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# 1        **Seasonal and episodic runup variability on a Caribbean reef-lined beach**

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## 9        **Key Points:**

- 10        • A camera derived time serie of 2 years and 10 months is used to evaluate processes  
11        involved on daily maximum runup
- 12        • Steric induced annual sea level periodicity modulate the daily maximum runup, tide level  
13        acts on short waves propagation through the reef
- 14        • Storms-induced runup is highly modulated by annual sea level periodicity and tidal level  
15

## 16 **Abstract**

17 Many low-lying coastlines are exposed to overwash and marine flooding during large wave  
18 events and the role of coastal ecosystems in reducing these hazards is more and more cited. The  
19 proposed article deals with the assessment of processes involved in runup-induced coastal  
20 flooding over two years and 10 months at Anse Maurice, a reef-fringed pocket beach located in  
21 Guadeloupe Island, in the Caribbean region. Daily maximum marine inundation was assessed  
22 using a fixed video system and two hydrodynamic measurements campaigns were organised to  
23 monitor local wave transformation through the reef system. Daily Highest Runups (DHR)  
24 remains primarily correlated to individual storm events as extreme runups are observed in  
25 correlation with storm swells. However, results evidenced that storm runup intensity is highly  
26 modulated by (1) the annual periodicity of sea level (24% of the global runup variability)  
27 showing minimums in May and maximums in November and (2) the tidal level influencing short  
28 waves and infragravity waves propagation into the reef flat. Those variabilities determine the  
29 reef submergence, an important parameter involved in wave transformation over reefs. This leads  
30 to different runup responses for similar incident wave conditions. For example, most of the  
31 winter storm events only induce moderate intensity runup while cyclonic events with the same  
32 swell intensity generate more extreme runups. The upperbeach vegetation also clearly influences  
33 the maximum swash excursion at the beach and potential back beach flooding by swash  
34 processes. This study brings new comprehensive elements on runup behavior and nearshore  
35 processes at different timescales on reef-lined beaches.

## 36 **Plain Language Summary**

37 Small Caribbean islands are highly vulnerable to coastal flooding hazard. The role of ecosystems  
38 its mitigation is increasingly emphasized. We assess the various physical processes involved in  
39 beach inundation at a reef-lined beach located in Guadeloupe Island in the Caribbean. A pluri-  
40 annual dataset from a fixed camera and two monthly hydrodynamic campaigns are used. This  
41 work highlights the implication of processes involved in wave-induced coastal inundation  
42 (runup) from annual to hour time scale. Seasonal variations are the consequence of fluctuations  
43 in sea temperature and salinity which act on water bodies expansion (called steric effect) and our  
44 results indicate that they can be responsible for 24% of runup variability. On shorter time scales,  
45 tides have an effect on wave propagation over the coral reef directly influencing residual  
46 agitation at shoreline level. Thus, storms events which are responsible for peaks in coastal  
47 inundation have an impact that is greatly modulated both by the annual periodicity of sea level  
48 and by the short timescale tidal level. The effect of tide is well-known, however the effect of  
49 annual periodicity of sea level had never been demonstrated, so this results brings new elements  
50 to understand wave induced coastal inundation in the context of reef-lined beaches.

## 51 **1 Introduction**

52 Small Caribbean Islands are highly vulnerable to coastal flooding. On the one hand since the  
53 limited space and topographical constraints have oriented human development near to the coastal  
54 areas and, and on the other hand because the Caribbean region is exposed to strong hydrodynamic  
55 events through winter storms and hurricanes. The strength of the latter is predicted to rise in the  
56 near future (Knutson et al., 2020) and in association with other effects of climate change like sea-  
57 level rise, the frequency of flooding events is expected to rise in the next decades (Vitousek et al.,  
58 2017) with its concomitant impact on human assets (Ferrario et al., 2014).

59 Considering hydrodynamic forcing, extreme sea-levels and direct wave impact are the principal  
60 parameters involved in coastal inundation. Short-term mean sea-level variability is related to both  
61 predictable parameters (e.g., tidal cycles) and stochastic parameters (e.g., wave and wind setup,  
62 storm surge). In the Caribbean maximum coastal flooding events are related to cyclones (Rueda et  
63 al., 2019). Sea-level fluctuations on a yearly basis are also well-known and may be the  
64 consequence of the association of seasonal variations of atmospheric pressure and winds, steric  
65 effect, ocean circulation (Torres and Tsimplis, 2012) and water mass transfer from the continents  
66 (ice sheets, glaciers or rivers). Other forcings with several years or even decennial cycles also  
67 modulate sea level such as El Niño Southern Oscillation (ENSO) (Chelton and Enfield, 1986) or  
68 solar activity (Valle-Levinson and Martin, 2020). In addition, sea level is expected to rise in the  
69 near future with geographically varying amplitudes (e.g. Losada et al., 2013, Stammer et al., 2013;  
70 Torres and Tsimplis, 2013; Slangen et al., 2014; Le Cozannet et al., 2020; Wang et al., 2021)  
71 which will inevitably affect coastal inundation (Storlazzi et al., 2018).

72 In opposition, there is strong evidence that healthy coastal ecosystems, and in particular tropical  
73 ecosystems, can substantially reduce coastal hazards (Spalding et al., 2014; Guannel et al., 2016).  
74 At reef-lined coasts, the attenuation of the impact of coastal hazards depends mainly on coral reef  
75 morphology (e.g., slope, width, structural complexity) and hydrodynamic forcing (e.g., water  
76 level) whose main effect is to dampening incident wave energy. Incident wave conditions show  
77 significant transformation across reefs both in intensity, as well as, in spectral dispersion. Wave  
78 propagation on coral reefs produces a tremendous energy dissipation (Harris et al., 2018) and a  
79 switch in waves spectrum from high Short Waves (SW, typically frequency  $> 0.04$  Hz) to  
80 Infragravity Wave (IG,  $0.004 < \text{frequency} < 0.04$  Hz) and Very Low Frequency waves (VLF,  
81 frequency  $< 0.004$  Hz) undulations often leading to a low frequency undulation dominance at the  
82 shoreline (Péquignet et al., 2009; Pomeroy et al., 2012; Roeber and Bricker, 2015; Cheriton et al.,  
83 2016 and 2020; Sous et al., 2019). In consequence, IG waves may be responsible of maximum  
84 runup, overwash events (Ford et al., 2013, Quataert et al., 2015, 2020; Roeber and Bricker, 2015)  
85 and beach erosion (Bertin et al., 2018). The two main processes considered in wave transformation  
86 over the reef are (1) nonlinear interactions in shallow areas: as short waves breaks, bound long  
87 waves are released and continue to propagate to the shore as a free wave (Longuet-Higgins and  
88 Stewart, 1962) and (2) breakpoint forcing on the reef crest which are linked to the variation of  
89 wave setup induced by wave groups generating a setup wave in phase with group waves (Symonds  
90 et al., 1982).

91 A meta-analysis conducted by Ferrario et al., (2014) estimated that even if results remain site-  
92 specific, coral reef assemblages dissipate an average of 97% of incident wave energy at the  
93 shoreline. Simultaneously, a fraction of incident SS is transformed to lower frequency waves: IG  
94 and VLF (Péquignet et al., 2014). This switch in energy frequency bands is commonly observed  
95 at reef-lined beaches (Masselink et al., 2019) but strongly depends in a one hand of  
96 hydrodynamic conditions (tidal level, atmospheric surge and wave parameters) and in a second  
97 hand of geomorphological characteristics of the reef platform (depth, width, front reef slope,  
98 channels, reef flat width and depth). The biological composition of the coral assemblage and may  
99 also have an impact on hydrodynamic with the most complex structures representing a stronger  
100 obstacle (e.g. *Acropora* species). IG and VLF may also be amplified by resonance when the  
101 energy frequency is near the reef natural frequency, depending in reef flat properties and in  
102 particular width and depth (Péquignet et al., 2009, 2014; Pomeroy et al., 2012; Gawehn et al.,  
103 2016). Several recent studies dealt specifically with runup and coastal flooding in a coral reef

104 context. Buckley et al. (2018) and Ning et al. (2019) focused on physical mechanisms  
105 conducting laboratory experiments in association with a numerical modeling for the latter. Both  
106 supported the hypothesis of a reduction of runup by the coral reef (30 % compared to smooth  
107 bed). Roelvink et al. (2021) carried out a laboratory experiment on optimization of reef  
108 restoration to reduce flooding where the results postulated the effectiveness of broad and shallow  
109 restorations. However, as reefs possess highly variable physical characteristics, particularly front  
110 reef slope, roughness and reef flat dimensions (width, and shallowness) their response to incident  
111 agitation also differs accordingly. A bayesian-based meta-model was developed to predict runup  
112 response in a wide panel of reef settings. It emerges that waves, water levels and reef width are  
113 the main parameters involved in backreef runup (Pearson et al., 2017). Nevertheless, high-  
114 resolution observations of runup on field are scarce. A recent study presents a runup dataset of a  
115 duration close to the year (Melito et al., 2022) but to the authors knowledge no study propose a  
116 continuous multi-years survey dataset preventing analysis of runup variability at daily to  
117 pluriannual time scale.

118 This study investigates the parameters involved in runup on a reef fringed pocket beach typical of  
119 the Lesser Antilles from varying time scales: an event level to years. The objectives are: (1) to  
120 identify the parameters most related to wave runup (such as sea level and incident wave conditions)  
121 on a pluri-annual basis: (2) to analyze the relative importance of these parameters (in particular  
122 wave setup, SS, IG and VLF) in daily runup fluctuations, and (3) to identify and quantify runup  
123 mitigation by the reef by evaluating wave transformation through the reef and by analyzing the  
124 effects of local longshore variability. Camera observations. were used for the medium to long-term  
125 analysis (seasonal to pluri-annual), and data from local hydrodynamic measurements were used  
126 for the analysis on short to medium-term (event scale to month scale). This study brings new  
127 elements on the observations of runup on reef-lined beaches. In particular through the use of a  
128 long-term video derived dataset in combination with onsite measurements to analyze sea level and  
129 runup component from daily to annual scale.

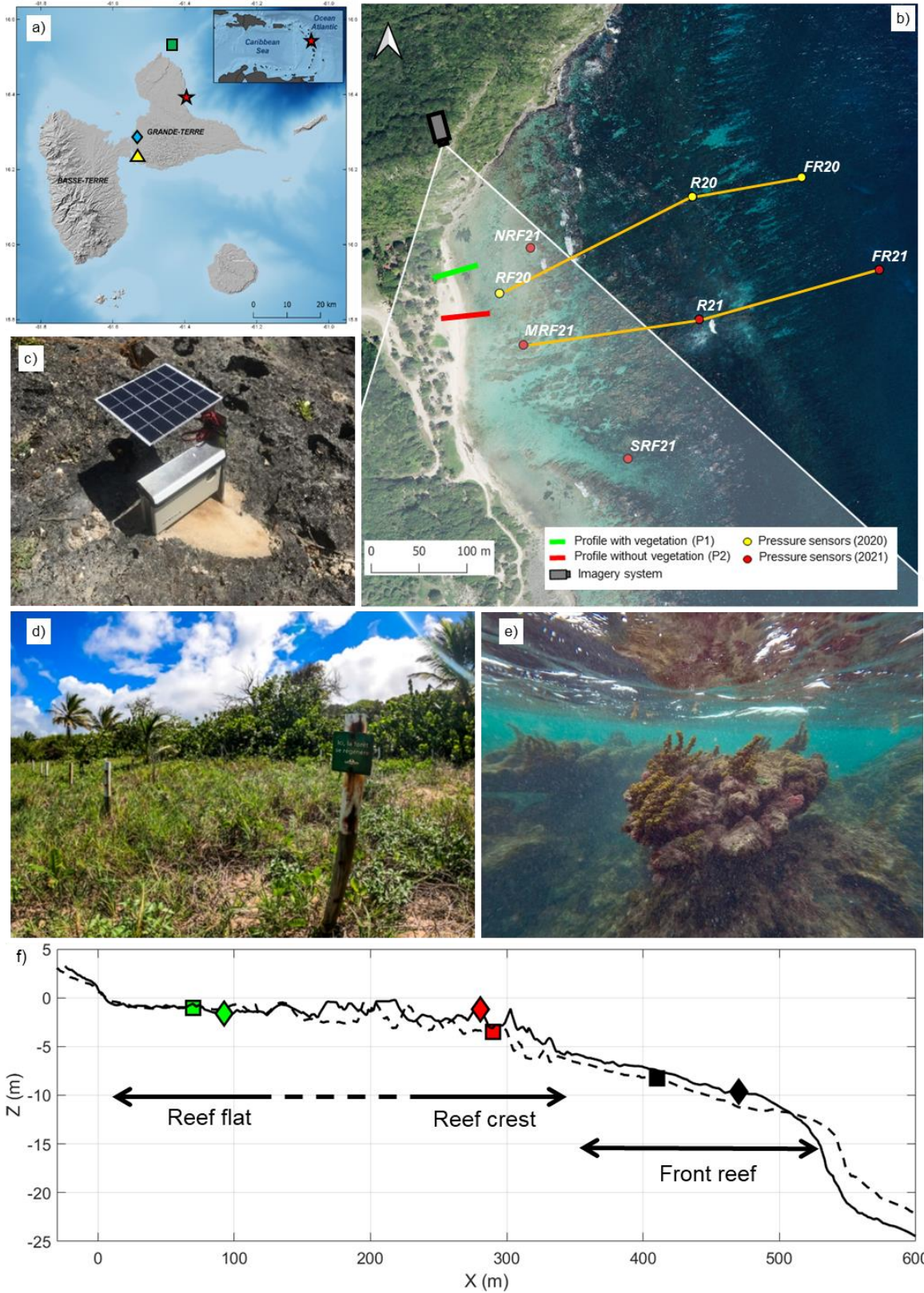
## 130 **2 Study area and methodology**

### 131 **2.1 Study site**

132 Anse Maurice is located in the Guadeloupe Island (France) in the Lesser Antilles (Figure 1 (a)  
133 and (b)). It is a small beach about 200 m long and between 5 and 20 m wide. Shoreline  
134 monitoring indicates a chronic erosion with a net retreat of 20 m on average between 1950 and  
135 2013 (Guillen et al., 2017).

136 The beach is bordered by a fringing reef mainly composed by *Acropora Palmata* dead colonies  
137 covered by algae. However, some complex structures of several meters in height are still  
138 observed (Figure 1 (e)). The reef flat is composed of discontinuous dead coral structures of about  
139 one meter in height and several meters in width as well as small colonies of living branching and  
140 encrusting corals. In the southern part of the site, an eastward channel is identifiable where the  
141 coral structures are sparser and deeper (Figure 1 (b)).

142 The upper beach is covered by heterogeneous patches of vegetation: crawling vegetation mainly  
143 represented by *Ipomoea Pes-Caprae* in the front line and shrubs like *Coccoloba Uvifera* in the  
144 back line (Figure 1 (d)). Several exogenous coconut trees are also present on-site.



145

146 **Figure 1.** (a) Location of Guadeloupe Island in the Caribbean and Anse-Maurice beach (red star)

147 at the East of the Island. Markers indicate the location of main regional datasets: ADCP (green

148 square), meteorological station (blue diamond) and tide gauge (yellow triangle). (b) Anse-  
149 Maurice beach orthophotography with location of instruments. (c) Imagery system installed at  
150 Anse-Maurice. (d) Upperbeach vegetation at the Anse Maurice. (e) Anse Maurice reef crest  
151 showing a dead *Acropora Palmata* colony covered with algae. (f) Instrumented cross-reef  
152 profiles with reef flat (green), reef crest (red) and front reef (black) sensors for 2020 campaign  
153 (dashed line and squares) and 2021 campaign (solid line and diamonds).

154 Beach vegetation at the Anse-Maurice site is very impacted by human activities and particularly  
155 by trampling and goat grazing. Obviously, lower layers of vegetation are the most touched,  
156 which obstruct the development of crawling vegetation and seedlings. Consequently, in the  
157 medium-term, the growth of a new generation of trees is then being hampered and the soil is  
158 more subject to erosion. Therefore, the French Forestry Agency (ONF) had implemented several  
159 revegetation enclosures (<https://www.carib-coast.com/en/news/anse-maurice-actions-carried-out-on-this-pilot-site-of-the-carib-coast-project/>). Those features consist of simple wooden sticks  
160 connected by wire mesh to avoid human trampling and goat grazing which facilitate the recovery  
161 of vegetation. After a few months, the effects are noticeable and a dense vegetation maybe  
162 restored after a few years (Johnston and Ellison, 2014; Ellison, 2018). Even in a deteriorated  
163 state, the role of the reef and upperbeach vegetation on coastal flooding attenuation is expected,  
164 although this has not been locally evaluated.

166 The site is a wave-dominated beach, offshore swells vary greatly with an annual mean of 1.2 m.  
167 It is exposed to strong Atlantic swells with most of the storms occurring during the winter season  
168 from December to March; these swells mainly comes from the North to East-North-East  
169 direction. The site is also subject to cyclonic events from July to November which can generate  
170 the most powerful waves reaching the island. Nevertheless, due to the site exposition, only  
171 swells from North to East direction impact it directly. Besides these two highly energetic wave  
172 regimes, waves generated by the trade winds affect the region all year round with wave heights  
173 ranging from 0.5 to 2 m (Reguero et al., 2013; CEREMA, 2021). The flooding risks are  
174 primarily associated to the occurrence of tropical cyclones (Krien et al., 2015; Rueda et al.,  
175 2017).

176 The area shows a semi-diurnal microtidal range, with diurnal and mixed inequality, a mean  
177 amplitude of 0.25 m and ranging from 0.1 m during neap tides to 0.7 m during spring tides  
178 (SHOM 2020).

179 Seasonal sea-level changes are the combined result of atmospheric pressure variations, wind  
180 effect and steric expansion. Atmospheric pressure annual variations in the Caribbean are the  
181 consequence of Inter Tropical Convergence Zone (ITCZ) displacement, surface winds are  
182 dominated by the Trade winds and steric expansion is due to temperature, salinity and pressure  
183 change of seawater (Torres and Tsimplis, 2012; Chadee and Clarke, 2015). In Guadeloupe Island  
184 in particular, the barometric effect is not significant ( $< 0.01\text{m}$ ) and most annual sea-level  
185 variations are the consequence of steric effects with an amplitude of 0.15 m in Guadeloupe  
186 Island, maximas on October and minimas in April (Torres and Tsimplis, 2012).

## 187 2.2 Field measurements

### 188 2.2.1 Video derived coastal state indicators

189 Video systems are nowadays widely used to evaluate coastal evolution and coastal  
190 hydrodynamics allowing the quantitative acquisition of optical signatures of shoreline position

191 (Holman and Stanley, 2007, Plant et al. 2007, Valentini and Balouin, 2020), nearshore  
192 morphologies (Bergsma and Almar, 2018; Aarninkhof, 2004), wave characteristics (Almar et al.,  
193 2008), surf zone wave-induced current (Rodríguez –Padilla et al., 2021) and wave runup  
194 (Salmon et al., 2007; Valentini et al., 2019). Recently, low-cost webcams are increasingly used  
195 (Andriolo et al., 2019; Paquier et al., 2020; Valentini et al., 2020) and have proven their ability to  
196 acquire reliable data at an affordable price.

197 In this study, two low-cost Solarcam© camera systems were implemented in April 2019 to  
198 monitor coastal evolution (Figure 1 (b) and (c)). Each system comprises an 8 MP resolution  
199 smartphone protected by a waterproof housing, and powered by a solar panel. The whole system  
200 is entirely autonomous as it is programmed to record an image every 10 minutes, and is able to  
201 record short videos (Valentini and Balouin, 2020). This low-cost device showed its applicability  
202 on several purpose (Valentini and Balouin, 2020; Moisan et al., 2021) but it is inadequate to  
203 study nearshore hydrodynamic as it is not able to record videos with sufficient duration and  
204 frequency.

205 A dataset of 2.5 years and 10 months has been analysed in this study. The images from the  
206 cameras were calibrated with ground control points using the Holland et al. (1997) methodology  
207 in order to obtain data in real-world scale. This rectification processing allows the transformation  
208 of U,V image coordinates to X,Y,Z world coordinates and allows the quantitative assessment of  
209 coastal indicators. After rectification, timestacks were generated corresponding to the location of  
210 profiles (Figure 1(b)). A timestack represents the plotted evolution over time of a particular line  
211 of pixels. Morphological markers like the limit between sand and vegetation, or the limit formed  
212 by marine debris are easily identifiable on images and may be monitored overtime with  
213 timestacks. For example, brown patterns located at the limit between sand and water (e.g., the  
214 shoreline) are sargassum algae deposits. Those are effective markers of maximum swash events  
215 on timestacks because they present a clear colorimetric contrast with the sand. During storm  
216 events, this data is useful to identify instantaneous runup position and maximum runup limit at  
217 upperbeach, potentially generating back beach inundation. This limit (Daily Highest Runup  
218 noted DHR) has been identified and extracted on a daily basis. A better precision was obtained  
219 by detecting the swash limit on raw oblique images rather than timestacks because of their rapid  
220 evolution. Vegetation limit evolution is more stable and was directly extracted from timestacks.  
221 To obtain a runup value, the position of the swash limit on profile is correlated with the local  
222 Digital Elevation Model (DEM). The latter is derived from RTK-GPS monitoring for the  
223 topography and from Lidar dataset (SHOM, 2016) for the bathymetry. The DHR elevation is  
224 then expressed in the local reference system (IGN88). For this research, two timestacks will be  
225 used and compared, the first one in a profile with dense upperbeach vegetation (the northern one  
226 on Figure 1 (b), hereafter called P1) and the other in a profile with limited upperbeach vegetation  
227 (hereafter called P2). The mean pixel resolution on each profile is respectively 0.15 m and 0.19  
228 m.

## 229 2.2.2 Hydrodynamic data and instrumentation

230 Offshore wave conditions were extracted from the mesoscale MARC model outputs available  
231 online. MARC is a reanalysis of the WAVEWATCH III® model at a regional scale; simulation  
232 results are provided by the IFREMER and available in real time (<http://umr-lops.org/marc>).  
233 Wave parameters (significant wave height  $H_s$ , peak period  $T_p$  and direction at the peak  $D_p$ ) were  
234 extracted at the location of Acoustic Doppler Current Profiler (ADCP) sensor for validation of  
235 MARC model outputs (Figure 1 (a)). The ADCP (©Nortek Aquapro) was installed at 50 m depth



236 to measure offshore waves from September to December 2020 (Figure 1 (a)). Beside a strong  
 237 correlation the ADCP measurements and the MARC model ( $R^2 = 0.90$ ), an observed difference  
 238 depending on the wave conditions exist (a greater variance was observed on extreme wave  
 239 conditions). This observation on offshore waves conditions is commonly made when comparing  
 240 instrumental data and models (e.g. Castelle et al., 2015). It was decided to apply a correction  
 241 method on the distribution of wave conditions and thus, a quantile by quantile correction had  
 242 been applied (Charles et al., 2012). The overall correlation slightly increase after the correction  
 243 ( $R^2 = 0.92$ ).

244 Furthermore, the method used by Masselink et al., 2016 was applied to detect and isolate storms.  
 245 On the  $H_s$  dataset, the percentile 95%  $H_{s, 95\%}$  (here 2.3 m) was extracted and identified as storm  
 246 peaks. The upcrossing and downcrossing on the 75% percentile defines the beginning and end of  
 247 storms (here 1.84 m).

248 In order to compare the DHR obtained from the video system, daily maximum wave parameters  
 249 were extracted from corrected MARC model outputs. Actually, the daily  $H_s$  maximum value was  
 250 extracted as well as  $T_p$  and  $D_p$  at the time of maximum wave height. A daily value of sea level  
 251 from Pointe-à-Pitre tide gauge (Figure 1(a)) was extracted following the same methodology.  
 252 Data from the tide gauge are provided by the French Hydrographic Service (SHOM) and  
 253 available on the REFMAR database ([www.http://data.shom.fr](http://data.shom.fr)).

254 Two campaigns of hydrodynamic measurements were organized during the North Atlantic  
 255 cyclonic season of 2020 and 2021. Sensor positions for both campaigns have been chosen  
 256 according to reef characteristics so they can be compared by the relative cross-shore position on  
 257 the reef. The former started on September 30<sup>th</sup> and lasted until October 29<sup>th</sup> 2020 (30 days).

258 Three Wisens Wave pressure sensors (NKE instrument©) were installed along a cross-shore  
 259 profile (see Figure 1 (b)): the first one on the front reef, the second one on the reef crest and the  
 260 last one in the reef flat. The second campaign started on August 26<sup>th</sup> and lasted until October 01<sup>st</sup>  
 261 2021 (31 days). Five pressure sensors were installed: three on a cross-shore profile as for the first  
 262 campaign and two on both sides of the transect in the reef flat in order to evaluate the effect of  
 263 reef longshore variability on wave transformation. Thus, one was placed at the North of the reef  
 264 flat in a shallow and sheltered area close to 2020 reef flat sensor position and the second at the  
 265 South of the reef flat in front of a clear depression of the reef.

266 For both campaigns, pressure sensors and the ADCP were set up to record bursts of 2048  
 267 readings at a sampling frequency of 2 Hz (~17 minutes duration) every hour. Table 1 details the  
 268 sensors setup. Firstly, the effect of atmospheric pressure on raw pressure records were removed  
 269 with the help of 3 hourly data from MeteoFrance station at le Raizet Airport at approximately 20  
 270 km of the site. From filtered datasets one-dimensional frequency spectra  $S(f)$  was then estimated  
 271 with the help of a Welch's averaged periodogram method with windows of half burst length and  
 272 50% overlapping. Then, for each burst and for SW, IG and VLF frequency band, several  
 273 statistical parameters were extracted. Cutoff frequencies were chosen in agreement with previous  
 274 works with SW:  $0.2 > \text{frequency} > 0.04$  Hz, IG:  $0.004 < \text{frequency} > 0.04$  Hz and VLF:  
 275  $\text{frequency} < 0.004$  Hz (e.g. Péquignet et al., 2009; Cheriton et al., 2016 and 2020; Quataert et al.,  
 276 2020). Root-mean-squared wave height ( $H_{rms}$ ) which can be described as:

$$277 \quad H_{rms} = \sqrt{8 \int_{f2}^{f1} S(f) df}$$

278 With  $f1$  and  $f2$  the lower and upper frequency limits. The peak period  $T_p$  value for each band  
 279 represents the peak  $1/f_p$  with  $f_p$  the frequency of the peak of energy. The  $H_{rms}$  transmission

280 coefficient between the front reef and the reef flat was also calculated on each frequency band. It  
 281 represent the ratio of  $H_{rms}$  measured by the sensors in the reef flat (transmitted) and  $H_{rms}$   
 282 measured by the sensors on the front reef (incident) (Lugo-Fernández et al., 1998; Costa et al.,  
 283 2016; Escudero et al., 2020). The transmission is then in percentage, values inferior to 100%  
 284 reflect an attenuation between the front reef and the reef flat and values above 100% reflect an  
 285 amplification.

286  
 287 The setup in the reef flat was also extracted from measurements and calculated following Vetter  
 288 et al., 2010 methods as:

$$\eta = h_{rf} - h_{fr} - (bt + c)$$

289  
 290 With  $\eta$  the wave-induced setup in the reef flat,  $h_{rf}$  and  $h_{fr}$  respectively the burst-averaged water  
 291 levels for the reef flat and the front reef sensor.  $b$  and  $c$  are empirically chosen and used to  
 292 account for drifts from pressure transducers over time and offset respectively.

293 A set of statistical analysis was performed to identify and quantify the dependency between  
 294 variables. Squared Pearson coefficient was calculating when comparing two linear random  
 295 variables with linear distribution (such as  $H_{rms}$ ,  $T_p$ , sea level) defined in Fisher (1958) as:

$$296 \quad R^2(A, B) = \left( \frac{1}{N-1} \sum_{i=1}^N \left( \frac{A_i - \mu_A}{\sigma_A} \right) \left( \frac{B_i - \mu_B}{\sigma_B} \right) \right)^2$$

297 With  $A$  and  $B$  the variables,  $N$  the number of observations,  $\mu_A$  the mean of  $A$  and  $\mu_B$  the mean of  
 298  $B$ ,  $\sigma_A$  as the standard deviation of  $A$ , and  $\sigma_B$  the standard deviation of  $B$ .

299 In order to compare a linear random variable with a circular random variable (such as  $D_p$ ) a  
 300 circular-linear correlation was performed as defined in Mardia and Jupp (2000) as:

$$301 \quad R^2(A, \theta) = \frac{r_{Ac\theta}^2 + r_{As\theta}^2 - 2r_{Ac\theta}r_{As\theta}r_{cs\theta}}{1 - r_{c\theta s\theta}^2}$$

302 With

$$303 \quad r_{Ac\theta} = \text{corr}(A, \cos \theta)$$

$$304 \quad r_{As\theta} = \text{corr}(A, \sin \theta)$$

$$305 \quad r_{c\theta s\theta} = \text{corr}(\sin \theta, \cos \theta)$$

306  $A$  and  $\theta$  are respectively the linear random variable and the circular random variable.

307 Both coefficients (Pearson and Circular-linear) range between 0 and 1, the association between  
 308 variable is stronger with greater values. In this study correlations above 0.2 were considered as  
 309 significant and correlations above 0.6 as strong.

Sensor name	Deployment period	Active duration (days)	Frequency		Relative distance to reef crest (m)	
			Burst sampling	Depth (m)		
FR20	Sept-Oct 2020	31	1 burst/ hour	2	6	-170
R20	Sept-Oct 2020	31	1 burst/ hour	2	3,65	-60
RF20	Sept-Oct 2020	31	1 burst/ hour	2	1,5	170
FR21	Aug-Sept 2020	37	1 burst/ hour	2	8,9	-200
R21	Aug-Sept 2020	37	1 burst/ hour	2	2,7	0
RF21	Aug-Sept 2020	37	1 burst/ hour	2	1	175
NRF21	Aug-Sept 2020	35	1 burst/ hour	2	1	150
SRF21	Aug-Sept 2020	36	1 burst/ hour	2	2,6	115

**Table 1.** Sensors setup during field campaigns. Sensors names correspond to the position over the reef and the year (FR: front reef, R: reef crest, RF: reef flat, NRF: north reef flat and SRF: south reef flat).

### 3. Results

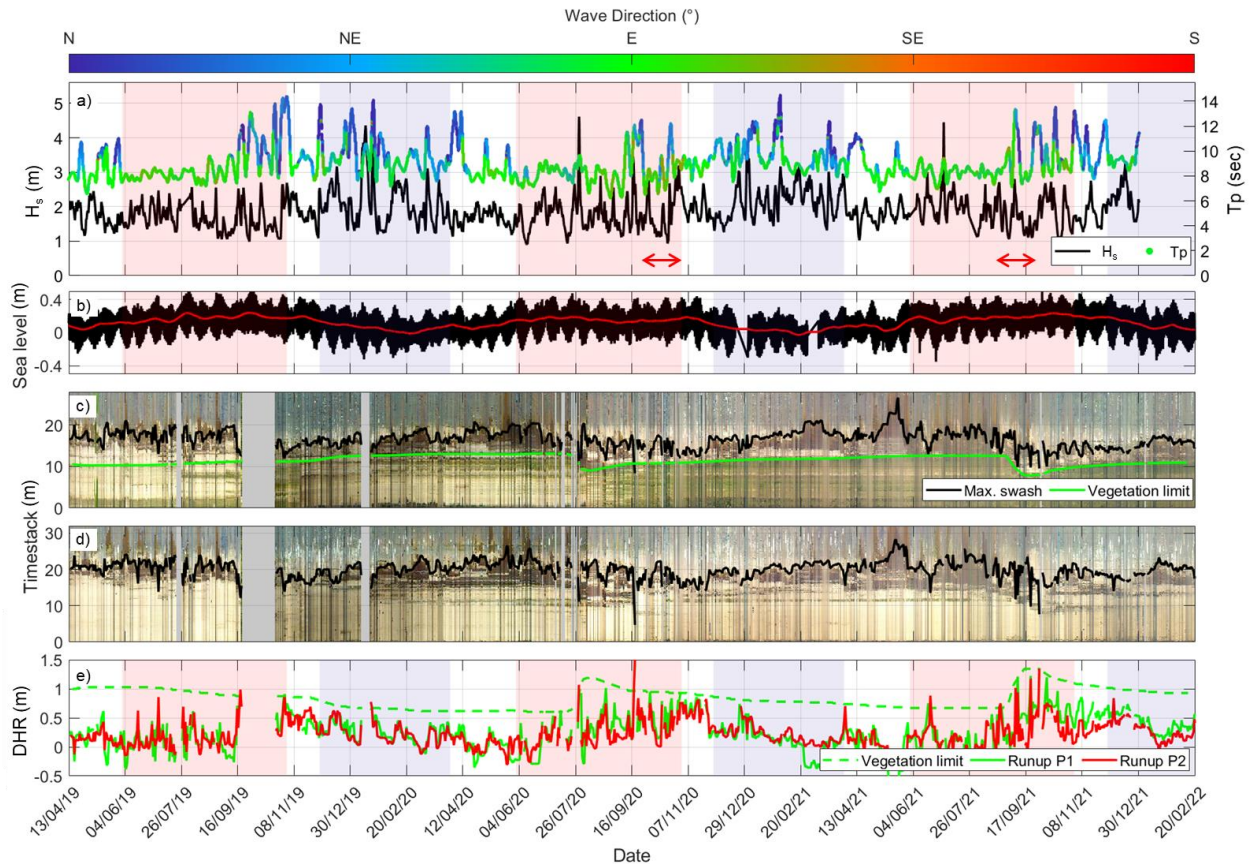
#### 3.1 Mid/long-term observations

Figure 2 presents observations over 1045 days. During this period, on corrected MARC model dataset, offshore  $H_s$  exceeded 3 m for 16 times, with three of these events over 4 m. The first was a winter storm with a peak on January 10<sup>th</sup> 2020 and the two others were cyclonic events peaking on July 20<sup>th</sup> 2020 and on September 20<sup>th</sup> 2020 related to Hurricane Teddy circulating at 800 km to the East of Guadeloupe Island (NHC, 2021). Waves generated by cyclonic events are easily identifiable because their direction evolves quickly (generally from East or South-East to North) and those are the only strong swells from the East direction. Winter events are strictly from the North or North-East and show the greater wave periods as those are mostly generated in North Atlantic mid-latitudes.

Figure 2 (c) and (d) present timestacks over the same period at two cross-shore locations represented by red lines on Figure 1 (b). As it is mentioned in Section 2.2.1, the northern timestack is located in an area with dense upperbeach vegetation mostly comprising of *Ipomoea Pes-Caprae*. The southern timestack is in an area where upperbeach vegetation is less developed and located more landward as a consequence of human trampling. Vegetation limit and maximum swash excursion are plotted. The influence of tide cycles is noticeable on the shoreline during calm period as for example on the first quarter of both stacks. The vegetation, only present on the northern timestack in Figure 2 (c), shows an evolution in vegetation density, materialized by variations from green color to yellowish behind the vegetation limit. The vegetation limit on the coastal border (plotted in green on Figure 2 (c)) shows slow growth periods interrupted by abrupt retreat in concomitance with extreme storm events. Two remarkable moves appear with net retreats of 3 and 4 m. The first one correspond to the event 8 and the second to event 15 on Table 2.

Seven major swash excursions events are easily identified on the timestacks: corresponding to events 1, 2, 7, 8, 13, 15, 16 and 17 on Table 2. The event number 8 (September 17<sup>h</sup> 2020) is the most extreme with maximum swash excursion of 12 m inland, and corresponding to runup exceeding 1.5 m, this event corresponds to the passage of Teddy Hurricane offshore Guadeloupe Island. All high runup events occurred during the cyclonic season and storms occurring during

343 winter and even the most extreme ones as the event number 4 in January 2020 seems to have not  
 344 generated major swash excursion.  
 345 Runup elevation (figure 2 (e)) has the same mean value for both vegetated and unvegetated  
 346 profiles. However, the profile with vegetation has a maximum runup of 1.42 m when the profile  
 347 without vegetation has a maximum of 1.54 m, thus an exceedance of 0.12 m when vegetation is  
 348 absent.



349  
 350 **Figure 2.** Camera derived observations and incident wave and sea-level conditions from April  
 351 2019 to May 2021. (a) Offshore significant wave height ( $H_s$ ) and peak period ( $T_p$ ) with  
 352 associated, wave mean direction ( $D_p$ ) is represented by the color of  $T_p$  points. Red arrows  
 353 represent period of local hydrodynamic measurements campaign on site. (B) Sea-level variations  
 354 on Pointe-à-Pitre tide gauge, 14 days moving mean is represented in red. (c) and (d) daily  
 355 timestacks with detection of maximum swash limit (red line) and vegetation limit (green line) on  
 356 P1 and P2 respectively. (e) Evolution of the DHR on both profile and vegetation limit height on  
 357 P1. On every plots but timestacks winter are indicated by a blue background and cyclonic  
 358 seasons by a red background.

359

Event id	Peak Date	Season	Hs (m)	Tp (sec)	Dp (°)	DHR (m)		Vegetation
						P1	P2	retreat (m)
1	17/09/2019	Cyclonic	2.5	12	15	0.7	0.7	-
2	29/10/2019	Cyclonic	2.6	14.6	40	0.9	0.9	-
3	17/12/2019	Winter	3.2	9.4	77	0.4	0.4	-
4	16/01/2020	Winter	4.4	10.8	54	0.7	0.8	-
5	08/02/2020	Winter	3.2	9.1	80	0.2	0.2	-
6	10/03/2020	Winter	3.1	13.7	354	0.1	0.1	-
7	29/07/2020	Cyclonic	4.6	11.1	76	1.0	1.1	-
8	17/09/2020	Cyclonic	3.4	10.8	110	1.4	1.5	3
9	29/10/2020	Cyclonic	3.1	9.3	78	0.8	0.8	-
10	01/01/2021	Winter	3.6	14.1	38	0.5	0.5	-
11	18/02/2021	Winter	3.2	9.3	76	0.1	0.1	-
12	18/03/2021	Winter	3	13.9	355	0.2	0.2	-
13	17/06/2021	Cyclonic	3	8.7	82	0.9	0.7	-
14	02/07/2021	Cyclonic	4.5	11.1	105	nd	nd	-
15	07/09/2021	Cyclonic	2.8	13.6	88	0.9	1.2	4
16	20/09/2021	Cyclonic	2.7	7.9	100	1.2	1.2	-
17	28/09/2021	Cyclonic	2.6	9.2	115	1.3	1.3	-
18	18/12/2021	Winter	3.3	9.8	61	0.6	0.5	-

360

361

**Table 2.** Storms observed during the study period. nd: no data.

362

363

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365

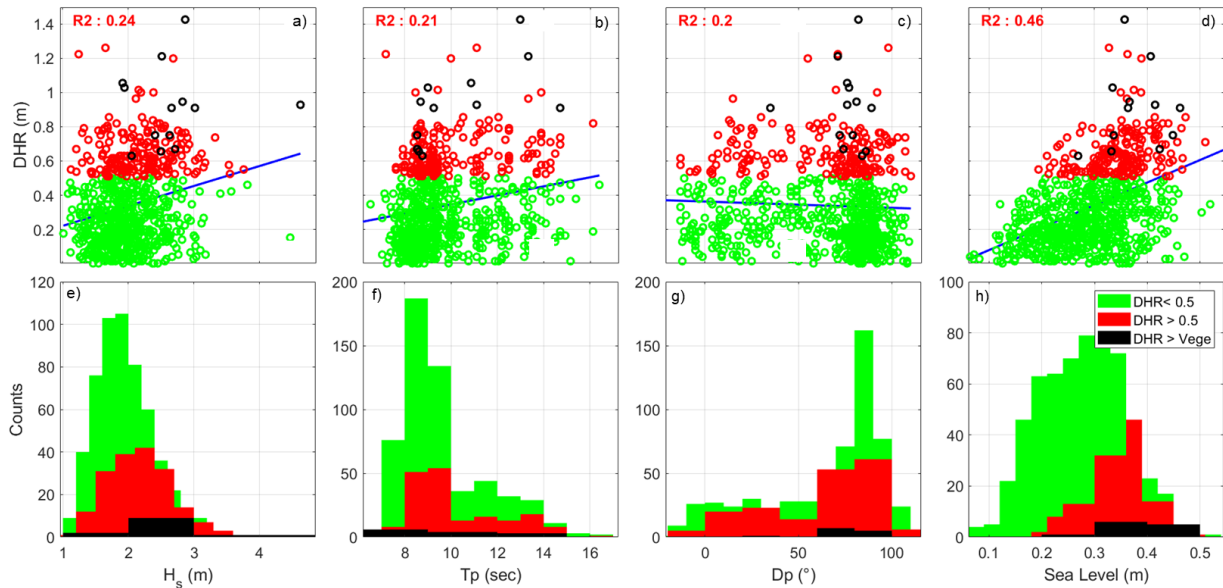
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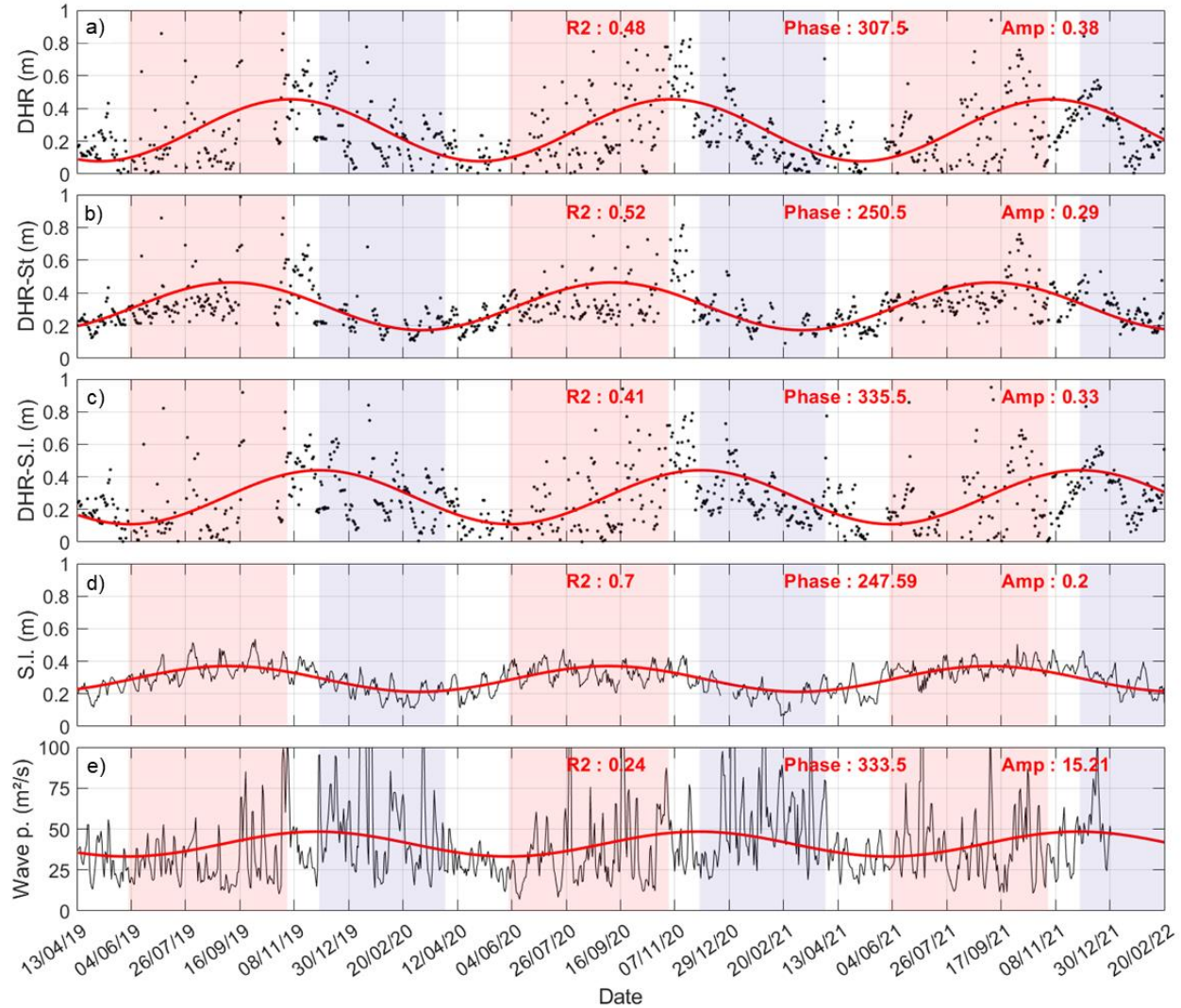
In order to evaluate the relation between offshore conditions and local DHR a set of linear regressions was performed. The mean value of runup (0.5 m) and the elevation of vegetation limit (evolving from 0.6 to 1.1 m) are used to classify runup intensities. Figure 3 shows the linear correlation between the DHR extracted from cameras and offshore hydrodynamic parameters. Figure 3 (a), (b) and (c) represent offshore wave parameters from corrected MARC model (respectively Hs, Tp, and Dp) and Figure 3 (d) represent the correlation with the sea level measured at Pointe à Pitre tide gauge. Correlations with offshore wave conditions are weak with  $R^2 < 0.3$ , while correlation with the sea level is moderate  $R^2 = 0.46$ .



370

371 **Figure 3.** Linear regressions of DHR and (a)  $H_s$ , (b)  $T_p$ , (c)  $D_p$  and (d) sea level. (e), (f), (g) and  
 372 (h) respective distribution histograms. Observations for runup less than 0.5 m are plotted in  
 373 green, for runup greater than 0.5 m are plotted in red and runup exceeding the vegetation limit  
 374 are plotted in black.

375 As the DHR dataset showed a great seasonal variability, a sinusoidal fitting was applied in order  
 376 to highlight the annual cyclicality. The amplitude of the annual cycle (365.25 days/cycle) is  
 377 estimated at 0.38 m, with a phase peak at day 307.5 (November 5<sup>th</sup>) with an  $R^2$  of 0.48 with raw  
 378 data, it represents 24% of the overall runup amplitude. In order to isolate the effect of sea level,  
 379 storm periods were removed from the timeseries of DHR to suppress the effect of storm surges  
 380 and unusual waves (see figure 4 (b)). Some extreme runup events remain visible in particular  
 381 around September 17<sup>th</sup> 2021. This may be due to an underestimation of waves by corrected  
 382 MARC Model, as the agitation is qualitatively validated by camera observations. The storm-  
 383 filtered annual signal has a phase peak at day 250.5, an amplitude of 0.29 m and a  $R^2$  of 0.52  
 384 with the storm filtered runup signal, thus very close to sea level annual component (phase peak at  
 385 day 247.6 and amplitude of 0.2 m (Figure 4.(d)). Furthermore, when the annual sea level cycle is  
 386 removed from the times series of the raw DHR, we obtained a runup signal that still shows an  
 387 annual cyclicality with a phase of 335.5 days and 0.33 m amplitude. Figure 4 (e) presents the  
 388 evolution and annual cyclicality of wave power ( $H_{rms}^2 * T_p$ ) in  $m^2/s$ . The signal obtained fluctuates  
 389 greatly and is very chaotic. The calculated annual periodicity shows bad skills with raw data ( $R^2$   
 390 = 0.24) suggesting a better correlation with another periodicity. Nevertheless, the phase is 333.5  
 391 days, which is very close to the sea level filtered runup signal.



392

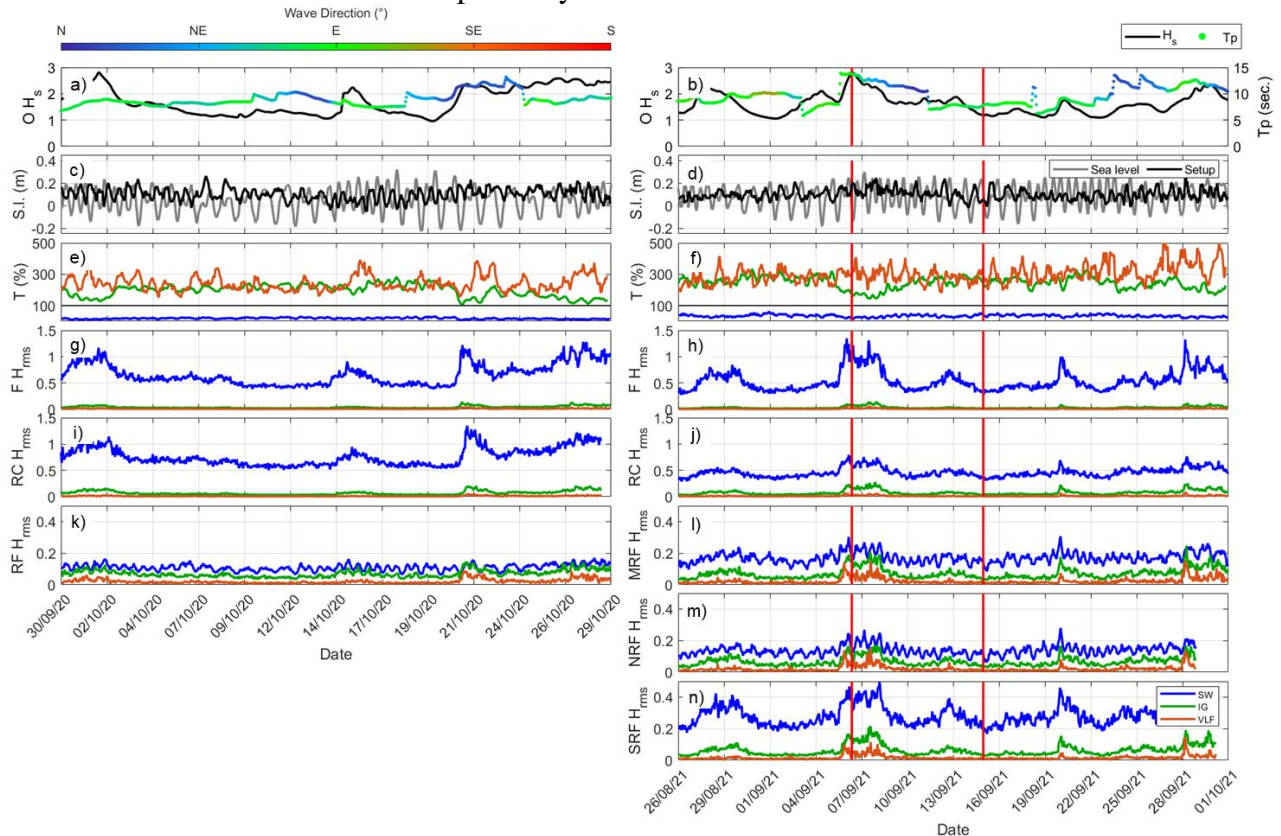
393 **Figure 4.** (a) Raw DHR observed on camera, (b) DHR with removal of storms periods, (c) DHR  
 394 with removal of sea level annual periodicity, (d) Sea level with tide effect subtracted, (e) Wave  
 395 power. Runup observations are plotted in black points, sea level and wave power in black line  
 396 and annual periodicity in red line.

397 These results indicate that the DHR signal presents a strong annual seasonality. When main  
 398 storms period is removed from the signal, the periodicity calculated on the residual is in phase  
 399 with the effect of sea level annual variability, suggesting a strong modulation of runup by sea  
 400 level annual seasonality. At the opposite, when this sea level variability is removed from raw  
 401 runup, a good correlation between the residual annual periodicity and swell annual periodicity  
 402 appears which may indicate a swell modulation as well on the runup. This double dependency of  
 403 sea level and wave climate annual cyclicity on runup induces a periodicity to the runup with a  
 404 specific phase.

#### 405 2.4 Mid/short-term observations

406 The data from onsite measurements were used to identify processes involved in nearshore  
 407 hydrodynamic transformation by the reef. Figure 5 presents the hydrodynamic times series

408 during both campaigns including offshore conditions from corrected MARC model, sea level  
 409 from Pointe à Pitre tide gauge. The 2020 campaign shows three energetic periods (offshore  $H_s > 2$   
 410 m), for more information see events A, B and C on Table 3. Maximum offshore  $H_s$  reached 2.9  
 411 m on October 01<sup>st</sup> (event A) according to corrected MARC model outputs. The 2021 campaign  
 412 shows 4 events above 2 m, events D, E, F, and G on Table 3. The maximum  $H_s$  is reached on  
 413 September 07<sup>th</sup> (event F) with a value of 2.8 m. All these events remained moderate in terms of  
 414 intensity and are related to cyclonic activity in the Atlantic basin relatively far from the study  
 415 site. It is visible from the measurements in the reef flat that spectral transformation inshore is not  
 416 constant over time. Indeed, periods of agitation show greater proportion of IG and VLF in the  
 417 reef flat than during calm periods. A clear tidal modulation is also visible on SW band in the reef  
 418 flat with greater values during high tides. On the 2021 campaign, the sensor at the North of the  
 419 reef flat (NRF21, on Figure 1 (b)) shows slightly lower agitation but with the same dispersion  
 420 than the reef flat sensor on the transect (RF21, on Figure 1 (b)). At the opposite, the sensor at the  
 421 south of the reef flat (SRF21, on Figure 1 (b)) shows values close to the reef crest sensor. Thus,  
 422 tidal modulation on SW is not visible and overall agitation is higher. Regarding  $H_{rms}$   
 423 transmission, percentages between the front reef and the reef flat (Figure 5 (e) and (f)) SW band  
 424 wave height is always highly dissipated with transmission ranging from 10 to 60 %, on the other  
 425 hand, SW and VLF band wave height are amplified at all time with transmission ranging from  
 426 115 to 300 % and 195 to 420 % respectively.



427  
 428 **Figure 5.** Left Column corresponds to hydrodynamic conditions for the 2020 campaign and right  
 429 column corresponds to hydrodynamic conditions for 2021 campaign. (a-b) Offshore  $H_s$  , (c-d)  
 430 sea level measured at Pointe-à-Pitre tide gauge setup from sensors, (e-f)  $H_{rms}$  transmission  
 431 percentage according to spectral bands between the front reef and the reef flat , the horizontal



432 line is set at 100 % and represents a strict conservation of  $H_{rms}$ .  $H_{rms}$  chronic specifying SW  
 433 (blue), IG (green) and VLF (orange) band for (g-h) front reef , (i-j) reef crest and (k-l) reef flat.  
 434  $H_{rms}$  evolution for sensors (m) at the North (n) at the South of the reef flat.

Event id	Peak Date	Hs (m)	Tp (sec)	Dp (°)	DHR (m)	
					P1	P2
A	01/10/2020	3.0	9.5	80	0.9	0.9
B	15/10/2020	2.1	7.5	90	0.6	0.7
C	29/10/2020	2.6	8.2	75	0.8	0.8
D	28/08/2021	2.2	9.0	95	0.2	0.3
E	07/09/2021	2.8	14.3	90	0.8	0.8
F	21/09/2021	1.9	9.6	90	1.2	1.0
G	28/09/2021	2.2	12.0	60	1.1	1.2

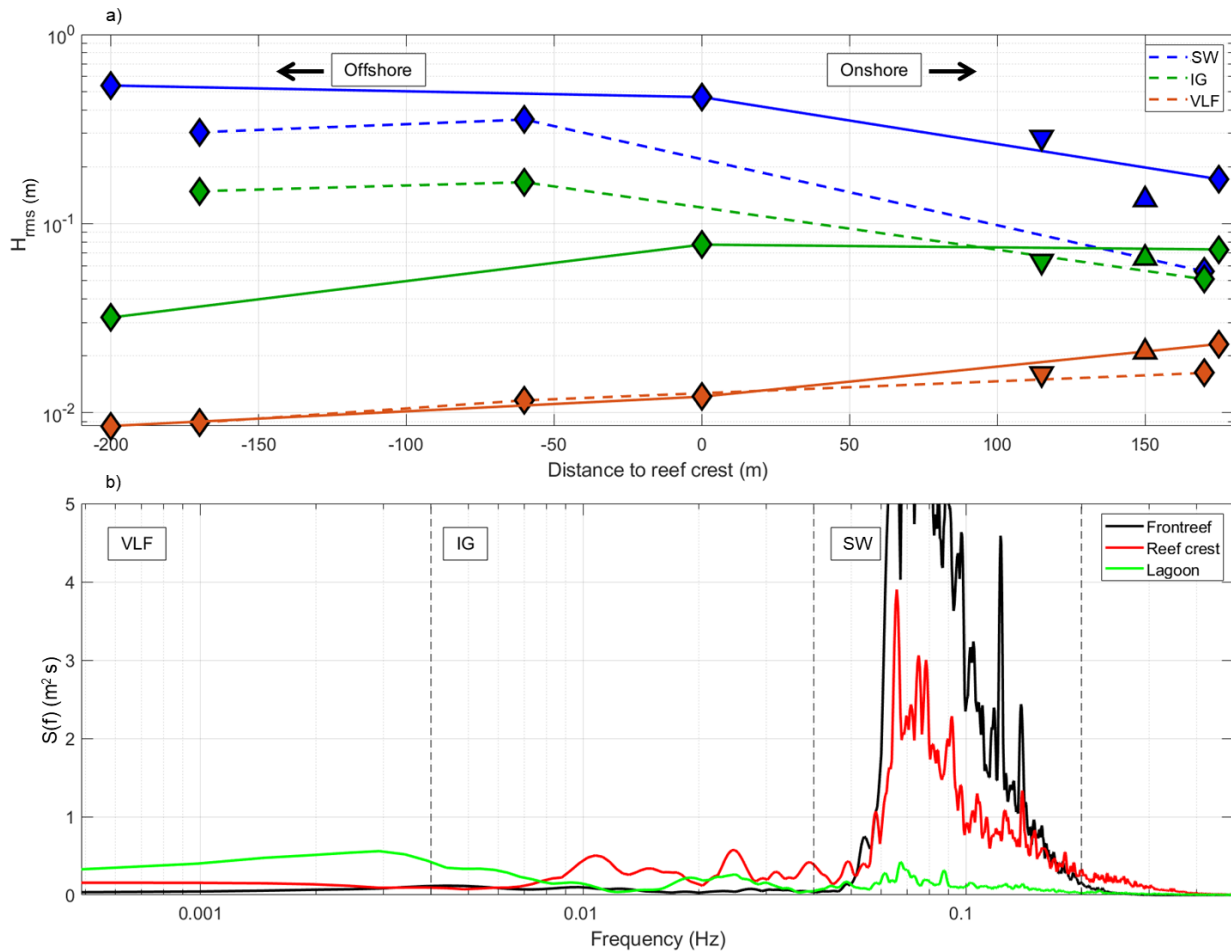
435

436 **Table 3.** Most agitated periods of 2020 and 2021 measurements campaigns

437 Figure 6.(a) presents mean  $H_{rms}$  value for each sensor. Sensors corresponding to a cross-shore  
 438 transect are bounded by a line as on Figure 1. This figure gives an overview of  $H_{rms}$  evolution  
 439 from the front reef to the reef flat compiling all sensors showing the specific behavior of each  
 440 kind of waves while propagating onshore. A clear attenuation of SW band appears when  
 441 comparing front reef and reef flat sensors. The sensor near reef crest for the 2020 campaign  
 442 shows greater values than offshore which could be due to the wave shoaling occurring at this  
 443 position. The reef crest sensor of 2021 campaign was positioned inshore, probably preventing to  
 444 observe this amplification. IG band shows a maximum at reef crest position and then an  
 445 attenuation in the reef flat and VLF band shows a progressive amplification from offshore to the  
 446 reef flat. Comparing to the sensor in the reef flat on the cross-shore transect, sensors located on

447 either side of the reef flat show higher SW band mean  $H_{rms}$  but lower IG and VLF band  $H_{rms}$  for  
 448 the southern sensor and lower mean  $H_{rms}$  values on all frequency bands for the northern sensor.

449 Figure 6.(b) presents the mean spectra for the three sensors on the cross-shore profile of the  
 450 2021 campaign. The progressive attenuation of energy in the sea-swell band is noticeable as well  
 451 as the amplification to the lower bands.



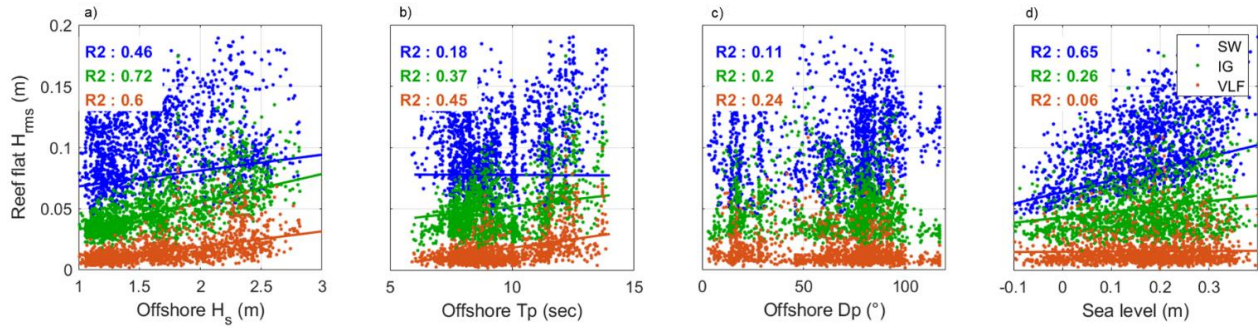
452

453 **Figure 6.** (a) Mean  $H_{rms}$  by sensor for the two campaigns. Sensors located on the same cross-  
 454 shore transect are plotted with diamonds and linked by a line. Dotted line corresponds to 2020  
 455 campaign and solid line to 2021 campaign. Sensors disposed at the North and South of the reef  
 456 flat for the 221 campaign are plotted with an upward triangle and a downward triangle  
 457 respectively. SW band observations are plotted in blue, IG band in green and VLF band in  
 458 brown. (b) Maximum wave spectrum for 2021 campaign. In order to facilitate observations on  
 459 low frequency band, the Y-axis is in logarithmic scale.

460 The set of regressions performed on figure 7 compare incident conditions with hydrodynamic in  
 461 the reef flat. Thus, it highlights relationships between offshore hydrodynamic (wave and sea-  
 462 level variations) and reef-induced nearshore wave transformation.

463 The  $R^2$  corresponds to the squared Pearson coefficient for all comparisons excepting those with  
 464  $D_p$  where the circular-linear correlation is applied. The correlation between SW band  $H_{rms}$  and  
 465 offshore  $H_s$  is moderate in the reef flat ( $R^2 = 0.46$ ) and strong for lower frequencies bands ( $R^2 =$

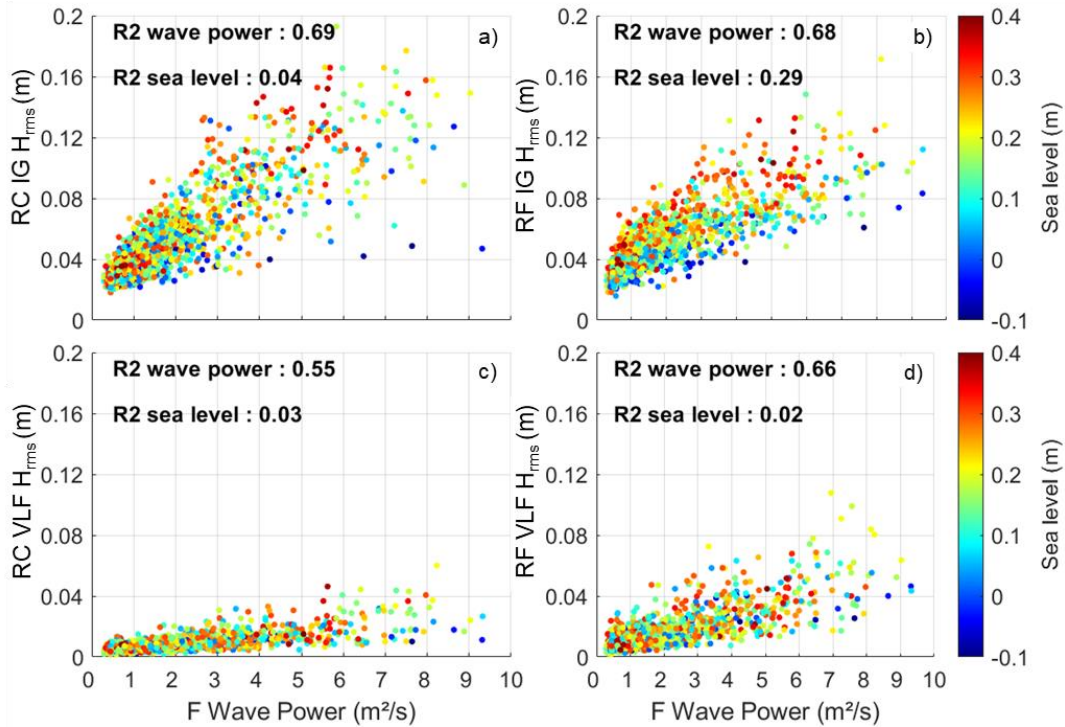
466 0.72 and 0.6 for IG and VLF respectively). Furthermore, correlations between sea level and  $H_{rms}$   
 467 in the reef flat show significant correlation for SW band primary but also for IG band but to a  
 468 lower extent ( $R^2 = 0.65$  and  $0.26$  respectively). VLF band  $H_{rms}$  seems correlated with offshore  
 469  $H_{rms}$  and  $T_p$ . The correlation with offshore  $D_p$  and  $H_{rms}$  remain relatively weak on each band  
 470 with  $R^2$  values ranging from 0.11 to 0.24.  
 471



472

473 **Figure 7.** Linear regressions of  $H_{rms}$  measured at the reef flat against offshore wave parameters  
 474 (a)  $H_s$ , (b)  $T_p$  and (c)  $D_p$  and (d) sea level measured at Pointe-à-Pitre tide gauge. This figure  
 475 combines 2020 and 2021 hydrodynamic measurements.

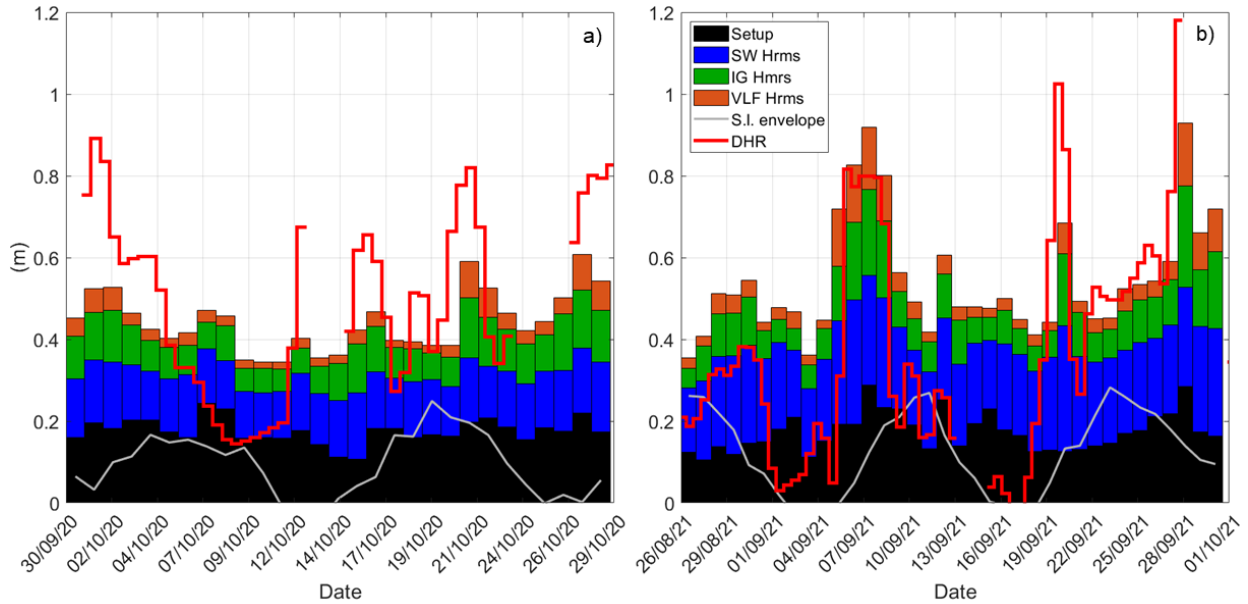
476 Adequate conditions for low frequency development was further analyzed. IG and VLF wave  
 477 heights on the reef crest and in the reef flat were compared to concomitant front reef wave  
 478 conditions expressed here by wave power ( $H_{rms}^2 * T_p$ ) in  $m^2/s$  as in Sous et al., (2019) (Figure  
 479 8). Overall, a strong correlation between front reef wave power and  $H_{rms}$  is identified with better  
 480 skills on low frequency waves  $H_{rms}$  ( $R^2$  ranging from 0.55 to 0.69) and in particular on the IG  
 481 band. The correlation in the latter remains constant through the reef while for the VLF the  
 482 correlation is greater in the reef flat ( $R^2 = 0.66$  in the reef flat against 0.55 on the reef crest). We  
 483 note a significant correlation between IG band  $H_{rms}$  in the reef flat and sea level ( $R^2 = 0.29$ ), such  
 484 correlation is not observed on the reef crest.  
 485



486

487 **Figure 8.** Front reef (“F”) wave power against IG band  $H_{rms}$  (upper row) and VLF band  $H_{rms}$   
 488 (lower row) on the reef crest (“R”, left column) and in the reef flat (“RF”, right column). The  
 489 color represents sea-level variations.

490 In order to identify the relative implication of different components of the agitation in the reef  
 491 flat on the runup, observations in the reef flat were associated with DHR extracted from cameras  
 492 for 2020 and 2021 campaign (Figure 9). The higher magnitude events observed on figure 8  
 493 appears clearly on the runup time series. Periods of particularly low runup are also identified  
 494 from September 07th to 11th 2020, from August 31th to September 5th and from September 11th  
 495 to September 18<sup>th</sup> 2021 and appears uncorrelated from local agitation. A visual check on images  
 496 indicates that those periods correspond to massive sargassum arrivals, which tends to disappear  
 497 from the reef system when the agitation gets greater. Excluding sargassum beaching periods,  
 498 DHR seems strongly correlated with agitation in the reef flat; the visual correlation is particularly  
 499 marked on 2021 campaign.

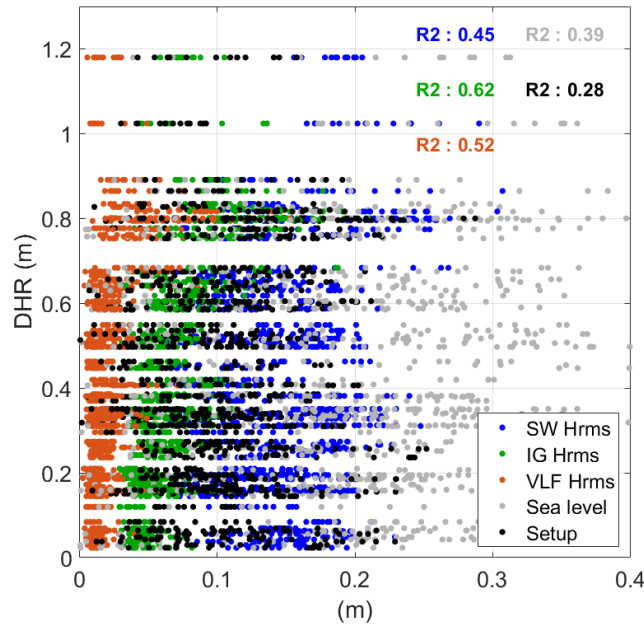


500

501 **Figure 9.** Hydrodynamic measurements in the reef flat (a) 2020, (b) 2021 represented by stacked  
 502 bar plot with setup in black, SW band  $H_{rms}$  in blue, IG band  $H_{rms}$  in green and VLF band  $H_{rms}$  in  
 503 brown. Sea-level envelope is plotted in gray and DHR from the camera in red.

504 A new set of regressions was performed in order to quantify observations from Figure 9 coupling  
 505 DHR and hydrodynamics in the reef flat. As an unique value per day is extracted for runup, it  
 506 would be inadequate to compare here runup with sea level signal including tidal semi-diurnal  
 507 variations. Therefore, the daily envelope was extracted and used for the regression. Figure 9  
 508 presents the result from the linear regressions.

509 A significant agreement with  $H_{rms}$  on every frequency band is identified with better results on  
 510 lower frequency band ( $R^2 = 0.62$  and  $0.52$  for IG and VLF band) than on SW band ( $R^2 = 0.45$ ).  
 511 Correlation with sea-level envelope is lower ( $R^2 = 0.39$ ) and the correlation with setup is the  
 512 lowest ( $R^2 = 0.28$ ).



513

514 **Figure 10.** Linear regression of SW band  $H_{rms}$ , IG band  $H_{rms}$ , VLF band  $H_{rms}$ , sea-level envelope  
 515 and setup from measurements in the reef flat position for 2020 and 2021 campaigns against DHR  
 516 from cameras.

517 Results from field measurements show a high correlation of offshore overall agitation with IG  
 518 and VLF intensity. When comparing processes measured in the reef flat with DHR from camera  
 519 observations, a strong correlation with lower frequency bands is noted. The difference in  
 520 sampling frequency between runup from the camera and on-site hydrodynamic measurements  
 521 limits the comparison at a finer scale.

522 IG and VLF development is highly dependent of the incident wave power in particular for IG  
 523 band. The attenuation visible in the reef flat suggests a dissipation on the reef crest and an  
 524 attenuation on the reef flat modulated by sea level. VLF components are well correlated to front  
 525 reef wave, which may indicate a development in the reef flat from SW, or IG band waves.

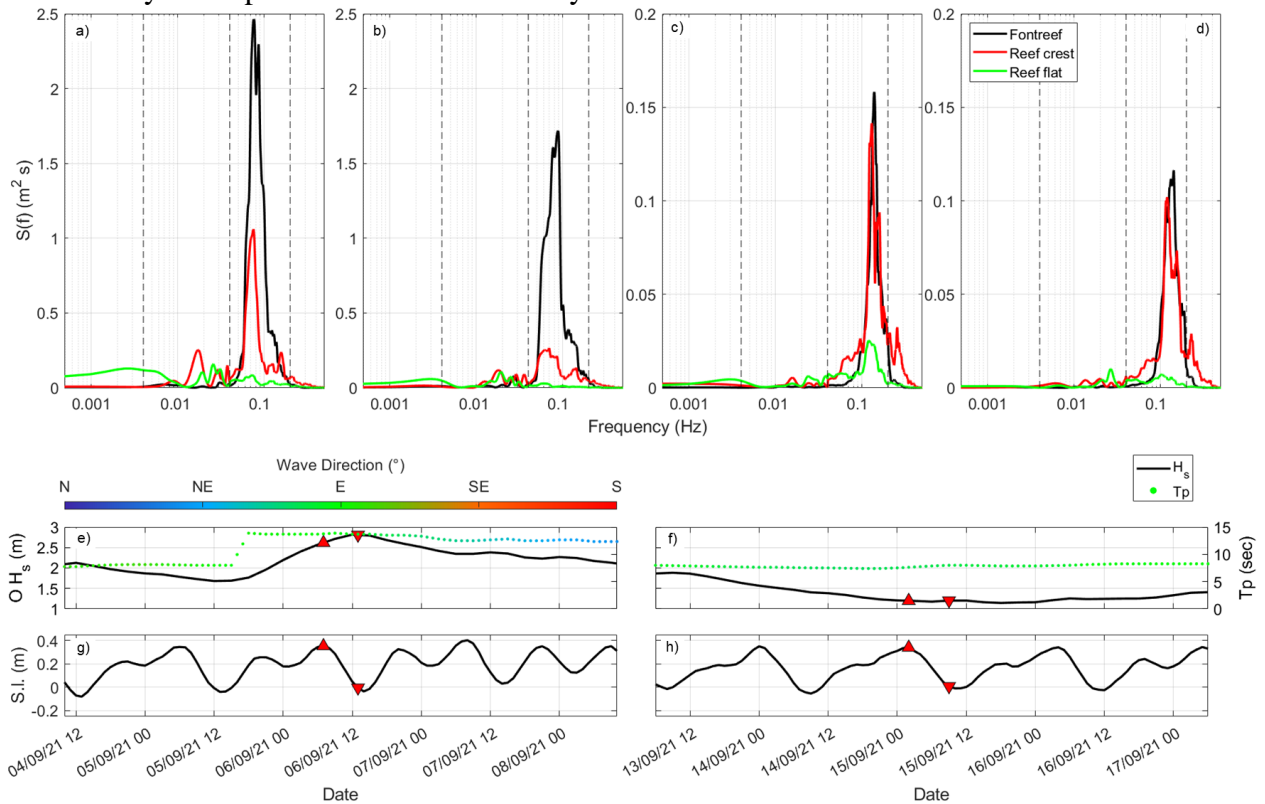
### 526 3 Discussion

527 In this study, a continuous multi-year runup time series obtained by video monitoring is used in  
 528 combination with offshore wave datasets and local hydrodynamic measurements in a fringing  
 529 reef system. This allows further analyses at different times and spatial scales of the key processes  
 530 and parameters involved in the control of the runup.

#### 531 3.1 Event scale processes

532 Wave transformation observations through the fringing reef from the sensor data installed on site  
 533 shows that overall wave energy is highly dissipated (overall mean attenuation of 65%). As  
 534 described in many previous studies, most of the attenuation occurs on the reef crest, which is the  
 535 location of wave shoaling and breaking (e.g., Lowe et al., 2005). The spectral analysis, allowing  
 536 the split of the whole spectra into a SW band, an IG band and a VLF band, indicates very  
 537 different behaviors between spectral bands. Indeed, only the short waves which represent the  
 538 vast majority of offshore spectra energy are subject to attenuation. IG band shows a net  
 539 amplification on the reef crest followed by a slight/moderate attenuation when reaching the

540 shoreline. This is visible from the slight reduction of IG undulations observed on the reef flat  
 541 sensors comparatively to the reef crest sensor. This attenuation is sea level dependent as lower  
 542 IG waves are observed for the same offshore conditions but for low tide levels. A similar  
 543 correlation with a stronger dependency was measured for SW waves in the reef flat. On the other  
 544 hand, VLF show a greater amplification in the reef flat suggesting a transmission of energy on  
 545 the reef crest from short waves to IG waves and progressively in the reef flat from IG waves to  
 546 VLF waves. At the opposite of IG waves, no correlation with sea level is noted in the  
 547 amplification. Figure 11 illustrates this by giving snapshots comparing waves spectral  
 548 transformation firstly during a storm at high and low tide and secondly during calm period also at  
 549 high and low tide. The energy switch from SW band to IG/VLF band is particularly important at  
 550 high tide and less marked at low tide. Furthermore, the amplification of IG on the reef crest is  
 551 followed by an amplification on late IG/early VLF band in the reef flat.



552 **Figure 11.** Energy spectras at front reef position (black line), reef crest (red line) and reef flat  
 553 position (green line) corresponding to storm conditions on September 06<sup>th</sup> at high (a) and low (b)  
 554 tides and calm conditions on September 15<sup>th</sup> at high (c) and low (d) tides. Offshore wave  
 555 conditions (e and f) and sea-level variations (g and h) are plotted under spectral graphs for both  
 556 periods. The period of the extracted bursts is represented by an upward red triangle for high tide  
 557 and downward red triangle for low tide.

### 559 3.2 Seasonal scale processes

560 Our results show a strong seasonal control on runup maximum elevation. However, this seasonality  
 561 appears to be different from the seasonal oscillations of the water level, and from the seasonal  
 562 variations of sea state in phase and amplitude. By retrieving sea-level seasonality from raw runup  
 563 dataset, one finds the wave runup signal with a phase very close to sea state seasonality and vice

564 versa. Wave climate periodicity is generated by both events mostly clustered on particular periods  
565 (winter and cyclonic seasons) and residual agitation (greater during winter) (Reguero et al., 2013).  
566 This cycle has an impact on runup periodicity as a similar pattern is found on runup signal with  
567 sea-level effect filtered. The effect of both cycles leads to an annual periodicity on DHR with its  
568 own phase with minimas in May and maximas in November.

569 In the context of Caribbean Islands and for the period of the study (3 years), among all processes  
570 involved in sea level variations, only the steric effect (Torres and Tsimplis, 2012) seems to be a  
571 good candidate to explain the seasonal DHR variability. Indeed, steric effect in this part of the  
572 Caribbean was reported to influence sea level about approximately 15 cm at seasonal time scale  
573 (Torres and Tsimplis, 2012). However, the direct effect of this periodicity on oscillation at  
574 shoreline level and the implication on coastal flooding has been rarely discussed (Rueda et al.,  
575 2019). Only a few studies focused on continental Caribbean beaches (without reef ecosystem)  
576 report an impact of such variation on coastal inundation (Orejarena-Rondón et al., 2019; Genes  
577 et al., 2021). Annual variability of wave climate is also known in the Caribbean (Reguero et al.,  
578 2013). Nevertheless, its impact on runup on reef line-coast had not been identified so far. Our  
579 results indicate that the effect of seasonal sea-level variation on DHR and swash excursion is  
580 significant. This periodicity present an amplitude of 0.37 m which represents 24% of the overall  
581 runup variability. During the low phase of the annual variability, which occurs in May, the effect  
582 of storms on runup is attenuated and during the high phase (peak) of the annual cycle occurring in  
583 October, storms of mild intensity may generate unexpected runup. Furthermore, a greater portion  
584 of incident energy reaches the shoreline level during the amplifying portion of the annual cycle  
585 and it is visible on figure 2 (c) and (d), which has an impact on shoreline morphology. In other  
586 words, this annual variation may be responsible for seasonal shoreline migration and beach  
587 morphologic evolution not directly attributable to wave forcing. This corroborates other shoreline  
588 observations from video system on reef-lined beach in Guadeloupe (Moisan et al., 2021).

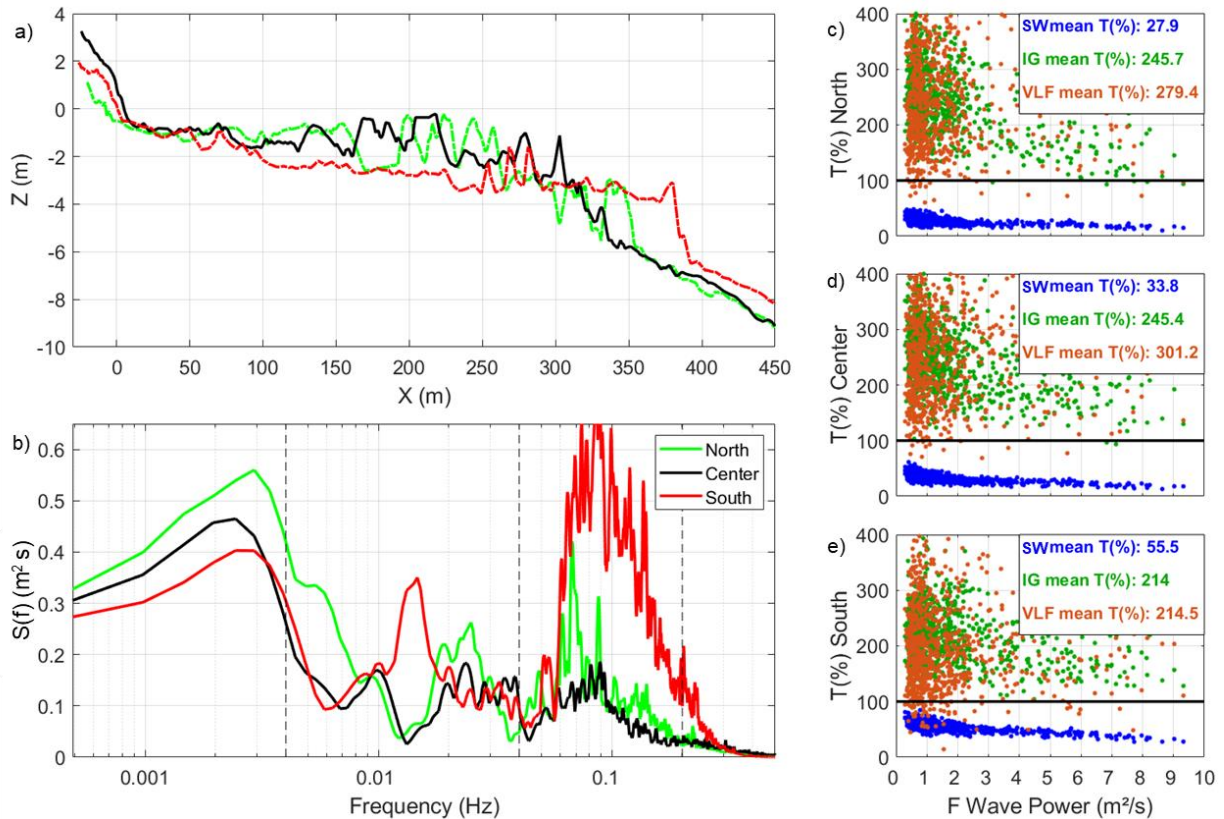
### 589 3.3. Coral reef implication

590 During a random storm, runup will present tidally controlled variations within the event (Figure  
591 11), and the occurrence of the event within the annual periodicity will induce an overall  
592 mitigation or amplification of the runup (Figure 4). These processes, comprising astronomic tide,  
593 steric expansion annual periodicity and wave climate, act on water depth and consequently on  
594 reef submergence. Coral reef wave filtering by wave breaking and bottom friction are dependent  
595 on water depth above the reef. Low water depth on the reef induces a high filtering of the swell  
596 while high water depth induces a lower filtering and a greater wave energy potentially reaching  
597 the beach. Such phenomenon is also observed on sandy beaches with sedimentary or rocky  
598 structures like bars (e.g., Melito et al., 2022) but it is amplified in the presence of a coral reef in  
599 consequence of the steepness, the potentially wide width of the coral platform, the high structural  
600 complexity and crest shallowness of such an environment. Overall, the wave transformation  
601 observed from the front reef to the reef flat reflects a shift from high to low frequencies leading  
602 to IG waves of the same order of magnitude as the SW as it approaches the coastline in particular  
603 during storms (up to 0.2 m on each frequency band), whereas these low-frequency undulations  
604 were almost insignificant before reaching the reef level (Figure 7). This result indicates that most  
605 IG and VLF are generated by breakpoint forcing (Symonds et al., 1982) and a minor fraction  
606 come from incident bound long waves (Longuet-Higgins & Stewart, 1964). This corroborates  
607 hydrodynamic observations commonly made on coral reefs environments (e.g., Péquignet et al.,  
608 2009; Pomeroy et al., 2012; Cheriton et al., 2016; Masselink et al., 2019). By quantifying



609 dissipation/amplification of the incident wave through the reef, we measured a difference on  
610 transmission between calm and agitated conditions. Indeed, the transmission in IG band from the  
611 front reef to the reef flat is inversely proportional to offshore wave conditions, thus a greater  
612 proportion of SW band waves must be transferred into IG band during calm conditions than  
613 during stormy conditions (although IG wave amplitude is positively correlated with offshore  
614 wave power as shown figure 7 (c) and (d)). As the transmission percentage also decreases with  
615 offshore agitation on the SS band and as VLF band waves transmission does not show  
616 correlation with front reef wave power (figure 12 (c), (d) and (e), we assume that a greater  
617 portion of incident waves is simply dissipated for storm conditions. Here, the generation and  
618 behavior of VLF band waves is poorly associated with parameters other than offshore wave  
619 power, which may be due to the chaotic aspect of the reef and the restricted dimensions of the  
620 site which could limit the generation of such undulations (Cheriton et al., 2020). It is also why  
621 overall mean wave energy dampening is approximately 65% while it can reach more than 90%  
622 on wider and continuous reefs (Harris et al., 2018). Thus, a majority of incident wave energy  
623 mainly carried by SW band waves is dissipated on the reef crest, a proportion of those incident  
624 SW band waves is transformed into IG band waves, again a proportion of those IG waves is  
625 transferred to VLF band waves in the reef flat.

626 Furthermore, additional sensors placed on either side of the transect in 2021 helped in  
627 understanding of the local longshore variability (Figure 12). The sensors installed at the South of  
628 the reef flat show the greater agitation in particular on SW band ( $H_{rms}$  up to 0.5 m during storm  
629 event and a mean transmission of 55.5%) and no tidal mitigation on  $H_{rms}$  at all frequency bands.  
630 This reflects the poor wave filtering by the reef at this cross-shore location as its structure is  
631 sparser (narrower overall) and deeper here. At the opposite, the sensors installed at the North of  
632 the system show a greater attenuation on the SW band and similar agitation on the IG and VLF  
633 band (SW band  $H_{rms}$  up to 0.23 m and a mean transmission of 27.9%). At this cross-shore  
634 location, the reef offers a continuous shallow barrier and the reef flat is shallower as well. This  
635 implies that the absence of the coral reef or a degraded version of the actual reef in width and  
636 crest shallowness would lead to less control on the agitation in the reef flat and hence an increase  
637 in runup. This confirms previous results observed or modeled on other studies stating that depth  
638 over reef and reef width are the main reef intrinsic parameters involved in backreef agitation  
639 (Cheriton et al., 2020) and runup (Pearson et al., 2017). This also supports the importance of  
640 living reef as a healthy coral ecosystem maintains a constant depth overtime while rocky  
641 structures constituted of dead colonies tend to erode. This latter point is in particularly significant  
642 in the actual context of sea level rise (Perry et al., 2018).



643

644 **Figure 12.** (a) Cross-shore profiles and (b) max spectrum corresponding to the three pressure  
 645 sensors installed in the reef flat for the 2021 campaign (see locations on Figure 1 (b)). Data  
 646 corresponding to North position are plotted in green, Center position in black and South position  
 647 in red.  $H_{\text{rms}}$  transmission on SW, IG and VLF band from front reef sensor to (c) North reef flat,  
 648 (d) Center reef flat and (e) South reef flat.

649

650 Finally, the comparison of two profiles, one with and without upperbeach vegetation, showed a  
 651 clear attenuation of runup by the vegetation during most extreme storm events (Figure 2 (c), (d)  
 652 and (e)). Pre-storm levels show equivalence between vegetated and non-vegetated profiles, but a  
 653 gap is systematically observed between the profiles when the swash reaches vegetation limit.  
 654 Events exceeding vegetation limit are rare on the study period but this dataset give promising  
 655 indications that will need to be further analyzed.

## 656 5 Conclusions

657 For several years now, reef coastlines have been the object of increasing attention, with a  
 658 particular focus on the hydrodynamic processes likely to generate coastal flooding, evidencing  
 659 the dominant role of wave transformation over the reef. Using a  $\sim 3$  years video monitoring of  
 660 wave run-up, as well as measurements of waves dynamics and water levels on the fringing coral  
 661 reef of Anse Maurice in Guadeloupe island, we analysed processes involved in swash inundation  
 662 from event scale to seasonal scale.

663 Sensor datasets highlighted the role of incident wave conditions on IG and VLF band wave  
 664 generation along the reef platform. The control on agitation in the reef flat by sea level was also  
 665 identified with more filtering of the SW and IG band waves in the reef flat at low tide.

666 A strong annual periodicity was detected on camera-derived DHR and appears to be linked to sea  
 667 level annual variations generated by steric effect and with annual variations of wave climate.  
 668 Spatial differences in runup during storms were also noticed due to upperbeach vegetation.  
 669 However, more research is needed to investigate the role of these ecosystem on reducing wave  
 670 runup and thus coastal inundation, particularly during more extreme events.  
 671 In a changing climate with sea-level rise and a possible increase of extreme events, the higher  
 672 submergence of reefs should induce an increase of runup and overwash events and reef  
 673 coastlines to become more and more vulnerable. Obviously, our dataset is far too short to  
 674 evaluate the effect of inter-annual oscillations (ENSO, NAO, etc.) or the effect of a rising sea-  
 675 level. However, this quite long timeseries of daily maximum runup provides the scientific  
 676 community with an unprecedented dataset for the validation of models to simulate more extreme  
 677 events or for an analysis of the effects of climate change on these environments. In the continuity  
 678 of this study, such a numerical experiment is being realized to study the processes during more  
 679 intense storms than those observed during the study period.

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 685

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