its relationship to breaking risk, utilizing data collected throughout 2023 from the Gold Coast. Our primary objectives are to:
(ii) Calculate wave steepness using significant wave height (Hs) and peak period (Tp) via the formula $S \approx \frac{2\pi H_s}{g T_p^2}$, and validate its applicability for the Gold Coast's unique wave climate,
(iii) Categorize waves into stability classes (gentle: S<0.01S<0.01; moderate: 0.01≤S<0.0250.01≤S<0.025; steep: 0.025≤S<0.040.025≤S<0.04; breaking risk: S≥0.04S≥0.04) to quantify breaking risk and inform coastal safety protocols,

(iv) Investigate seasonal variations in wave steepness, and explore the correlation between peak period and wave steepness, while emphasizing the need for accurate characterization of wave dynamics,

(v) Explore the correlation between peak period and wave steepness,

(vi) Assess deviations from classical wave models by comparing empirical data (e.g., C=Tz/Tp mean ≈ 0.58) with theoretical values (Pierson-Moskowitz: 0.86), deriving site-specific equations (e.g., Tp=1.78Tz) to improve local hazard assessments.

To achieve these goals, we employed the formula $S \approx \frac{2\pi H_S}{g T_p^2}$ to compute wave steepness from 17,520 observations of Hs and Tp. Waves were classified into four stability categories: gentle (S<0.01), moderate (0.01≤S<0.025), steep (0.025≤S<0.04), and breaking risk (S≥ 0.04). Our analysis revealed that only 0.34% of waves exceeded the critical breaking threshold of S>0.04, with notable seasonal fluctuations-October showing the highest mean steepness (0.0127) and June the lowest (0.0052). Additionally, a strong negative correlation (r=-0.78) was observed between peak period and wave steepness, reinforcing theoretical expectations.

Material and Methods

Dataset and Study Area

The study focuses on the coastal region of the Gold Coast, Australia, which is renowned for its dynamic coastal processes and significant recreational and economic importance (Figure 1). The dataset covering the year 2023 captures a wide range of wave conditions driven by local meteorological systems and oceanographic influences. To facilitate application of these findings to coasts with similar dynamics, key characteristics of the study area are: bathymetry near the measurement site features a gentle slope of approximately 1:50, with a sandy seabed dominant up to 20 m depth. Wave data were collected at a buoy located 2 km offshore (depth: 15 m), where prevailing winds are southeasterly (mean speed: 8 m/s) and wave direction is predominantly ENE (70% of observations). The local wave climate is characterized by mean significant wave heights (H_s) of 1.2–2.5 m and peak periods (T_p) of 8–12 s during non-storm conditions. These parameters align with fetch-limited, open-coast environments experiencing moderate wind-sea and swell mixing.

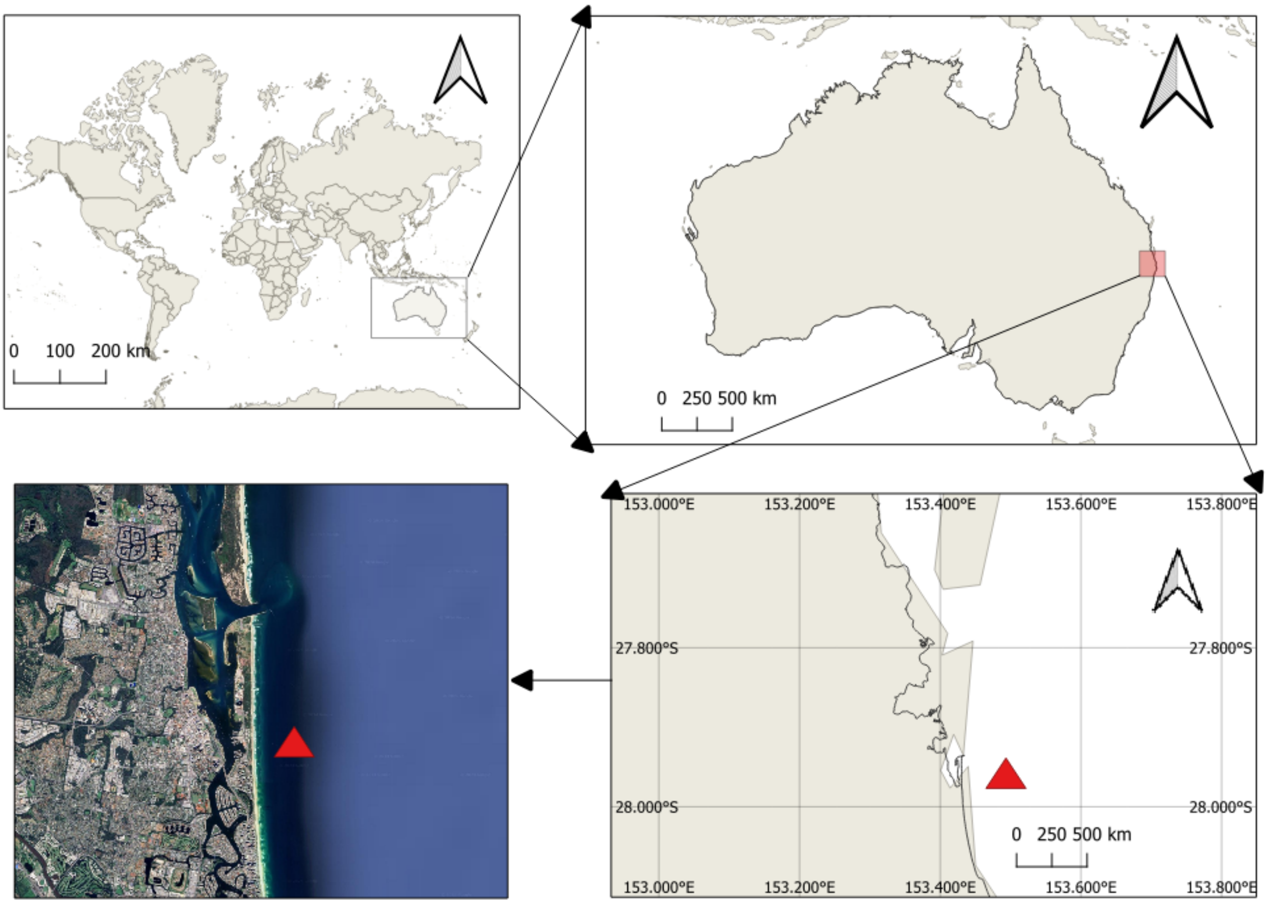

Figure 1. Study area

The geographical location and coastal configuration make the Gold Coast an ideal natural laboratory for investigating wave dynamics, particularly wave steepness and breaking potential.

The dataset used in this study, titled Gold_Coast_2023_Cleaned.csv, comprises 17,520 observations recorded at 30-minute intervals throughout 2023. The primary variables included in the dataset are:

Date/Time (AEST): Timestamp for each observation in Australian Eastern Standard Time, *Hs (m):* Significant wave height (in meters), representing the average height of the highest one-third of waves, *Hmax (m):* Maximum wave height observed, *Tz (s):* Zero-crossing period (in seconds), reflecting the time interval between successive wave troughs, *Tp (s):* Peak wave period (in seconds), the period associated with the most energetic frequency component of the wave spectrum, *Peak Direction (degrees):* Wave propagation direction in degrees, *SST(°C):* Sea surface temperature in degrees Celsius, *Wave Steepness (S):* A dimensionless measure calculated to evaluate wave stability and breaking risk (generated from the dataset).

Data Quality and Preparation

Prior to analysis, rigorous quality control steps (verification of data integrity, handling missing data, data calibration) were applied to the dataset to ensure reliability. All numeric columns were inspected to validate the absence of erroneous negative values, particularly in the wave period, which must remain positive. Observations with missing or incomplete values were either corrected or removed. The dataset was calibrated using standard meteorological and oceanographic measures, ensuring consistency across all parameters.

This combination of the comprehensive dataset and the established physical relationships enables a robust analysis of wave dynamics, providing significant insights into the coastal wave conditions at the Gold Coast over the study period.

Calculation of Wave Steepness

A key parameter analyzed in this study is the wave steepness, defined by the relationship between the significant wave height and the associated wavelength. In deep-water conditions, the wavelength (λ) is estimated using the peak wave period (T_p) with the dispersion relation:

$$\lambda \approx \frac{gT_p^2}{2\pi} \quad (1)$$

where: g is the acceleration due to gravity (9.8 m/s^2).

Thus, the wave steepness, represented by, S, can be approximated as the ratio of the significant wave height to the wavelength. The formula implemented based on the dataset is:

$$S \approx \frac{2\pi H_s}{gT_p^2} \quad (2)$$

In this equation: H_s is extracted from the “Hs (m)” column, $T_p$is extracted from the “Tp (s)” column, 2π is a constant derived from wave mechanics.

Results

Our analysis of the Gold Coast 2023 ocean wave data reveals several significant findings regarding wave steepness, its seasonal variability, and associated breaking risks. The first four rows generated values of S from Hs and Tp are given in Table 1.

Table 1. Generated S from raw dataset of Hs and Tp.

ID	Date/Time (AEST)	Hs (m)	Tp (s)	Wave Steepness
1	2023-01-01T00:00:00.000	1.702	10.526	0.0098488748
2	2023-01-01T00:30:00.000	1.694	10.526	0.0098025816
3	2023-01-01T01:00:00.000	1.827	10.526	0.0105722058
4	2023-01-01T01:30:00.000	1.669	11.111	0.0086676993
5	2023-01-01T02:00:00.000	1.866	10.0	0.0119636977

The corresponding time series plot (Figure 2) shows a relatively stable trend over the year, with intermittent spikes in steepness. Notably, the maximum recorded steepness of 0.0564 occurred on December 1, 2023, indicating short-term events that could be associated with storm conditions. Horizontal dashed lines thresholding the categories further highlight the boundaries between gentle, moderate, steep, and high-risk conditions.

Monthly statistics summarized in the study show clear seasonal patterns in wave steepness. For instance, October exhibits the highest average steepness (0.0127), while June experiences the lowest average (0.0052). These trends align with seasonal meteorological and oceanographic drivers in the region.

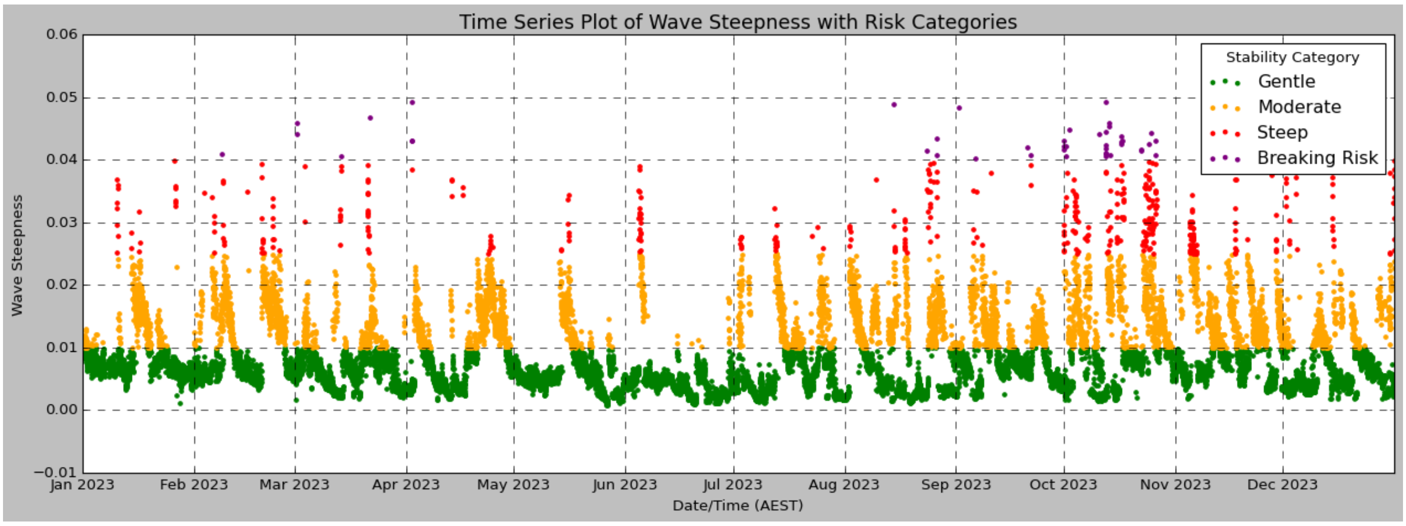

Figure 2. Time series plot of wave steepness with risk categories

The analysis reveals a comprehensive picture of local wave dynamics over the examined period. In summary, 60 potential breaking events (where S > 0.04) were identified—accounting for 0.34% of the total observation time—with the highest recorded wave steepness reaching 0.0564 on December 1, 2023, at 14:00.

Figure 3 presents an integrated view of monthly trends and key correlations related to wave steepness. The top panel shows the monthly average steepness values, with notable seasonal variation. October records the highest average steepness (~0.0127), while June presents the lowest (~0.0052), consistent with calmer winter sea states and more energetic spring conditions in the southern hemisphere. Monthly statistics provide further detail on the variability of wave behavior (Figure 3):

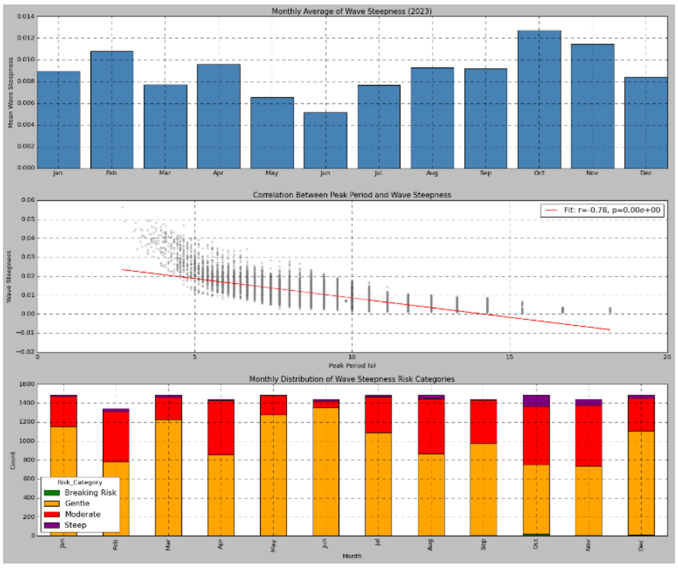

Figure 3. Monthly and correlation-based insights into wave steepness variability for 2023 at the Gold Coast

January: Mean steepness ≈ 0.00894, maximum ≈ 0.04002 (across 1488 records). February: Highest average steepness at about 0.01082 with a maximum of ≈ 0.04101 (over 1344 records)

March & April: Notable maximum values of ≈ 0.04689 and ≈ 0.04936, respectively. June: The lowest average steepness at ≈ 0.00516, with a maximum near 0.0390.

The middle panel illustrates the negative correlation between wave peak period (Tp) and wave steepness (S), with a Pearson correlation coefficient of −0.78 and a p-value below 0.001, indicating statistical significance. As expected, shorter-period waves are steeper, a key insight that supports theoretical models and justifies the use of steepness as a risk indicator.

Table 2. Monthly wave steepness statistics

Month	Mean	Max	Count
Jan	0.00893	0.0400	1488
Feb	0.01081	0.0410	1344
Mar	0.00772	0.0468	1488
Apr	0.00959	0.0493	1440
May	0.00655	0.0344	1488
Jun	0.00515	0.0389	1440
Jul	0.00769	0.0322	1488
Aug	0.00931	0.04901	1488
Sep	0.00921	0.04839	1440

These statistics reflect seasonal variability typical of the southern hemisphere, where summer months (December through February) tend to experience more energetic wave conditions compared to the generally calmer winter months (Table 2).

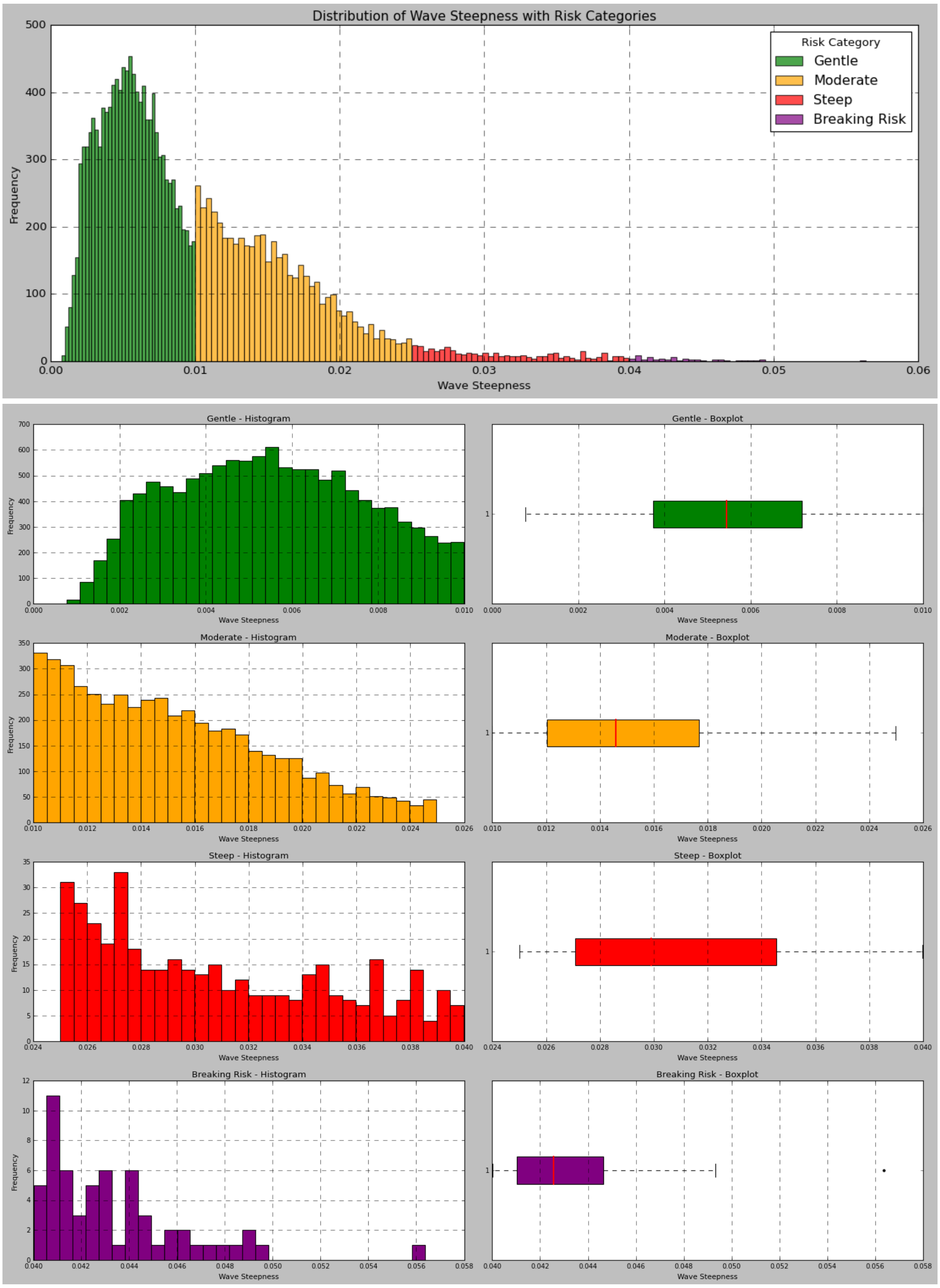

Figure 4. Wave steepness across the four defined risk categories—gentle, moderate, steep, and breaking risk

The bottom panel displays the monthly distribution of wave steepness classes, stacked by risk category. Across all months, the *gentle* and *moderate* classes dominate. However, October and November exhibit slight increases in the *steep* and *breaking risk* categories, reinforcing the conclusion that springtime (Australian season) generates higher-risk wave conditions. The visualization provides a granular look at temporal patterns in wave stability, offering valuable input for monthly or seasonal coastal hazard assessments.

The overall distribution by wave steepness category is also insightful: gentle: 12,099 instances, moderate: 4,952 instances, steep: 409 instances, breaking risk: 60 instances.

Figure 4 synthesizes wave steepness distributions across four risk classes: Gentle, Moderate, Steep, and Breaking Risk.

The aggregated histogram (top panel) confirms the predominance of low-steepness waves (Gentle, <0.01), which constitute ~69% of observations. Higher-risk categories diminish in frequency, with Breaking Risk events (steepness>0.04) representing just 2.3% of cases.

Individual category panels (lower section) reveal distinct statistical patterns. Gentle waves cluster tightly near zero (median = 0.003), while Moderate (0.01–0.02) and Steep (0.02–0.04) classes show progressively right-shifted distributions with rising medians (0.014 and 0.026, respectively). The Breaking Risk category exhibits the widest spread, with a median of 0.045 and outliers nearing the theoretical breaking limit (~0.056). Boxplots underscore incremental variability between classes, particularly in the Breaking Risk group, where the interquartile range (0.042–0.049) and outlier density reflect heightened instability.

Minimal overlap between adjacent categories and systematic median progression (Δ≈0.011–0.019 per class) validate the classification thresholds. This framework robustly isolates rare, high-impact breaking conditions, critical for coastal hazard assessments.

A correlation analysis (Figure 5) displays the relationships among key wave parameters, revealing a strong negative correlation between peak wave period (Tp) and wave steepness (r≈-0.78). This indicates that shorter peak periods are associated with higher steepness values, reinforcing the theoretical basis of our calculations based on the formula ($S \approx \frac{2\pi H_s}{g T_p^2}$).

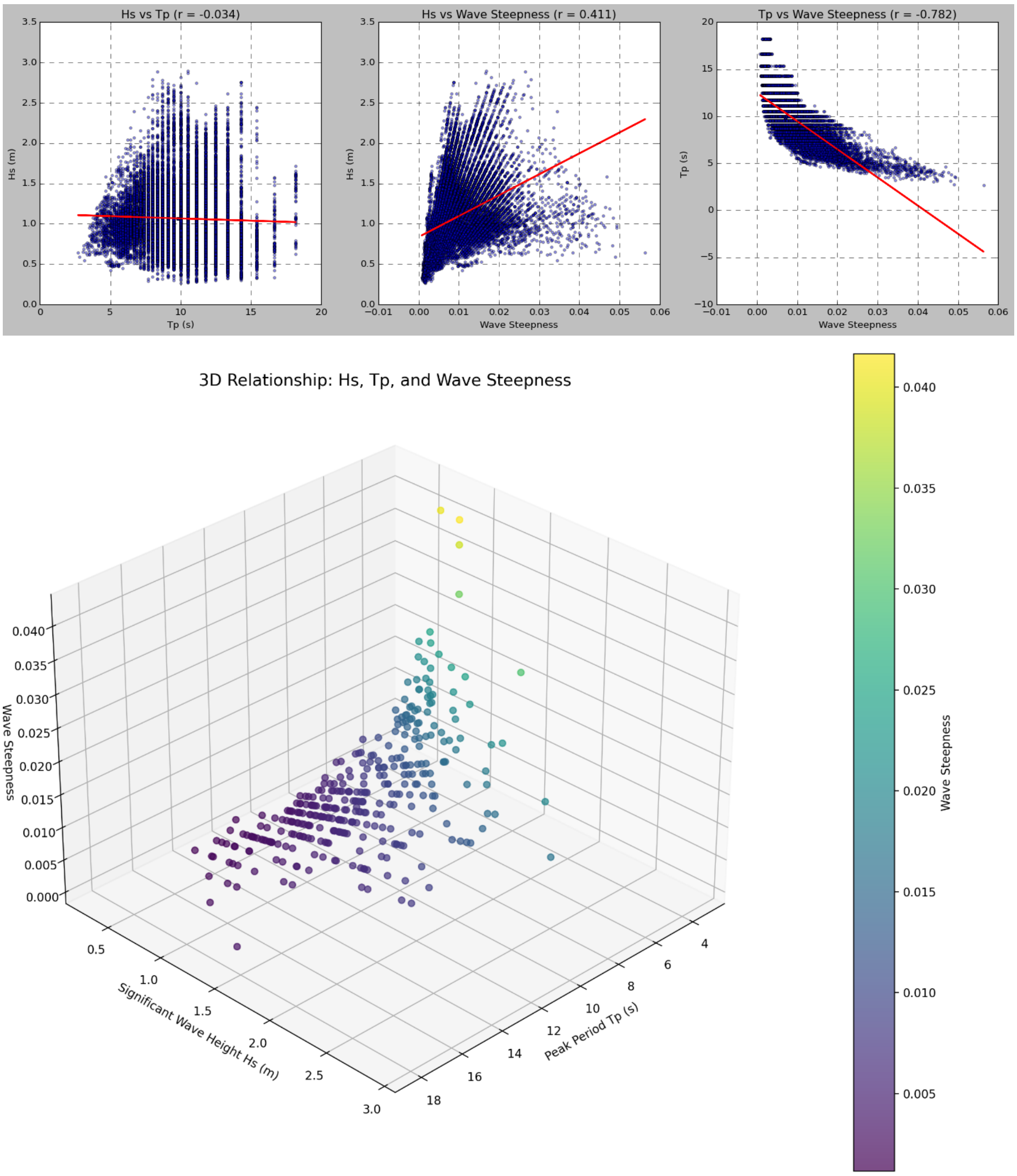

Figure 5. Correlation analysis

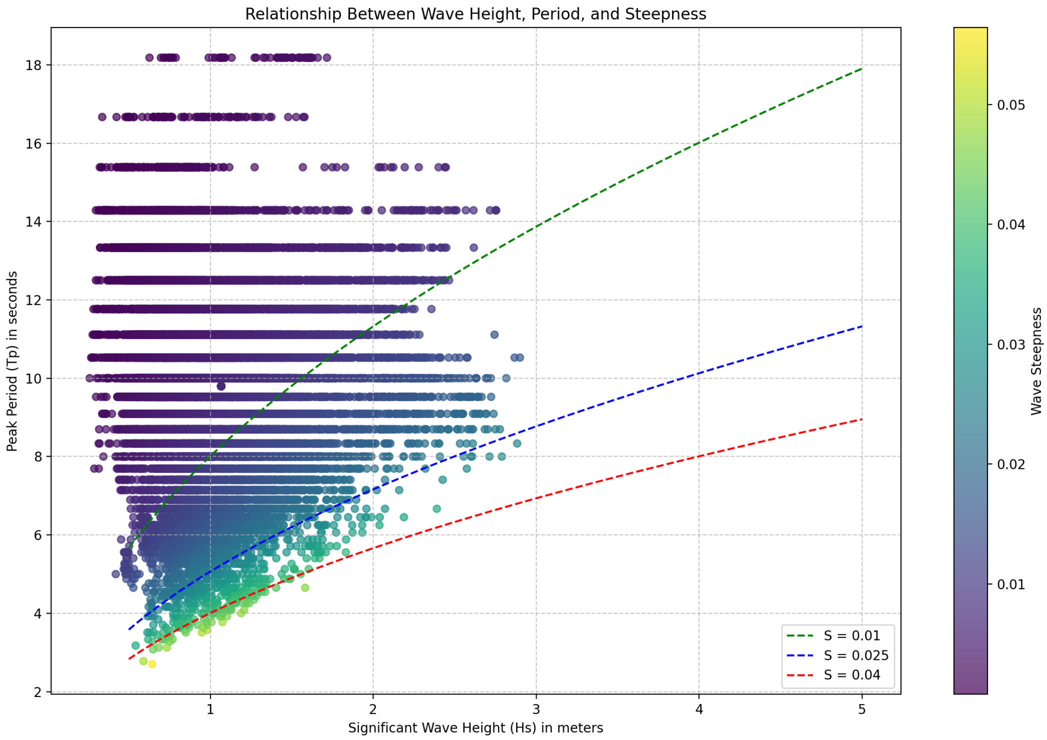

Figure 6. Variation of wave steepness with significant wave height and peak period

Additionally, the joint scatter plot (Figure 6) delineates the relationship between Hs and peak period Tp, with point colors representing wave steepness. Overlaid contour lines for constant steepness values (at thresholds of 0.01, 0.025, and 0.04) provide visual guides to interpret the wave conditions. This visualization confirms that for a given wave height, shorter peak periods lead to increased steepness, thereby enhancing the risk of wave breaking. The clustering of data points and the alignment with the contour lines support the theoretical expectations and suggest that variations in these parameters can be used to predict instances of high wave breaking risk.

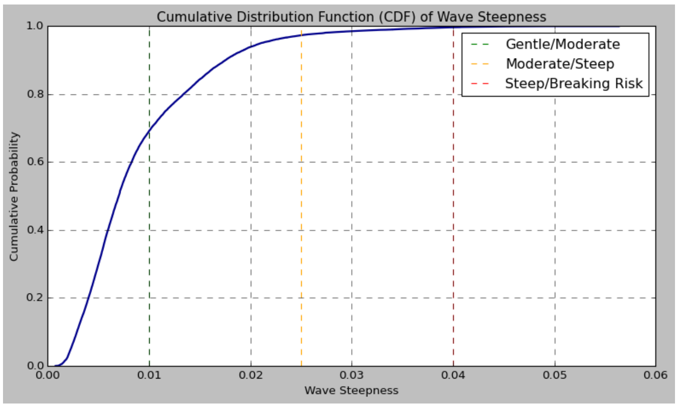

Figure 7. Cumulative distribution function (CDF) of wave steepness

Figure 7 illustrates the cumulative distribution function (CDF) of wave steepness. The CDF provides a probabilistic overview, showing the proportion of wave steepness values below specific thresholds. Vertical dashed lines demarcate critical steepness thresholds: gentle/moderate ($S \leq 0.01$, green), moderate/steep ($S \leq 0.025$, orange), and steep/breaking risk ($S \leq 0.04$, red), aligning with the contour lines from Figure 6. The curve indicates that approximately 40% of waves fall below the gentle/moderate threshold ($S \leq 0.01$), while the steep/breaking risk category ($S \leq 0.04$) encompasses about 90% of the data, reinforcing the earlier observation that shorter peak periods significantly increase steepness and breaking risk. This distribution further validates the predictive utility of Hs and Tp variations in assessing wave breaking potential.

Figure 8 presents the density distribution of wave steepness categorized into risk levels. The histogram reveals that the majority of waves (69.1%) fall within the gentle/moderate category ($S \leq 0.01$, green), with a significant portion (28.3%) classified as moderate/steep ($S \leq 0.025$, orange), and a smaller fraction (2.3%) reaching the steep category ($S \leq 0.04$, yellow). Notably, only 0.3% of waves enter the breaking risk zone ($S > 0.04$, red), consistent with the CDF analysis indicating that extreme steepness values are rare. The vertical dashed lines align with the thresholds identified in Figure 7, reinforcing the earlier findings that shorter peak periods, as observed in Figure 6, contribute to increased steepness and heightened breaking risk. This distribution underscores the infrequency of hazardous wave conditions while affirming the predictive relationship between wave parameters and breaking potential.

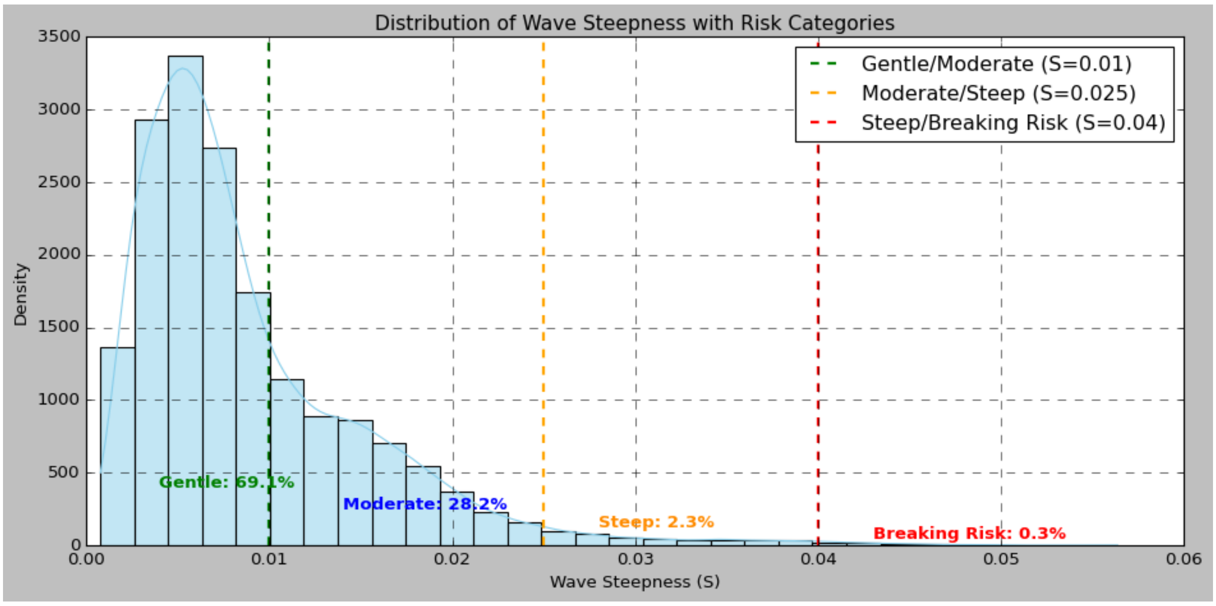

Figure 8. Distribution of wave steepness with risk categories

Discussion

Our analysis of wave steepness in the Gold Coast region, utilizing a dataset of 17,520 observations from 2023, revealed that only 0.34% of waves exceeded the critical breaking threshold of S > 0.04. This suggests that wave conditions in this region were predominantly stable throughout the year, with a maximum recorded steepness of 0.0564 on December 1, 2023. However, seasonal variations were apparent, with October exhibiting the highest mean steepness (0.0127) and June the lowest (0.0052). These results align with the theoretical framework of wave breaking in deep water, where steepness values exceeding approximately 0.04 indicate a propensity for breaking. The observed maximum steepness of 0.0564 further corroborates this threshold, reflecting conditions where breaking becomes probable. Breaking wave height, a crucial parameter, can be estimated using time-exposure images from coastal video monitoring systems (Andriolo et al., 2020). These systems provide a practical way to overcome the difficulties associated with direct wave measurements.

The observed seasonal peaks in wave steepness (e.g., October's mean of 0.0127) suggest periods of heightened coastal vulnerability. Since wave steepness is closely associated with wave runup, steeper waves likely contribute to elevated swash zone dynamics, increasing the risk of beach erosion and overwash during storms (Durap, 2023). This underscores the need for steepness-based early warning systems. October, a transitional month in the Southern Hemisphere Spring, often experiences weather shifts that generate more energetic wave fields, potentially driven by increased wind activity or distant storm systems (Balas et al., 2024b; Durap, 2025b). Conversely, June, occurring during the austral winter, corresponds to a period of typically calmer seas, consistent with reduced wave energy. Identifying meteorological conditions associated with seasonal patterns can improve understanding of wave dynamics (Morley et al., 2018). These temporal patterns emphasize the need to account for seasonality when assessing wave-related risks for coastal management and safety planning in this region. The influence of extreme weather events, such as tropical cyclones, can significantly affect coastal hydrodynamics (Zhong et al., 2024).

A key finding of this study is the strong negative correlation (r = -0.78) between peak period (Tp) and wave steepness, which reinforces the theoretical relationship encapsulated in the formula $S \approx \frac{2\pi H_s}{gT_p^2}$. The visual representation in Figure 9 reinforces the statistically significant and theoretically grounded relationship between peak period and wave steepness. The marginal histograms on both axes show the distribution of peak periods and steepness values, respectively, while the regression line clearly illustrates a downward trend. The correlation coefficient (r=– 0.78) is statistically significant (p<0.001) and supports the expected inverse relationship from deep-water wave theory. Notably, the coefficient of determination (R^2=0.61) implies that over 60% of the variance in wave steepness can be explained by variations in peak period alone, making this a robust predictor. The extremely low standard error (0.0000) further enhances confidence in the reliability of the regression line. These findings emphasize the practical importance of monitoring wave period alongside wave height for early warning systems and coastal risk assessments.

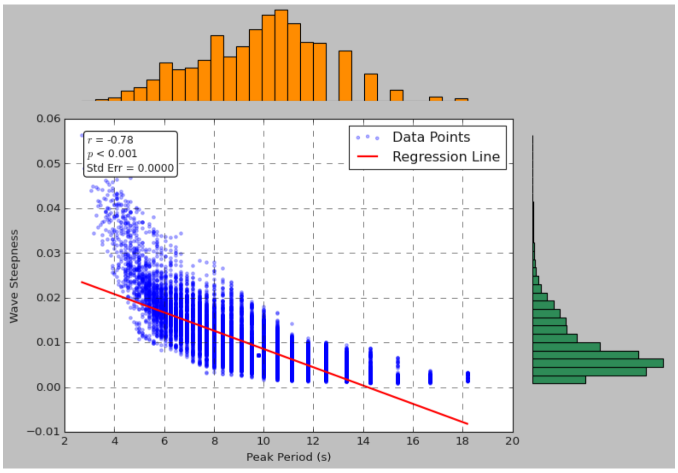

Figure 9. Scatter plot showing the correlation between peak period (Tp) and wave steepness, with marginal histograms

This inverse relationship indicates that, for a given significant wave height (Hs), shorter peak periods result in steeper waves, thereby elevating the likelihood of breaking. This underscores the importance of considering both wave height and period as interdependent parameters when evaluating wave stability and breaking potential, rather than relying solely on wave height as a standalone metric. Machine learning techniques can be used to predict wave data, offering a way to estimate the best possible route for maritime autonomous surface ships by predicting weather changes (Domala et al., 2022).

The classification of waves into four stability categories—gentle ($S < 0.01$), moderate ($0.01 \leq S < 0.025$), steep ($0.025 \leq S < 0.04$), and breaking risk ($S \geq 0.04$)—offers a practical tool for interpreting wave conditions. With 69% of waves classified as gentle, 28% as moderate, 2.3% as steep, and only 0.3% posing a breaking risk, this framework provides actionable insights for coastal stakeholders. For example, periods with elevated frequencies of steep or breaking-risk waves, such as those observed in October, may necessitate heightened precautions for maritime activities, including surfing, fishing, or small vessel navigation. Wave peel tracking can also be used to assess surf amenity and analyze breaking waves, providing a quantitative method for evaluating surfing breaks (Thompson et al., 2021).

These findings carry significant implications for coastal engineering and management along the Gold Coast. The predominance of stable wave conditions suggests that the region is generally well-suited for water-based recreational and economic activities. However, the occasional occurrence of steep waves—particularly during high-steepness months—highlights the importance of designing coastal structures, such

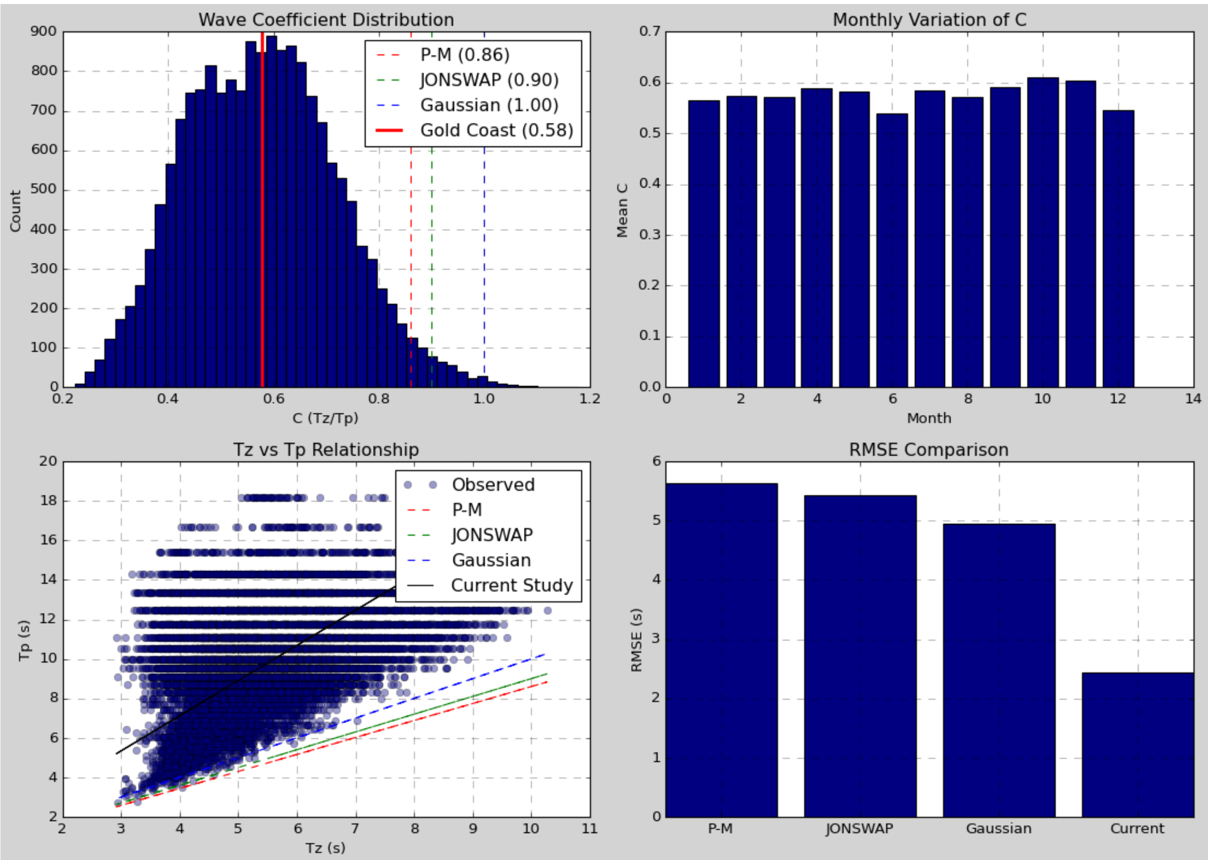

Figure 10. Analysis of wave period characteristics at the Gold Coast

as breakwaters and seawalls, to withstand the forces exerted by these events. Floating platforms are economically viable for harvesting wind energy in deeper waters (Buyruk et al., 2024; Durap, 2025a), offering an alternative for countries with steep continental shelves (Pascual et al., 2021). Moreover, wave steepness influences sediment transport and erosion dynamics, with steeper waves capable of mobilizing greater sediment volumes. Understanding the frequency and distribution of steep waves can thus inform beach nourishment strategies and erosion mitigation efforts, enhancing the resilience of the Gold Coast's iconic shorelines (Durap, 2024b).

To support such engineering applications, accurate characterization of wave dynamics is essential. As shown in Figure 10, the distribution of the wave coefficient $C=Tz/Tp$ is heavily skewed toward lower values, with a mean around 0.58, which is significantly lower than the classical values suggested by the Pierson–Moskowitz (0.86), JONSWAP (0.90), and Gaussian (1.0) models (Ahn, 2021). This deviation reflects the unique wave climate of the Gold Coast. Monthly variations in C (top-right panel) also suggest seasonal consistency with slight peaks in Australia spring. The Tz–Tp relationship (bottom-left) shows a moderate correlation (r = 0.42), and the locally derived equation Tp = 4.716 + 0.941Tz (or Tp = 1.78Tz), which demonstrates improved predictive accuracy (RMSE = 2.25 s) over traditional models. This site-specific relationship reflects the unique wave environment of the Gold Coast and provides a more reliable tool for coastal design and hazard assessment.

From a maritime safety perspective, this refined understanding of local wave dynamics is crucial for identifying periods of elevated wave steepness, which is essential for issuing targeted warnings to mariners and recreational users. Although the overall incidence of breaking-risk waves is low (0.3%), rare yet extreme events—such as the December maximum of 0.0564—underscore the necessity for real-time monitoring and forecasting systems. Technologies such as wave glider-based platforms with towed hydrophone arrays offer autonomous, real-time monitoring capabilities, contributing to safer navigation and better detection of marine hazards (Premus et al., 2022). Furthermore, coastal management strategies must also incorporate considerations of non-linear surges and extreme wind-wave interactions, particularly in light of projected mean sea level rise scenarios, to mitigate long-term risks to coastal infrastructure and ecosystems (Tran et al., 2024).

Conclusion

This study presents a detailed investigation into wave steepness and its implications for breaking risk along the Gold Coast of Australia, drawing on a comprehensive dataset of 17,520 wave observations recorded throughout 2023. By integrating significant wave height (Hs) and peak period (Tp) to compute wave steepness (S), we classified waves into four stability categories: gentle, moderate, steep, and breaking risk. Our analysis revealed that only 0.34% of waves surpassed the critical breaking threshold of S > 0.04, with the highest steepness of 0.0564 recorded on December 1, 2023. Seasonal patterns emerged, with October showing the highest mean steepness (0.0127) and June the lowest (0.0052). Furthermore, a robust negative correlation (r = -0.78) between peak period and wave steepness was identified, aligning with theoretical predictions.

These findings offer critical insights for coastal management, maritime safety, and engineering design. The predominance of stable wave conditions—69% gentle and 28% moderate—indicates that the Gold Coast generally supports safe conditions for maritime and recreational activities. However, the presence of steep and breaking-risk waves, particularly in high-steepness months like October, highlights the need for targeted monitoring during these periods. By establishing quantitative thresholds for breaking risk, this study provides a practical tool for assessing wave conditions, which can be adapted to other coastal regions with similar dynamics.

The significance of these results lies in their contribution to a deeper understanding of wave behavior in the Gold Coast. The strong negative correlation between peak period and wave steepness underscores the necessity of evaluating both wave height and period to fully assess wave stability, rather than focusing solely on height-based metrics. This holistic approach enhances the accuracy of wave risk predictions, benefiting applications such as coastal erosion control, infrastructure planning, and safety protocol development.

Accurate characterization of wave dynamics is critical for engineering applications, particularly in regions like the Gold Coast with distinct wave climates. Our analysis reveals that the wave coefficient (C=Tz/Tp) exhibits a mean value of 0.58 (Figure 10), markedly lower than classical theoretical values (Pierson-Moskowitz: 0.86; JONSWAP: 0.90; Gaussian: 1.0). This deviation underscores the limitations of generic models in capturing local hydrodynamic conditions. Seasonal trends in C further highlight variability tied to Australian spring peaks, aligning with observed steepness fluctuations. The derived empirical relationship Tp=1.78Tz (RMSE=2.25s) outperforms traditional formulations, offering enhanced predictive accuracy for coastal hazard assessments. These findings advocate for site-specific wave parameterization in engineering design, particularly for breakwaters, sediment transport models, and maritime safety systems sensitive to period-steepness interactions.

Despite its contributions, this study is constrained by its single-year scope, which limits its ability to capture long-term trends or interannual variability influenced by climatic factors like El Niño or La Niña. To address this, future research should prioritize multi-year data collection to elucidate decadal patterns in wave steepness. Additionally, integrating bathymetric data and shallow-water wave transformation models could improve breaking risk assessments in nearshore zones, where wave dynamics are further complicated by seabed interactions.

In summary, this research lays a data-driven groundwork for understanding wave steepness and breaking risk in the Gold Coast, delivering actionable insights for coastal stakeholders. By incorporating these findings into planning and safety frameworks, and through ongoing monitoring and expanded studies, the region can better adapt to evolving wave conditions, ensuring the sustainable management of its valuable coastal environment.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Not applicable.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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