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Frictional dissipation of incident waves over a spatially-varying rough barrier reef in Mayotte, Indian Ocean

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Abstract. Coral reefs serve as a highly effective natural barrier against incoming ocean waves. However, climate change and human-induced degradations are threatening reefs, reducing their capacity to protect coastal populations by diminishing the frictional processes that dissipate wave energy. The most common approach to represent wave energy dissipation through bottom friction relies on the estimation of a representative roughness length, whose definition on coral environments remains to be elucidated. As a consequence, a generic parametrization for friction processes on coral reef systems is still lacking. In this study, high-resolution hydrodynamical and topographical data collected at the South-West barrier reef of Mayotte, Indian Ocean, were used to perform an estimation of wave friction. The hydraulic roughness estimated across the reef varies spatially, and attempts are made to connect this information with the diverse bed morphologies observed in the field.

Keywords: Friction, Roughness definition, Reef hydrodynamics

1 Introduction

Low-lying tropical islands are particularly exposed to coastal hazards such as tropical cyclones and storms which can lead to disastrous flooding. Those islands often exhibit coral reef systems that act as a natural barrier against ocean swell by dissipating their energy through breaking and friction processes (Lowe et al., 2005; Sous et al., 2019). In the context of climate change, which is leading to a global decline in coral reef ecosystems (Walker et al., 2024), friction processes linked to the geometric complexity of reefs will be modified (Carlot et al., 2023), potentially resulting in greater vulnerability to submersion risks. In spectral wave models, friction processes are modeled through the wave friction coefficient f_w (Jonsson, 1966) that is often related to a single length metric that does not include bio-ecological characteristics of corals (Lowe et al., 2005, Lentz et al., 2016). However, reefs display high variability of f_w (between

0.01 up to 5) due to both varying hydrodynamic condition and geometrical structure (Monismith et al., 2015), leading to a poor representation of friction in rough context. A clear understanding of the frictional processes appears to be essential; this work aims to improve the understanding of friction and extend the link between friction and coral structural complexity based on a new comprehensive field experiments carried out in Mayotte, Indian Ocean. The experimental barrier reef is exposed to a macrotidal regime which offers a unique opportunity to examine frictional dissipation under conditions where wave breaking can be confidently excluded. This site avoids the constraints of studying only mild waves, enabling the investigation of a broader range of orbital excursion amplitudes than typically addressed in previous studies.

2 Material and methods

2.1 Study site

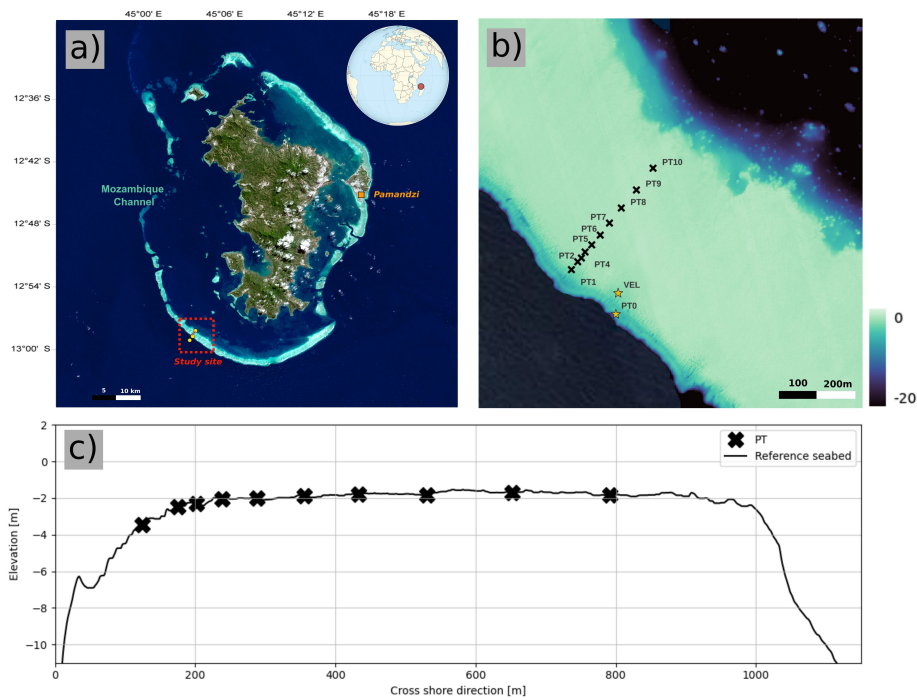


Fig. 1. Picture of Mayotte Island and barrier reef showing a) satellite view and location; b) instrument deployment and bathymetry with respect to MSL; c) cross section of the reference transect.

This study has been conducted on the southern barrier reef of Mayotte, France, located in the Mozambique Channel (Fig 1a). This barrier is typical of reef systems with very rough elements or meso and macro-geomorphological formations like spur and groove.

On the offshore side of the barrier reef, three distinct slopes can be identified: the lower part of the reef slope, characterized by a gradient steeper than 1:10, the upper part of the reef slope, with a slope of approximately 1:20, and the reef flat, which exhibits a slope of approximately 1:1000. The site is mesotidal with tidal range reaching 4 m; the reef is exposed to trade winds, southern long swells and is regularly in the path of tropical cyclones.

An array of bottom-fixed pressure transducers, namely PT1 to PT10, was deployed along a SW-NE (39.4°, nautical convention) cross-barrier transect from 25-August to 1-October 2023. This transect is visible on Fig 1.b) with corresponding cross shore elevation profile shown on Fig 1.c). The sensors were configured to continuously monitor waves and local water depth across the reef flat (RF) at a sampling frequency of 2 Hz. An Acoustic Doppler Current Profiler (hereafter VEL) was deployed on the fore-reef in 5.6 m depth and configured in an hourly burst mode, recording 2,048 samples at 2 Hz. The pressure measured by the ADCP instrument was used to compare the performance of different reconstruction methods, using the signal measured by the Acoustic Sensor Transducer (AST) colocated with the pressure sensor as a reference. Incident wave conditions were measured by an additional RBR Virtuoso (hereafter PT0) deployed at roughly 8 m depth with respect to MSL.

2.2 Data processing

Pressure data were corrected from atmospheric pressure and local depth corrections were applied (Marques et al. 2024). Corrected pressure timeseries were reconstructed into free surface elevation (FSE) data using the non-hydrostatic non-linear method of Martins et al. (2021), which granted best reconstruction of the higher frequency harmonics and the asymmetric shape of individual waves. In order to quantify friction over the study site, a 1D frequency-integrated energy balance model was used over pairs of adjacent sensors, assuming no breaking (only bursts where the ratio between the wave heights and the depth H_s/D is smaller than 0.25 are considered) and with consideration of non-linear transfers between triad frequencies. The wave friction coefficient f_w was calculated for each hourly burst and pair by combining discrete wave energy balance and frictional energy dissipation rate. To facilitate comparison, the resulting temporal series of median f_w were averaged on log-bins of wave orbital excursion A_b . For each pair, the associated Nikuradse roughness k_s^{opt} was estimated using the least-square optimization method of Sous et al. (2023). Spatially-averaged global $\overline{k_s^{opt}}$ was also computed as the median of all the local k_s^{opt} . All the roughness lengths were then compared to roughness statistics extracted from high-resolution bed elevation signal, following the methodology of Sous et al. (2024).

3 Results and discussion

A reduction of the short wave (SW, 0.05-0.35 Hz) heights up to 92% was observed at Mayotte southern reef which thus stands as a protection against incoming waves. Re-

duction of SW heights was proven to be modulated by both the tide and the power of the incident waves. The barrier serves as a low-pass filter as the SW are reduced while the infra-gravity waves (IG, 0.003-0.05 Hz) can reach the mainland shore, since they either do not dissipate sufficiently or even grow across the reef flat of the outer barrier (average growth of +30% at hide tide). Non-linear energy transfers are observed from the SW towards the high frequencies mostly, thus contributing to the modification of the energy of the SW frequency band.

Fig. 2) shows the estimation of wave friction factor f_w computed from observations of energy flux gradients and non-linear transfers. The bin-averaged observations are in the range 0.06 - 1.3, which are typical values observed in field experiments (Gerritsen et al., 1980, Péquignet et al., 2011, Monismith et al., 2015, Sous et al., 2023). Friction estimates follow global trends with decreasing f_w associated with increasing $\frac{A_b}{k_s}$ ratio.

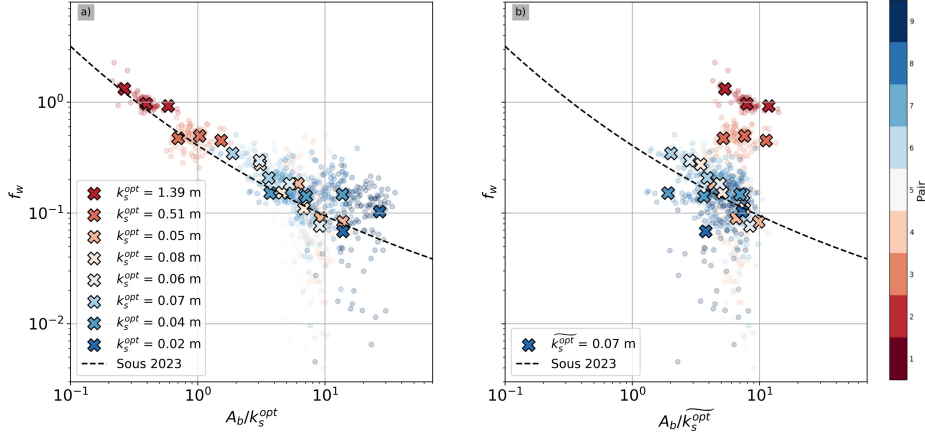


Fig. 2. Wave friction coefficient f_w computed for each pair against orbital excursion A_b and hydraulic roughness k_s^{opt} deriving from the least-square optimization of Sous et al. (2023) formulation with a) Pair-specific k_s^{opt} and b) Median k_s^{opt} for all pairs.

For each pair of sensors, the friction factors vary temporally due to variations in incident wave condition and tide; the range of f_w values also vary spatially due to wave attenuation and/or different roughness scales. The width of the barrier implies that spatially-integrated friction contributes from 25 up to 94 % of the total dissipation (breaking included) of SW energy.

The roughness length k_s have been optimized to fit with existing parametrization of friction; the computed values range from 2 cm to 1.4 m with decreasing values from the reef crest to the lagoon. Usually, k_s is uniform for a considered site due to the lack of spatial resolution (Lentz et al., 2016). In this study, the spatial sensor coverage of

the reef flat has allowed us to estimate k_s^{opt} at different location, as the geomorphology of a barrier reef exhibits spatially non-uniform coral characteristics. Optimized k_s^{opt} were greater (~ 1 m) at the beginning of the reef flat and the reef crest, coinciding with visually found coral corymbose; coral skeletons and sand were generally observed in the middle of the reef flat, leading to lower k_s^{opt} (~ 1 cm). When using global $k_s^{opt} = 0.07$ m, friction estimates show poor agreement to predictions, especially for pair 2 and 3 (Fig. 2b). Considering the same k_s^{opt} for all pairs leads to diverging f_w values for similar $\frac{A_b}{k_s}$ conditions for all pairs. Those results highlight the need to consider pair-specific estimates of roughness k_s^{opt} to make observations fit empirical laws (Fig. 2a).

The optimized roughness lengths need to be compared with bed metrics computed over the high-resolution bathymetry. This ongoing work aims at verifying whether or not the law proposed by Lowe et al. (2005) linking the roughness scale to the standard deviation of the bed height applies at Mayotte site. This will offer the possibility to linkage the theoretical hydraulic roughness to other bed metrics like structural complexity (Carlot et al., 2023), spectral parameters (Sous et al., 2024) or roughness statistics (Dealbera et al., 2024).

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