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# Bottom drag coefficient on a shallow barrier reef

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## Key Points:

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9	•	Field estimates of bottom drag coefficient over a shallow rough coral barrier reef
10		using a bulk momentum balance approach
11	•	Drag coefficients are dependent on the local depth and colony structure, and
12		well predicted by a log dependency
13	•	The recovered data allows for a discussion of the connection between hydrody-
14		namic roughness scale and high resolution seabed topography

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#### 15 Abstract

The present paper reports of a field experiment over a shallow, roughness-varying 16 barrier reef at Maupiti island, French Polynesia. The depth-averaged momentum bal-17 ance is used to estimate the bottom drag coefficient  $C_d$ , which varies from 0.01 to 18 0.3, with dependence on both depth and reef structure. The depth effect on  $C_d$  is 19 well predicted by a log dependency, as used in previous laboratory and fields observa-20 tions. The present results extend the approach to a system with more wave exposure 21 and higher roughness-to-depth ratio. Additionally, the statistical relationship between 22 high-resolution reef topography and hydrodynamical parameters is discussed. 23

### <sup>24</sup> Plain Language Summary

Coral reefs are essential for human societies and ecosystems in many tropical 25 coastlines. Having reliable hydrodynamic models of these systems is important for 26 proper management and engineering applications. Reefs play an important role in 27 sheltering shorelines by attenuating wave energy and slowing currents. Thus, they 28 must be accounted for in the models. However, due to the complexity of coral geometry, 29 there is still no reliable manner to represent or translate the physical observation of 30 corals' geometrical structure to a friction term in the governing equations of the models. 31 Additional representative challenges exist due to the varying importance of friction, 32 depending on the water depth. This paper demonstrates good alignment between a 33 metric of the physical geometry of coral to a frictional parameter used in the governing 34 equation, the momentum balance. Additionally, the depth dependence of our results 35 is described well by a classical equation meant to describe turbulence near a wall, 36 log-layer theory. In total, the results yields good agreement between terms in the 37 momentum balance and aid in the fundamental connection of the physically-observed 38 and the numerically-representation reefs. 39

#### 40 1 Introduction

Coral reefs are in decline worldwide, with dramatic consequences for tropical
ecosystems and human communities. Anticipating and mitigating the impacts of
coral reef degradation requires a comprehensive knowledge of reef hydrodynamics
(Monismith, 2007), which in turn strongly affect wave transformation (Hearn, 1999;
Lowe et al., 2005; A. Pomeroy et al., 2012; Sous et al., 2019), water residence time
(Chevalier et al., 2015; Reid et al., 2020) and sediment transport (A. W. Pomeroy et
al., 2017) in reef-lagoon systems.

As emphasized by the review from Davis et al. (2020), coral colonies generally 48 exhibit a spectacular geometric complexity which plays an overwhelming role in the 49 frictional dissipation of water motions in coral reef-lagoon systems. Over the last two 50 decades, significant research efforts have been made to capture the effects of coral 51 reef roughness on both the wave energy and momentum balance equations used in 52 nearshore wave and circulation models (Lowe et al., 2005; Rosman & Hench, 2011; 53 Monismith et al., 2015; A. W. Pomeroy et al., 2017; Lentz et al., 2018; Sous, Dodet, et 54 al., 2020). Of particular importance is the representation of bottom friction processes 55 in the momentum balance, which is often considered in the depth-averaged formulation 56 in shallow nearshore systems to allow for exploration and prediction of the dominant 57 drivers of water levels and current dynamics in reef-lagoon systems. While simple 58 linear functions have been used in early analytical models (Symonds et al., 1995; Hearn, 59 1999), currently the most common approach is to parameterize the bottom stress as 60 a quadratic function (M. R. Gourlay & Colleter, 2005; Monismith, 2007; Davis et al., 61 2020), using a dimensionless bottom drag coefficient,  $C_d$  as a key parameter. Field 62 studies on coral reef have shown that coral reef  $C_d$  are generally at least one order 63 of magnitude larger than their counterparts observed on sandy beaches owing to the 64

preponderant effect of pressure drag over skin friction drag (Rosman & Hench, 2011). 65 Field-inferred  $C_d$  also show a very large spread between sites, measurement methods 66 and  $C_d$  definition (Rosman & Hench, 2011). This variability is explained by the 67 variability of natural coral reef systems, the surface wave effects, and by the fact that in 68 such a complex context, local measurements may be affected by specific terrain features 69 (Hench & Rosman, 2013) and therefore may not be representative of the integrated 70 effect of the coral reef on bottom friction (Reidenbach et al., 2006). For large roughness 71 height to depth ratio, the usual framework of drag processes over rough bottoms 72 can be undermined by the additional role of the flow within the coral colony, often 73 called in-canopy flow (Rosman & Hench, 2011; Davis et al., 2020). This emphasizes 74 the importance of the local depth relative to the physical height of coral colonies in 75 frictional processes, which can be parameterized with empirical power-laws of depth 76 (McDonald et al., 2006) or with formulations derived from the turbulent boundary 77 layer theory (A. Pomeroy et al., 2012; Lentz et al., 2017, 2018; Sous, Dodet, et al., 78 2020). However, it is worth mentioning that, apart from these few latter exceptions, 79 the depth-effect is not systematically explored and field-inferred  $C_d$  are often presented 80 as constant for a given site. A pivotal research prospect is to establish a connection 81 between the hydrodynamic parameters describing bottom friction, such as the bottom 82 drag coefficient or other hydrodynamic roughness heights, and the actual geometrical 83 structure of the reef colony (Lowe et al., 2005; Davis & Monismith, 2011; Lentz et 84 al., 2017; Rogers et al., 2018). This remains a fierce challenge, since it requires both 85 a robust characterization of the hydrodynamic parameters related to bottom friction 86 and a fine knowledge of the reef geometry. Aiming to explore this issue in the coral reef 87 context, a specific field site was selected due to (i) an overall high roughness to depth 88 ratio, (ii) a spatially-varying and well partitioned geometrical reef structure that allows 89 for an assessment of geometric variations effect on bottom friction, (iii) a series of high-90 resolution measurements of the coral colony structure (Sous, Bouchette, et al., 2020), 91 and (iv) a hydrodynamic field campaign designed to provide robust characterization 92 of the bottom drag coefficient. The objectives of the present study are to present 93 and discuss these latter field measurements and to discern the potential relationship 94 between hydrodynamic bottom friction and the actual coral colony topography. A 95 particular focus is given on both depth and reef structure effects on the bottom stress. 96

#### 97 **2** Experiment

The field site, instrumentation, and data processing methods were chosen and designed to allow for a bulk analysis of bottom friction through the depth-averaged momentum balance equation (Eq. 1).

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# 2.1.1 The Maupiti island

2.1 Field site and instrumentation

Maupiti ("the Stuck Twins") is a diamond-shaped island located in the western part of the Society archipelago in French Polynesia. The study site is a cross-reef transect located in the south-west barrier (Fig. 1A). This living reef barrier is nearly rectilinear, extending over about 5 km from the west motu (emerged land) to the south pass. The cross-shore profile of the selected area appears representative of the nearly uniform reef structure observed over 4 km of this southwestern barrier (Figs. 1A, B).

119 **2.1.2** Bathymetry

A series of high-resolution topo-bathymetric surveys were carried out to characterize the fine geometrical structure of the reef barrier, see (Sous, Bouchette, et al., 2020), and combined with larger scale bathymetry data. Profiles P1 and P2 from Sous



Figure 1. Field site, experimental setup, and meteo-marine conditions. A: satellite view of 109 the Maupiti island with the instrumented transect (red line) extending from S4 to AQP1. B: 110 zoomed satellite view of the instrumented transect with the four selected zones as Reef Crest 111 (RC), Backreef A (BrA), Backreef B (BrB) and Backreef C (BrC). C: cross-shore profile with 112 high-resolution seafloor elevation (P1 and P2 from Sous et al. (Sous, Bouchette, et al., 2020), in 113 grey dots), reference seafloor elevation (solid line) and pressure sensors (red dots). The vertical 114 dashed lines highlight the structural reef zonation. D: SW significant wave heights at S4, OSS2, 115 OSS4, and OSS6. E: Mean Water Level at OSS2, OSS4 and OSS6. F: cross-barrier transport and 116 depth-averaged velocity. The grey patches indicates the periods selected for the analysis of the 117 momentum balance. 118

et al. (2020), which closely overlap the instrumentation presented here, are combined to provide high-resolution reef topography denoted in grey dots in Figure 1C. The breaking zone extending from the mid-forereef to the reef crest remains inaccessible due to violent wave dynamics.

The definition of the actual seabed is not straightforward in such a complex en-127 vironment. The approach used here is based on the analysis of the geometrical reef 128 structure proposed by Sous et al. (2020). The high-resolution reef topography is pro-129 cessed with a 7m-wide moving window, corresponding to the fractal breakup observed 130 131 on reef elevation spectra (Sous, Bouchette, et al., 2020). A statistical threshold is selected to extract the seafloor elevation from the distribution of reef elevation ob-132 tained in each moving window. Specifically, the Reference Seafloor Elevation (RSE) 133 used in the momentum balance is defined as the 10-th percentile of the reef eleva-134 tion. This approach preserves topographical wave-lengths larger than 7 m, which are 135 deemed bathymetry-related terrain features (mainly dead substratum), while smaller 136 length-scales associated with living reef colonies are considered roughness-related ter-137 rain features. An initial discussion of this choice has been proposed by Sous et al. 138 (2020) from geometrical, biological, and reef-history perspectives. Additional hydro-139 dynamic arguments are discussed in the Discussion section (Section 4). 140

In order to characterize the reef geometry, the reef is divided into four successive zones. Zones were distinguished using a series of statistical metrics, spectral analysis, and/or underwater observations (Sous, Bouchette, et al., 2020). For each zone, we describe the geometry using statistical parameters from the distribution of reef elevation. The zones are highlighted in Figure 1 by vertical dashed lines. Positions along the studied cross-reef transect are defined in a onshore-directed reference starting at isobath -20m.

- The reef crest (RC) is the highest portion of the barrier, extending from X = 195to X = 225 m. It is made of small compact coral colonies, typically 20 cm high. This compact, homogeneous structure is related to small values of standard deviation ( $\sigma = 0.050$  m) and skewness (-0.37) of reef elevation across the zone.
- The first part of the backreef (BrA), from X = 225 to X = 274 m, shows a gentle downward slope (-0.6%). While a compact reef structure remains, it is broken by numerous channels up to 50 cm deep. The standard deviation here is  $\sigma = 0.19$  m while the skewness is strongly negative (-0.63), tending toward a *d*or  $\delta$ -type roughness (Jiménez, 2004; Leonardi et al., 2007).
- The second part of the backreef (BrB), from X = 274 to X = 385 m, shows a lower downward slope (-0.3%). The reef structure is more open with the presence of higher, larger, and scattered reef elements. This results in a similar standard deviation as Zone A ( $\sigma = 0.19$  m) and a weaker, but still negative, skewness (-0.38).
- The last part of the backreef (BrC), from X = 385 to X = 585 m, is nearly horizontal (average slope -0.023%) and made of spaced out meter-high reef coral mounds on a smooth substratum partly covered by a thin layer of sand (10-30 cm). The standard deviation increases slightly ( $\sigma = 0.24$  m), and the skewness shifts to strongly positive value (0.71), revealing the transition toward a k-type roughness, i.e. distinct and well spaced roughness elements on a nearly flat bed (Wooding et al., 1973; Jiménez, 2004; Rogers et al., 2018).

#### 169 2.1.3 Instrumentation

The instrumentation was deployed on a single cross-shore transect (Fig. 1) from July, 5 to 18, 2018. Incoming wave conditions are provided by a S4DW electromagnetic current meter deployed on the forereef, in 10.5 m depth, recording 20-min bursts of data every 3h. Five bottom-mounted pressure sensors (OSSI-010-003<sup>®</sup>, 10Hz

sampling frequency), namely OSS2 to OSS6, were deployed across the reef barrier 174 to monitor wave and mean water levels. OSS2 was located at the top of the reef 175 crest. Other sensors were placed at the boundaries of the three backreef zones, such 176 that sensor pairs OSS2-OSS3, OSS3-OSS4, OSS4-OSS5, and OSS5-OSS6 allow for 177 monitoring the four barrier portions RC, BrA, BrB, and BrC, respectively. The effect 178 of dynamic pressure was minimized by placing the sensors in reef grooves with a nearly 179 alongshore direction. To capture transport, an acoustic Doppler profiler AQP1 (Nortek 180 sidelooking Aquadopp<sup>®</sup>) was bottom moored in the lagoon, 500m beyond the barrier. 181 The velocity profiles were recorded every 15s over a 10-cm cell in 1.5 to 2m water 182 depth. The measured velocities were projected onto the reef barrier axes to obtain the 183 cross and along-reef components. 184

185 2.2 Data processing

#### 2.2.1 Waves

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Free surface energy spectra were computed over 60-min bursts subdivided from the continuous record. For each pressure sensor, a discrete Fourier transform was computed without any windowing. The resulting bottom pressure spectra were then converted into free surface elevation spectra using linear wave theory.

#### 2.2.2 Mean water levels and vertical positioning

Particular attention was given to the mean water level measurement in order 192 to improve the accuracy of momentum flux estimates with respect to previous field 193 work (Sous, Bouchette, et al., 2020). Each pressure sensor was repeatedly positioned 194 by Real Time Kinematic Differential Global Navigation Satellite System (DGNSS-195 RTK). The overall uncertainty is similar to the one estimated during high-resolution 196 topography measurements performed by (Sous, Bouchette, et al., 2020), approximately 197 3 and 15 cm in vertical and horizontal positioning, respectively. The mean water levels 198 were computed from the continuous records subdivided in 60-min bursts. All pressure 199 measurements were corrected using a 3-point calibration carried out ashore just before 200 deployment and after retrieval, and the atmospheric pressure measured ashore. 201

#### 202 2.2.3 Momentum terms calculation

Under the assumption of purely cross-reef, steady, alongshore-uniform flow averaged over many wave cycles, the depth-averaged momentum balance can be written (Sous, Dodet, et al., 2020)

$$\underbrace{g\rho\frac{\partial\bar{\eta}}{\partial x}}_{M_s} = -\underbrace{\frac{1}{(\bar{\eta}+h)}\frac{\partial S_{xx}}{\partial x}}_{M_r} - \underbrace{\frac{1}{(\bar{\eta}+h)}\bar{\tau}_b}_{C_dM_f} \qquad \left[N.m^{-3}\right] \tag{1}$$

where g is the gravitational acceleration,  $\rho$  the water density,  $\bar{\eta}$  the wave setup, 206 h the still water depth,  $S_{xx}$  the radiation stress, and  $\tau_b$  the bed shear stress. The 207 three terms in Equation 1 will be referred to as Slope  $(M_s)$ , Radiation  $(M_r)$  and 208 Friction  $(M_f)$  terms. Note that the total friction momentum flux has been written as 209 the product  $C_d M_f$  in order to easily extract  $C_d$ , the bottom drag coefficient, through 210 the comparison of the three momentum fluxes. The contribution of advection flux in 211 Equation 1 is assumed to be negligible from the reef crest owing to moderate variations 212 of depth (Symonds et al., 1995; Hearn, 1999; M. Gourlay, 1996; Buckley et al., 2015; 213 Sous, Dodet, et al., 2020). Following the approach of Sous et al. (2020), depth-214 averaged fluxes are estimated between each successive sensor pair over continuous 215 records subdivided into 60-min bursts. The total water depth  $(\bar{\eta} + h)$  used for the 216

calculation in Radiation and Friction terms is taken as the mean water depth between
 two adjacent sensors.

#### 219 Slope term

The Slope term  $M_s = g\rho \frac{\partial \bar{\eta}}{\partial x}$  is computed using the mean water level at each sensor. A positive Slope term at a given location corresponds to a locally positive mean surface slope in a shoreward direction. Uncertainties in the Slope term computation are mostly related to the accuracy in vertical positioning and sensors distance. Considering typical ranges of setup and horizontal distance of  $0.2 \pm 0.015 m$  and  $100 \pm 0.075 m$ , uncertainty on the Slope term is estimated around  $\pm 1.5N.m^{-3}$ .

#### 226 Radiation stress term

The wave radiation stress term  $M_r = \frac{1}{(\bar{\eta}+h)} \frac{\partial S_{xx}}{\partial x}$  is estimated from bottom pressure wave height measurements using linear theory (Longuet-Higgins & Stewart, 1962), neglecting wave-roller effects (Buckley et al., 2015). Typical ranges of water depth, wave height, and horizontal distances of  $1 \pm 0.015$  m,  $1 \pm 0.05$  m, and  $100 \pm 0.075$  m, yield uncertainty estimates on the radiation stress term around  $3 N.m^{-3}$ .

#### 232 Friction term

A classic quadratic law is used to compute the total bed shear stress (Feddersen et al., 2000; Buckley et al., 2016) combining the contributions of the depth-averaged current U and the wave bottom orbital velocity  $u_b$ :

$$\tau_b = \rho C_d \overline{|U + u_b| (U + u_b)} \tag{2}$$

where  $C_d$  is the bottom drag coefficient. This current-wave decomposition is generally valid for the thick boundary layer present in coral reefs (A. W. Pomeroy et al., 2017; Lentz et al., 2018; Sous, Dodet, et al., 2020). The depth-averaged current U in each zone is estimated from the time-averaged depth-averaged profile of cross-reef velocity measured at AQP1 weighted by the depth ratio. The horizontal component of the orbital velocity at the bottom,  $u_b$ , is estimated from the time series of instantaneous bottom pressure  $P_b$  using linear wave theory:

$$u_b = \frac{CP_b}{\rho g(\bar{\eta} + h)},\tag{3}$$

where  $C = (g(\bar{\eta} + h))^{1/2}$  is the wave celerity.

Note that (i)  $u_b$  includes all wave components, i.e. both short and infragravity waves and, (ii), the ratio  $u_b/U$  ranges here between 1.6 and 25, i.e. generally much higher than the values observed by Lentz et al. (Lentz et al., 2017), making the present dataset particularly useful to quantify the influence of waves on drag over coral reefs. Finally, the Friction term defined in Equation 1 can be directly derived from the in-situ measurements as

$$M_f = \frac{\rho}{(\bar{\eta} + h)} \overline{|U + u_b| (U + u_b)} \tag{4}$$

#### Momentum-based bottom drag coefficient

Based on the estimation of the three momentum fluxes described above, an experimental value of the bottom drag coefficient,  $C_d^{exp}$ , can be obtained from Equation 1:

$$C_d^{exp} = -\frac{M_s + M_r}{M_f} \tag{5}$$

Theoretical bottom drag coefficient

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The depth-dependence of the bottom drag coefficient is furthermore assessed in the framework of the canonical turbulent logarithmic mean velocity profile (law of the wall). In the presence of large and highly variable roughness, the proper definition of a z = 0 datum (here the RSE) is generally not straightforward. A displacement height d is generally introduced to define the hydrodynamic origin, leading to the following formulation of the law of the wall (Kundu & Cohen, 1990):

$$\langle u(z) \rangle = \frac{U_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right)$$
 (6)

where  $\langle u(z) \rangle$  is the time-averaged velocity profile at elevation z above the bed,  $U_*$  is the friction velocity,  $\kappa = 0.41$  the Karman constant, and  $z_0$  and d are the roughness and displacement heights, respectively. Depth-integration of Equation 6 leads to a theoretical expression for the drag coefficient (A. Pomeroy et al., 2012; Sous, Dodet, et al., 2020):

$$C_d^{th} = \left[\frac{\kappa}{\left(\ln\left(\frac{h+\bar{\eta}-d}{z_0}\right) - 1\right)}\right]^2.$$
(7)

In the following, both the experimental momentum-derived  $C_d^{exp}$ , and log-derived theoretical  $C_d^{th}$ , will be considered and compared. To be valid, Equation 7 requires the full development of the boundary layer throughout the water column, meaning that (i) the velocity defect correction (Coles, 1956) can be neglected and (ii) the roughnessto-depth ratio remains weak otherwise in-canopy flow should be considered (Rosman & Hench, 2011). This latter constraint is further discussed in Section 4.

#### 242 **3 Results**

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#### 3.1 Overview

Figure 1 shows time series of wave heights across the barrier (Fig. 1D), mean 244 water levels (MWL, Fig. 1E) and cross-reef current and transport (Fig. 1F). The 245 wave climate is representative of the south-west coast conditions, with mean significant 246 wave height of 1.9 m and mean peak period about 13.5 s. The mean wave direction 247 hits the forereef with a  $17^{\circ}$  southward incidence. With expected further refraction 248 across the forereef (Sous et al., 2019), the overall wave forcing of the reef barrier is 249 mainly reef normal. The swell attenuation is very effective, with less than 25% and 250 3% of the forereef wave height remaining at OSS2 and OSS6 stations, respectively. 251 The MWL time series (Fig. 1E) shows the typical microtidal regime at Maupiti, with 252 tide amplitude between 5 and 10cm. In most cases, the reef crest MWL (OSS2 in 253 Fig. 1E) is higher than further shoreward on the backreef, mostly due to wave setup. 254 This trend weakens during the most energetic event, due to the larger extension of the 255 surf zone. The top of the reef crest colony has been measured at 5.8 cm, indicating 256 that the reef is submerged during low water periods, by less than, on average, 15cm. 257 For the following analysis of depth-averaged momentum fluxes, two specific periods 258 are selected (grey patches in Figures 1D, E, F) where the reef crest submergence is at 259 least 20 cm, allowing for a well-established cross-reef dynamics, with a deviation from 260 the cross-reef direction lower than  $15^{\circ}$ . Cross-reef current and transport (Fig. 1E) are 261 clearly driven by incoming wave energy (Sous et al., 2017; Sous, Dodet, et al., 2020): 262 the larger the waves, the stronger the cross-barrier barotropic pressure gradient, thus, 263 the stronger the current is. 264

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### 3.2 Depth-averaged momentum fluxes

Figure 2 shows Radiation and Slope terms relative to Friction, for the four selected zones. Two experimental constant-value  $C_d$  are displayed for each zone:  $C_d^{exp,f}$ ,



Figure 2. Cross-shore depth-averaged momentum fluxes for the four selected zone (RC: Reef Crest, BrA: Backreef A, BrB: Backreef B, BrC: Backreef C). The local depth is given in color levels. The value  $C_d^{exp,f}$  refers to the value obtained from the linear fit of the  $M_s + M_r$  vs  $M_f$ relationship, while  $C_d^{exp,m}$  refers to the time-averaged value of all the individual estimates.

which refers to the value obtained from the linear fit of the  $M_s + M_r$  vs  $M_f$  relation-268 ship, and  $C_d^{exp,m}$  which refers to the averaged value over all the individual estimates. 269 The constant  $C_d$  approach results in an overall unsatisfactory representation of the 270 observed physics. The quality of the regression  $(R^2 = 0.84)$  is acceptable for the 271 deeper part of the backreef (BrC, Fig. 2D) but  $R^2$  strongly decreases when moving 272 offshore. The bottom drag coefficients obtained for the three backreef zones show 273 significant variations, with no clear trend for both  $C_d^{exp,f}$  and  $C_d^{exp,m}$ . In addition, 274 strong differences appear between  $C_d$  estimates obtained with linear fit and global 275 average methods. A well marked depth effect is observed, as indicated by color levels 276 of zone-averaged depths in Figure 2. 277

Further insight is gained by plotting the time-varying bottom drag coefficient, 282 calculated using Eqn. 5, versus the local depth (see Figure 3A). For each zone, a 283 straightforward depth-dependence is observed. The bottom drag coefficient strongly 284 increases in shallow depth, following previous observations (McDonald et al., 2006; 285 A. Pomeroy et al., 2012; Lentz et al., 2017, 2018; Sous, Dodet, et al., 2020). In 286 Figure 3A, the depth-dependent  $C_d$  at each zone is compared with the theoretical 287 predictions of the log-layer  $C_d^{th}$  formulation given in Equation 7,  $z_0$  and d being used 288 as least-square fitting parameters. A satisfactory agreement is obtained, with a good 289 representation of the observed depth-dependent  $C_d$  for all zones. In addition to the 290 full-data model fitting presented in Figure 3, a bootstrap analysis over 100 40-item 291 subsamples randomly selected from the initial 140-item dataset was carried out to 292 estimate uncertainties on d and  $z_0$ . This leads to mean values of 0.35, 0.52, 0.93 293



Figure 3. A: Depth-dependence of the bottom drag coefficient for the four zones. Circles and dashed lines correspond to field measurements and  $\log -C_d$  fitted formulations, respectively. For each zone, the  $\log -C_d$  fit provides the displacement d and roughness  $z_0$  heights (in m). B and C: Cross-shore depth-averaged momentum balance with the log-derived bottom drag coefficient for Reef Crest (RC) and BackReef B (BrB) zones, respectively. The local depth is given in color levels.

and 1.2 m for d and 0.015, 0.017, 0.03 and 0.14 m for  $z_0$  for RC, BrA, BrB and 294 BrC, respectively, and standard deviations of 0.0011, 0.0026, 0.003 and 0.0018 m for 295 d and 0.011, 0.059, 0.042 and 0.054 m for  $z_0$  for RC, BrA, BrB and BrC, respectively. 296 Various sub-sample sizes (ranging from 20 to 50) were tested, with no clear influence 297 on the results. The overall trend is that d increases from the reef crest to the backreef 298 while the roughness height  $z_0$  is more constant throughout. The implementation of 299 the log- $C_d$  clearly improves the balance between the depth-averaged momentum terms 300 compared to the constant approach (compare Fig. 3B and C with Fig. 2A and C). 301 Linear determination coefficients between  $M_s + M_r$  and  $C_d^{th}M_f$  are 0.85, 0.82, 0.81 302 and 0.87 for RC, BrA, BrB and BrC, respectively, indicating a much better closure of 303 the momentum balance than with the constant  $C_d$  approach used in Figure 2. 304

#### 311 4 Discussion

The present study aims to take advantage of a specific barrier reef site, selected for its well-structured roughness variability, to provide new insights on friction processes

and bottom drag coefficients in coral reef environments. The strategy followed here is 314 to infer the drag coefficient from a careful examination of the governing momentum 315 equation over selected zones of the barrier (Lentz et al., 2017; Sous, Dodet, et al., 2020). 316 This bulk approach, i.e. deducing the bottom drag coefficient from momentum balance, 317 allowed us to spatially integrate the bottom drag effect over a large area (Reidenbach et 318 al., 2006) and to minimize the potential local effects which may explain the discrepancy 319 often observed between friction estimates obtained with different methods at the same 320 site (Dewey & Crawford, 1988; Sanford & Lien, 1999; Stahr & Sanford, 1999; Johnson 321 et al., 1994; Lu et al., 2000; Luznik et al., 2007). The overall good balance between 322 momentum fluxes validates the depth-effect parameterization for  $C_d$ . In addition, it 323 enforces the relevancy of the simple mean current - wave component splitting used 324 in the bed shear stress calculation, as suggested by (Wright & Thompson, 1983) and 325 later used by (Lentz et al., 2018; Sous, Dodet, et al., 2020) in the coral reef context. 326

Our depth-effect parameterization is based on the framework provided by the 327 log-layer boundary layer theory. The full development of such a constant flux layer 328 requires that the typical roughness elevation remains small compared to the total water 329 depth, while high roughness-to-depth ratio conditions should be addressed by canopy 330 approaches (Rosman & Hench, 2011). The small roughness-to-depth ratio hypothesis is 331 most likely violated in a number of our observations, where coral mounds can protrude 332 above half of the water column, leaving too little space for a fully turbulent log-layer 333 to develop. This should explain why unrealistically high values of d are reached when 334 fitting the log-layer  $C_d$  model to the observations. The exact threshold of roughness-335 to-depth ratio required to reach the full development of a log layer remains an open 336 question in such complex environment and would require a comprehensive space and 337 time averaging of velocity profiles across the considered area. One notes however that 338 the proposed log-based parameterization of  $C_d$  remains quite robust in describing the 339  $C_d$  depth-dependency. The question arises then on the possible connection between 340 the fitting parameters of the model, inferred from purely hydrodynamical observations, 341 and the coral reef topography. 342

Understanding the relationship between the geometric structure of the bottom 343 and the hydrodynamic parameters remains an open challenge. For simple geometri-344 cal structures, a "discrete" approach can be used to connect frictional height with a 345 combination of real roughness element scales such as height, width, and spacing. Well-346 known scalings for log-layer roughness height are for instance  $z_0 = h_r/30$  (Bowden, 347 1978), where  $h_r$  is grain diameter for sandy beds, or  $27.7H^2/L$  for ripple beds (Grant & 348 Madsen, 1982) where H and L are the ripple height and width. More complex geome-349 tries, observed on most rock and reef seafloors, are often treated similarly by assuming 350 the existence of a single representative hydrodynamic roughness height (Schlichting & 351 Gersten, 2016). The question arises then on the connection of the roughness height 352 with the real geometric structure of the seabed. Roughness heights being spatially-353 integrative parameters, the discrete estimators may need to be complemented by a 354 "continuous" approach of seabed complexity through statistical moments and moment 355 functions (Flack & Schultz, 2010; Stewart et al., 2019; Davis et al., 2020). Only re-356 cently has there been progress in the in-situ fine spectral description of living coral reef 357 topography over a relevant range of length-scales (Nunes & Pawlak, 2008; Jaramillo 358 & Pawlak, 2011; Duvall et al., 2019; Rogers et al., 2018; Sous, Dodet, et al., 2020). A 359 proper assessment of friction processes over complex seabeds will require a long-term 360 research effort, combining field and laboratory databases, such as the exploration of 361 the friction processes over laboratory synthetic self-affine surfaces (surfaces including 362 a spectral power law dependence on wavenumber (Turcotte & Brown, 1993)) carried 363 out by Stewart et al. (2019). Our depth-effect parameterization is based on two fitting parameters,  $z_0$  and d. The former showed no clear connection with the seabed 365 statistical features derived by Sous et al. (2020). The latter can be connected to the 366 standard elevation of the seabed  $\sigma$  (see Figure 4). Considering the 10-th percentile 367



Figure 4. Displacement height d vs bed elevation standard deviation  $\sigma$  for the four selected zones. The dashed line  $d = 4\sigma$  is given as statistical reference.

RSE (black dots in Fig. 4), an overall linear tendency is observed, revealing the con-368 nection between the topography statistics and the displacement height ( $d = 4\sigma$  is given 369 in Fig. 4 as a statistical reference). It is however worth mentioning that the BrA zone 370 displays a lower displacement height than the overall trend, i.e. the standard deviation 371 of bed elevation is not a comprehensive predictor of d. While showing nearly similar 372 standard deviation of bed elevation as the BrB zone, the BrA zone displays a much 373 higher negative skewness of the coral elevation distribution. The lower displacement 374 height for BrA, associated with a lower friction, may be attributed to an evolution 375 of the boundary layer structure, closer to a  $\delta$ -type roughness functioning for BrA, 376 with skimming flow over colony crest and stable circulation cells in troughs, and more 377 similar to a k-type roughness functioning for BrB, with more unstable eddies. While 378 a comprehensive characterization of the 3D flow structure remains to be done, this 379 observation indicates that, even if many reefs can be hydrodynamically associated to 380  $k - \delta$ -type roughness (i.e. with lee eddies and flow reattachment between roughness 381 elements) (Rogers et al., 2018), the bottom drag remains very sensitive to the actual 382 colony geometrical structure. 383

Another important discussion point is the distinction between bathymetry and 386 roughness. Any flow feels the bed effect as a whole, therefore the need to distinguish 387 between these scales mostly arises from the requirements of numerical models, in par-388 ticular the horizontal resolution. In essence, bathymetry is resolved and roughness is 389 parameterized. The effective spatial resolution is determined by both the numerical 390 strategy (computational effort) and the resolution of the available bed topography 391 measurements. Apart from specific cases, the horizontal resolution in nearshore and 392 coastal models usually ranges from a few meters to a few dozen meters. This indi-393 cates that a large range of the living reef topographic complexity cannot be explicitly 394 resolved and must be parameterized as roughness. In addition, the definition of the 395 bathymetry reference datum in turn defines the water depth, and is therefore of pri-396 mary importance to assess the depth-effect on bottom friction. The present analysis 397 of the momentum balance has been based on the 10-th percentile of bed elevation. A 398 sensitivity analysis has been performed with additional RSE estimations using the 30, 399 50, 70 and 90-th percentiles, i.e. gradually rising the bathymetry. The quality of the 400 momentum balance regression remained satisfactory in any case. The displacement 401 height d obtained from the log-fitted- $C_d$  showed an overall decrease with increasing 402 bathymetry (see Fig. 4), while no clear trend was observed on the roughness height 403  $z_0$ . A lower displacement height for BrA zone was found to be systematically lower 404 (Figure 4). These observations emphasize the need to carefully define the bathymet-405 ric referential in attempts to assess or to parameterize friction over multi-scale rough 406 seabeds. 407

#### **5** Summary and conclusion

Results from a 3 week experiment on the Maupiti south-west barrier reef demon-409 strate that, even at the scale of a single barrier reef,  $C_d$  is strongly variable in time and 410 space. We extend on previous observations (McDonald et al., 2006; Lentz et al., 2017) 411 of  $C_d$ 's strong dependence on both local depth and reef topographical structure, to 412 a wave-exposed environment with higher roughness values and large  $C_d$ . For a given 413 site,  $C_d$  ranges by one order of magnitude due to the range of depths observed. The 414 dependency of the bottom drag coefficient on both water depth and reef structure can 415 be convincingly represented by a log depth-dependent  $C_d$  formulation. At the higher 416 end of the depth range observed here, the bottom drag coefficient tends to a nearly 417 depth-independent value ranging 0.02 and 0.035. 418

In addition to depth, the geometrical structure of the coral colony affects the 419 bottom drag coefficient. The connection between reef geometry and its hydrodynami-420 cal function can be identified through the roughly linear relationship observed between 421 the standard deviation of the reef elevation and the displacement height used in the 422 log depth-dependent  $C_d$  formulation. Third-order statistical moment (skewness) of 423 bed elevation is also observed to affect bottom drag, likely associated with an effect 424 on the near-bed flow structure. The analysis raises the need for more comprehensive 425 in-situ data connecting hydrodynamic friction parameters and structural complexity 426 of reef colony. 427

### 428 6 Open Research

The presented data can be freely available at https://doi.org/10.34930/9db3bec4 0bbf-4531-8864-f100c4b8eced

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