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# Bottom drag coefficient on a shallow barrier reef

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## Key Points:

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

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## 15 **Abstract**

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

## 24 **Plain Language Summary**

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

## 40 **1 Introduction**

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

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

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

## 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).

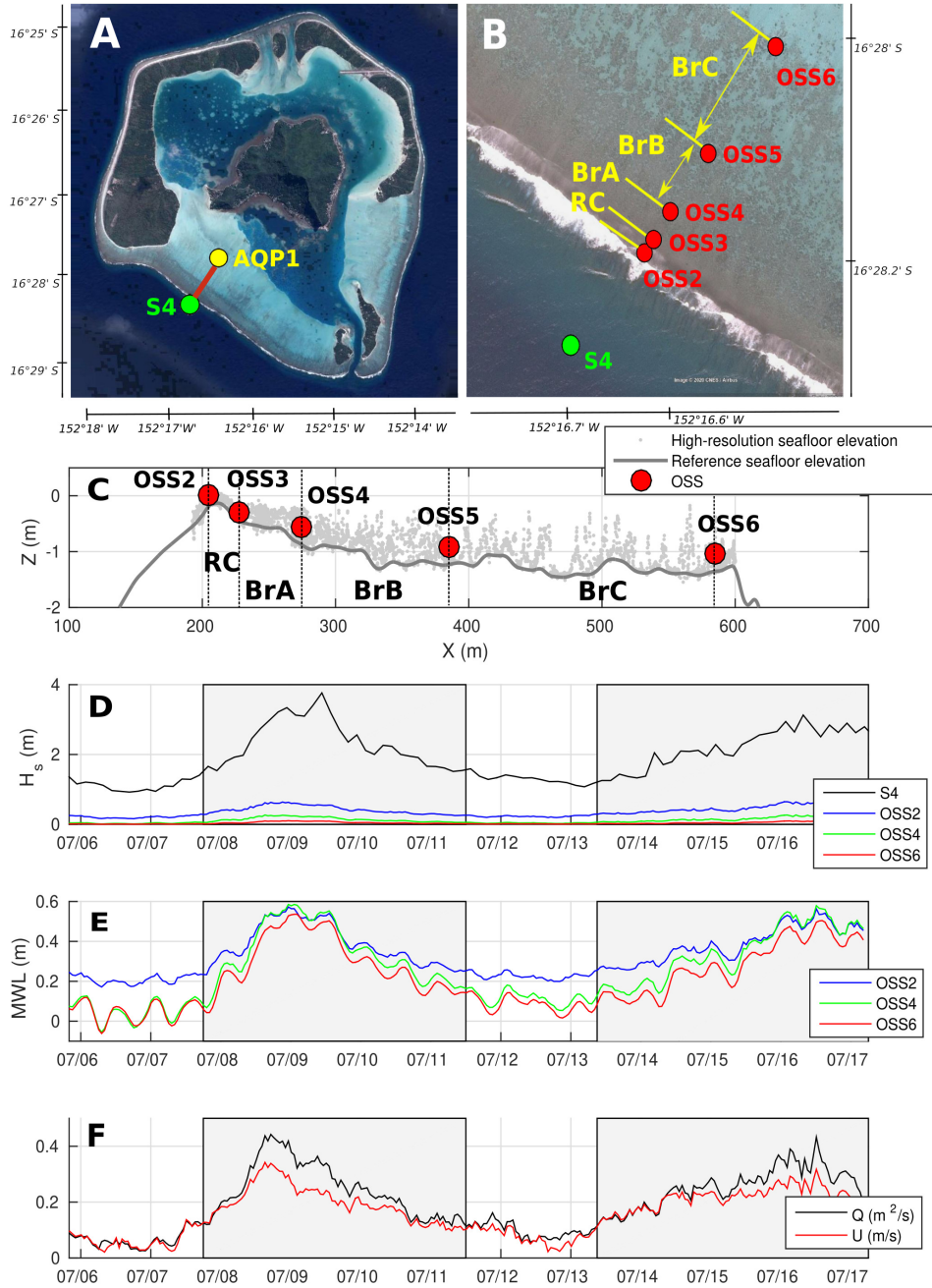
### 2.1 Field site and instrumentation

#### 2.1.1 *The Maupiti island*

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).

#### 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



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

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

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

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

- 148 • The reef crest (RC) is the highest portion of the barrier, extending from  $X = 195$   
 149 to  $X = 225$  m. It is made of small compact coral colonies, typically 20 cm high.  
 150 This compact, homogeneous structure is related to small values of standard  
 151 deviation ( $\sigma = 0.050$  m) and skewness (-0.37) of reef elevation across the zone.
- 152 • The first part of the backreef (BrA), from  $X = 225$  to  $X = 274$  m, shows a  
 153 gentle downward slope (-0.6%). While a compact reef structure remains, it is  
 154 broken by numerous channels up to 50 cm deep. The standard deviation here is  
 155  $\sigma = 0.19$  m while the skewness is strongly negative (-0.63), tending toward a *d-  
 156 or  $\delta$ -type* roughness (Jiménez, 2004; Leonardi et al., 2007).
- 157 • The second part of the backreef (BrB), from  $X = 274$  to  $X = 385$  m, shows  
 158 a lower downward slope (-0.3%). The reef structure is more open with the  
 159 presence of higher, larger, and scattered reef elements. This results in a similar  
 160 standard deviation as Zone A ( $\sigma = 0.19$  m) and a weaker, but still negative,  
 161 skewness (-0.38).
- 162 • The last part of the backreef (BrC), from  $X = 385$  to  $X = 585$  m, is nearly hor-  
 163 izontal (average slope -0.023%) and made of spaced out meter-high reef coral  
 164 mounds on a smooth substratum partly covered by a thin layer of sand (10-  
 165 30 cm). The standard deviation increases slightly ( $\sigma = 0.24$  m), and the skew-  
 166 ness shifts to strongly positive value (0.71), revealing the transition toward a  
 167 *k-type* roughness, i.e. distinct and well spaced roughness elements on a nearly  
 168 flat bed (Wooding et al., 1973; Jiménez, 2004; Rogers et al., 2018).

### 169 **2.1.3 Instrumentation**

170 The instrumentation was deployed on a single cross-shore transect (Fig. 1) from  
 171 July, 5 to 18, 2018. Incoming wave conditions are provided by a S4DW electro-  
 172 magnetic current meter deployed on the forereef, in 10.5 m depth, recording 20-min  
 173 bursts of data every 3h. Five bottom-mounted pressure sensors (OSS1-010-003<sup>®</sup>, 10Hz

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

## 185 **2.2 Data processing**

### 186 **2.2.1 Waves**

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

### 191 **2.2.2 Mean water levels and vertical positioning**

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

### 202 **2.2.3 Momentum terms calculation**

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

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

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

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

219 Slope term

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

226 Radiation stress term

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

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  $u_b$ :

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

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:

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

233 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

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

234 Momentum-based bottom drag coefficient

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

$$C_d^{exp} = -\frac{M_s + M_r}{M_f} \quad (5)$$

235 Theoretical bottom drag coefficient



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):

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

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):

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

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

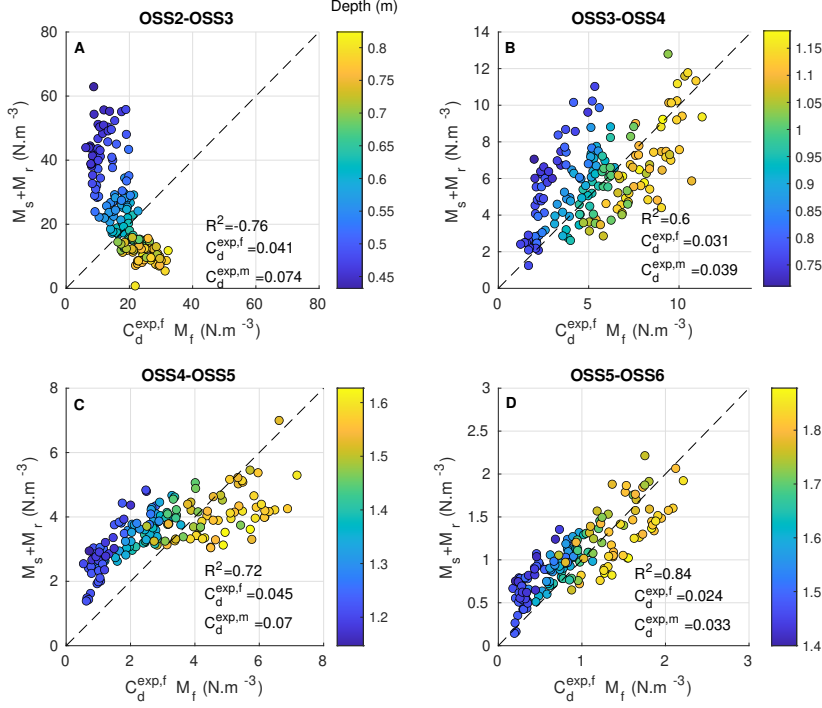
## 242 3 Results

### 243 3.1 Overview

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

### 265 3.2 Depth-averaged momentum fluxes

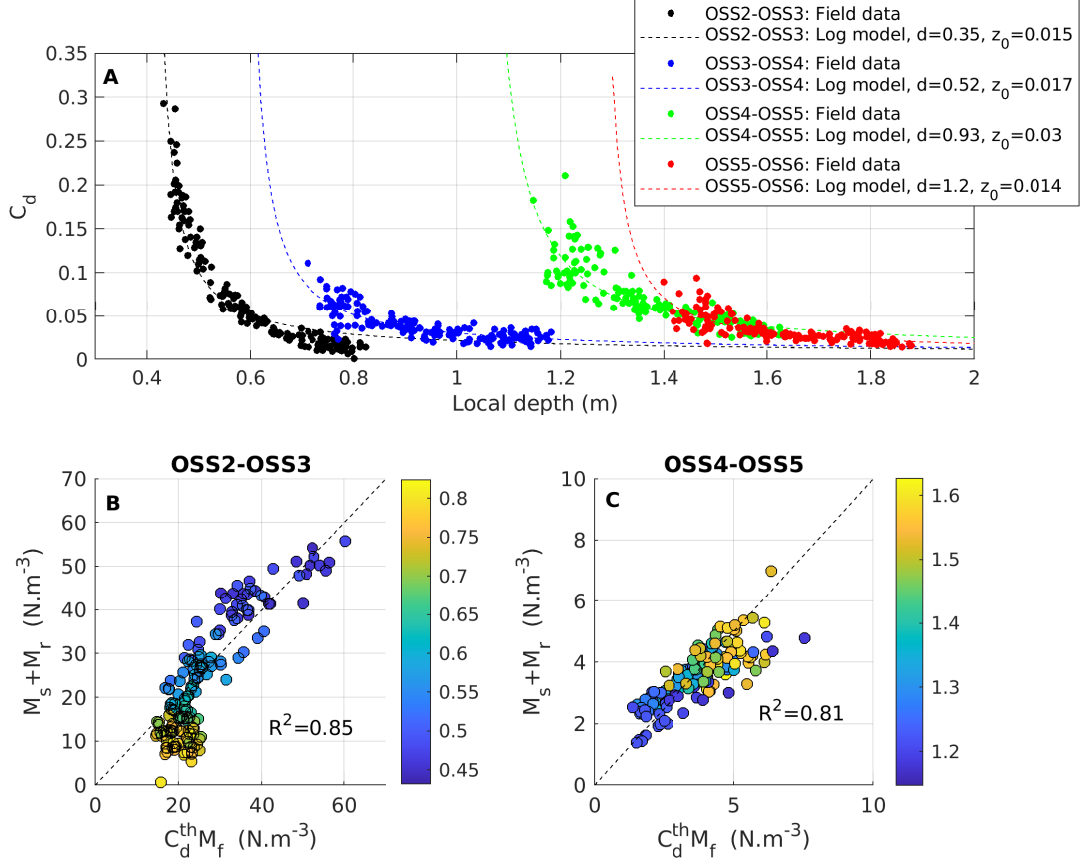
266 Figure 2 shows Radiation and Slope terms relative to Friction, for the four se-  
 267 lected zones. Two experimental constant-value  $C_d$  are displayed for each zone:  $C_d^{exp,f}$ ,



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

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

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



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

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

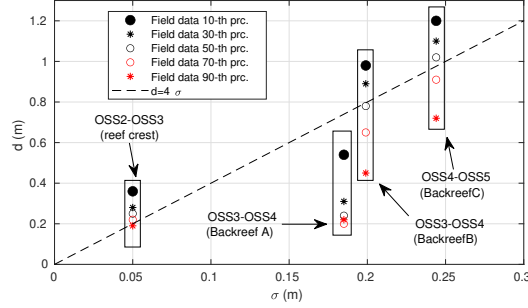
## 311 4 Discussion

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

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

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

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



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

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

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

## 5 Summary and conclusion

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

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

## 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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