

## Loss of coral reef growth capacity to track future increases in sea level

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**Abstract :**

Sea-level rise (SLR) is predicted to elevate water depths above coral reefs and to increase coastal wave exposure as ecological degradation limits vertical reef growth, but projections lack data on interactions between local rates of reef growth and sea level rise. Here we calculate the vertical growth potential of more than 200 tropical western Atlantic and Indian Ocean reefs, and compare these against recent and projected rates of SLR under different Representative Concentration Pathway (RCP) scenarios. Although many reefs retain accretion rates close to recent SLR trends, few will have the capacity to track SLR projections under RCP4.5 scenarios without sustained ecological recovery, and under RCP8.5 scenarios most reefs are predicted to experience mean water depth increases of more than 0.5 m by 2100. Coral cover strongly predicts reef capacity to track SLR, but threshold cover levels that will be necessary to prevent submergence are well above those observed on most reefs. Urgent action is thus needed to mitigate climate, sea-level and future ecological changes in order to limit the magnitude of future reef submergence.

41 Sea-level rise (SLR) is predicted to elevate water depths above coral reefs and to increase coastal wave exposure  
42 as ecological degradation limits vertical reef growth, but projections lack local reef growth-sea level interaction  
43 data. Here we calculate the vertical growth potential of >200 Tropical Western Atlantic and Indian Ocean reefs, and  
44 compare these against recent and projected rates of SLR under different Representative Concentration Pathway  
45 (RCP) scenarios. Whilst many reefs retain accretion rates close to recent SLR trends, few will have capacity to track  
46 SLR projections under RCP 4.5 scenarios without sustained ecological recovery, whilst under RCP 8.5 most reefs  
47 are predicted to experience mean water depth increases >0.5 m by 2100. Coral cover strongly predicts reef capacity  
48 to track SLR, but threshold cover levels necessary to prevent submergence are well above those observed on most  
49 reefs. Urgent action to mitigate climate, sea-level and future ecological changes are thus needed to limit  
50 magnitudes of future reef submergence.

51

52 Sea-level rise (SLR) will directly impact coastal communities through shoreline inundation and erosion<sup>1,2</sup>. Along coral reef  
53 fronted coastlines the maintenance of reef surface elevation relative to sea-level will critically influence magnitudes of future  
54 shoreline change and flooding risk<sup>3,4</sup>. This is because reef structure and water depth modulate across-reef and nearshore  
55 wave energy regimes<sup>5-7</sup>. Mean water depth increases will occur where vertical growth rates lag behind actual or relative  
56 (e.g., from glacial isostatic adjustment or land subsidence) increases in sea-level<sup>4,8</sup>. This is a widely discussed scenario as  
57 reef-building species abundance declines globally, limiting reef growth potential<sup>9-14</sup>, whilst at the same time significant sea  
58 level increases are projected (global mean 0.44 m under RCP2.6 by 2100, 0.74 m under RCP8.5 [Representative  
59 Concentration Pathways<sup>15</sup>]<sup>16</sup>. Even modest depth increases of ~0.5 m above reefs are projected to increase coastal flooding  
60 risk, and change nearshore sediment dynamics<sup>3,5,17,18</sup>. However, datasets to support predictions of magnitudes of above-  
61 reef submergence and how these may vary geographically under different RCP scenarios are sparse<sup>25</sup>. This is a major  
62 knowledge gap with significant socio-economic and policy implications for urbanised tropical coastlines and reef islands  
63 given projected costs of adaptation and mitigation planning<sup>4</sup>.

64

65 To estimate reef growth capacity under future SLR we calculated mean water depth increases above reefs using an  
66 unprecedented dataset of reef carbonate budget data collected from >200 reefs around two major reef-building regions, the  
67 Tropical Western Atlantic (TWA) and Indian Ocean (IO). These data, based on in-situ ecological metrics (see Methods),  
68 were collected between 2009 and 2017 allowing us to explore intra-regional variations in contemporary carbonate budget  
69 states and site specific temporal dynamics in budget states. Using these data we derived first-order estimates of maximum  
70 vertical reef accretion potential ( $RAP_{max}$ ) ( $mm\ yr^{-1}$ ) (see Methods) to explore four key issues. First, we assess inter- and

71 intra-regional variations in site-specific  $RAP_{max}$  rates in the context of recent disturbance histories. Second, we use pre-and  
72 post-2016 bleaching datasets from impacted IO sites to quantify changes in  $RAP_{max}$  rates and consider the implications for  
73 reef growth given the increasingly important control bleaching has on reef health<sup>14,20,21</sup>. Third, we derive best-estimate  
74 predictions of reef capacity to track projected rates of SLR, and project total minimum water depth increases at each site by  
75 2100, by comparing site specific  $RAP_{max}$  rates against recent (1993-2010) altimetry-derived regional SLR rates and those  
76 projected under RCP4.5 and 8.5 scenarios<sup>29</sup>. Fourth, we quantify the relationship between mean coral cover (as the most  
77 widely used reef “health” metric<sup>9,10</sup>) and reef submergence under these same SLR scenarios over the next few decades to  
78 identify regional coral cover thresholds necessary to limit reef submergence.

79

### 80 Carbonate budgets and reef accretion potential

81 Our data show that contemporary carbonate budgets ( $G$ , where  $G = \text{Kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ ) of most shallow water (<10 m  
82 depth) reefs across the TWA (mean  $\pm$  SD:  $2.55 \pm 3.83 \text{ G}$ ) and IO (mean:  $1.41 \pm 3.02 \text{ G}$ ) are currently low (Fig. 1A), and are  
83 substantially below optimal rates reported under high coral cover states for both regions (range  $\sim$ 5-10  $G$ <sup>23</sup>). Mean carbonate  
84 budgets do not differ significantly between the two ocean regions (GLMM;  $p=0.485$ ), but there were significant differences  
85 among regions within ocean basins (GLMM;  $p=0.046$ ). In the TWA highest carbonate budgets were calculated on Leeward  
86 Antilles reefs (mean  $\pm$  SD:  $5.75 \pm 4.87 \text{ G}$ ; Fig. 1A), a rate closer to historical optimal rates<sup>23</sup>. The lowest rates were along  
87 the Mesoamerican Reef (Mexico mean  $\pm$  SD:  $0.14 \pm 3.81 \text{ G}$ ; Belize:  $1.52 \pm 2.19 \text{ G}$ ), in Florida (mean  $\pm$  SD:  $0.16 \pm 1.96 \text{ G}$ )  
88 and Grand Cayman (mean  $\pm$  SD:  $0.28 \pm 1.74 \text{ G}$ ; Fig. 1A; SI Table 1). These trends mirror those in coral cover reported in  
89 recent basin-wide analyses<sup>24</sup>, and provide compelling evidence that both coral carbonate production (mean  $4.22 \pm 4.06 \text{ G}$ )  
90 and bioerosion rates (mean  $1.74 \pm 1.46 \text{ G}$ ) are low across many TWA reefs. As with Net  $G$  there is marked intra-ocean  
91 variability (Extended Data Fig. 1) and we note that only sites in the south-east, such as Bonaire (Fig. 1B), are characterised  
92 by both high carbonate production and bioerosion rates (mean  $\pm$  SD:  $8.12 \pm 4.60 \text{ G}$  and  $2.79 \pm 1.08 \text{ G}$  respectively; see  
93 Extended Data Fig 1) that are close to historically estimated regional rates<sup>25,26</sup>. In the IO, highest contemporary budgets  
94 were calculated on reefs in Mozambique (mean  $\pm$  SD:  $4.78 \pm 5.01 \text{ G}$ ) and Ningaloo, Australia (mean  $\pm$  SD:  $2.46 \pm 2.01 \text{ G}$ ).  
95 The lowest (and net negative) rates were calculated at Seychelles (mean  $\pm$  SD:  $-1.51 \pm 1.90 \text{ G}$ ) and Maldives sites (mean  $\pm$   
96 SD:  $-2.98 \pm 1.30 \text{ G}$ ) (Fig. 1A; SI Table 1).

97

98 Low carbonate budget states are reflected in low calculated  $RAP_{max}$  rates at many sites across both oceans. In the TWA, the  
99 mean  $RAP_{max}$  rate across all sites is  $1.87 \pm 2.16 \text{ mm yr}^{-1}$ , but there is significant intra-ocean variability (GLMM;  $p=0.032$ ).

100 Highest  $RAP_{max}$  rates were calculated from sites in the southern Lesser Antilles (mean  $\pm$  SD:  $2.16 \pm 1.93 \text{ mm yr}^{-1}$ ) and

101 Leeward Antilles (mean  $\pm$  SD:  $4.87 \pm 2.71$  mm yr<sup>-1</sup>; Fig. 1B). Low RAP<sub>max</sub> rates characterise all reefs examined in Florida  
102 and the Greater Antilles (Gd. Cayman  $0.46 \pm 0.66$  mm yr<sup>-1</sup>, Florida  $0.19 \pm 0.93$  mm yr<sup>-1</sup>; Fig. 1B) and along the  
103 Mesoamerican Reef (Belize mean  $\pm$  SD:  $1.29 \pm 0.89$  mm yr<sup>-1</sup>, Mexico  $0.28 \pm 1.52$  mm yr<sup>-1</sup>; Fig. 1B). These low RAP<sub>max</sub> rates  
104 are likely to result from a prolonged period (at least multi-decadal in duration) of ecological decline driven by various  
105 regional-scale factors (fishing pressure, coral disease, bleaching, loss of herbivorous taxa, water quality declines<sup>13,27</sup>) that  
106 have changed reef ecology.

107

108 In the IO, mean calculated regional RAP<sub>max</sub> rates are only  $2.01 \pm 2.33$  mm yr<sup>-1</sup>. Sites in East Africa (Mozambique, mean  $\pm$   
109 SD:  $4.00 \pm 2.78$  mm yr<sup>-1</sup>; Kenya,  $1.72 \pm 1.32$  mm yr<sup>-1</sup>) and Ningaloo, Western Australia ( $2.41 \pm 2.01$  mm yr<sup>-1</sup>) have the  
110 highest mean RAP<sub>max</sub> rates, whilst western and central IO sites are on average net negative (Seychelles, mean  $\pm$  SD:  $-0.43$   
111  $\pm 0.95$  mm yr<sup>-1</sup>; Maldives,  $-0.84 \pm 0.47$  mm yr<sup>-1</sup>) (Fig. 1B). This reflects the fact that these areas were extensively impacted  
112 by the 2016 bleaching event (Extended Data Fig. 2), with widespread coral mortality to depths of at least 6-7 m<sup>28</sup>. Chagos  
113 corals also suffered high mortality during 2016<sup>29</sup> and although post-event budget assessments have yet to be undertaken it  
114 is likely that the relatively high mean RAP<sub>max</sub> rates we report ( $2.94 \pm 2.06$  mm yr<sup>-1</sup>; Fig. 1) for Chagos far exceed  
115 contemporary rates. At sites with both pre- and post-2016 data, bleaching significantly reduced both Net G (GLMM;  
116  $p < 0.001$ ) and RAP<sub>max</sub> (GLMM;  $p < 0.001$ ). Declines were greatest in the Maldives and on "recovering reefs" (sensu Graham  
117 et al.<sup>30</sup>) in the Seychelles (Extended Data Fig. 2). There were negligible differences on "regime shifted" Seychelles reefs as  
118 coral cover, Net G and accretion were already low. The major consequence of the 2016 event is that most reefs in the  
119 impacted areas are presently in net erosional or non-net accretionary states. Furthermore, given: 1) that not all Seychelles  
120 reefs recovered successfully from past (1998) bleaching<sup>30</sup>; and 2) that models predict the rapid onset of annual bleaching for  
121 the central IO, under both RCP4.5 and 8.5 scenarios<sup>21</sup> (i.e., well inside the timescales necessary for reef recovery<sup>31,32</sup>) the  
122 capacity for IO reefs to regain high accretion states is increasingly questionable.

123

#### 124 **Reef accretion and projected sea level rise**

125 To assess reef capacity to track local SLR we compared our calculated RAP<sub>max</sub> rates against recent altimetry measured  
126 SLR rates for the period 1993–2010 (see Methods) and rates projected under RCP4.5 and 8.5<sup>29</sup> (see Methods; SI Table 2).  
127 In both regions only ~45% of reefs have calculated mean RAP<sub>max</sub> rates close to (within  $\pm 1$  mm yr<sup>-1</sup>) or above local recent  
128 (altimetry derived) SLR rates. Thus for many reefs there is already a divergence between reef growth potential and the local  
129 recent rate of SLR (Fig. 2). However, these values fall to only 6.2 % and 3.1% respectively in the TWA when we compare  
130 calculated RAP<sub>max</sub> rates for each site to projected mean local RCP4.5 and 8.5 rates for the 21<sup>st</sup> century<sup>22</sup>. In the Indian

131 Ocean only 2.7% of reefs have mean  $RAP_{max}$  rates close to (within  $\pm 1$  mm  $yr^{-1}$ ) RCP4.5 projections and 1.3% close to  
132 mean RCP8.5 projections (Fig. 2). Whilst a more positive prognosis would be implied in the IO based on pre-bleaching  
133 states (59% of the reefs had  $RAP_{max}$  rates close to (within  $\pm 1$  mm  $yr^{-1}$ ) recent measured SLR rates; Fig. 2), our data  
134 suggest that few reefs in either region will be able to match average 21<sup>st</sup> century projected SLR rates (see SI Table 2) if  
135 current ecological conditions persist.

136

### 137 **Projections of reef submergence**

138 To assess magnitudes of future reef submergence we used our calculated  $RAP_{max}$  rates to predict total minimum water  
139 depth increases above each reef by the end of this century (Fig. 3), and in the IO for selected sites based on pre- and post-  
140 2016 bleaching data. These predictions are however likely at the more optimistic end of the spectrum in terms of reef keep-  
141 up capacity, both for methodological reasons (see Methods) and because of the lag time between climate warming and  
142 SLR. Thus calculated magnitudes of water depth increase should be considered as best case scenarios and the minimums  
143 for which regions should prepare. Allowing for these caveats our current projections are that if strong climate mitigation  
144 actions can be rapidly implemented (e.g., an RCP2.6 type scenario) that restricts SLR rates to close to those measured  
145 across our study areas over the last few decades (i.e.,  $< 3$  mm  $yr^{-1}$ ; see SI Table 2) then the difference between reef  
146 accretion and SLR rate will on average be low in both regions assuming ecological conditions do not deteriorate further  
147 (mean  $< 10$  cm increases by 2100; see SI Table 3).

148

149 In contrast, significant water depth increases are projected above these reefs by 2100 under both RCP4.5 and 8.5  
150 scenarios. Under RCP4.5 projections water depths on the TWA reefs are predicted to increase 14–66 cm (5–95% CI range)  
151 (mean  $\sim 40$  cm, or 4.8 mm  $yr^{-1}$ ), and between 16–104 cm (5–95% CI range) (mean  $\sim 60$  cm, or 7.2 mm  $yr^{-1}$ ) under RCP8.5  
152 (Fig. 3). In the IO mean water depth is estimated to increase 14–72 cm (5–95% CI range) (mean 47 cm, or 5.6 mm  $yr^{-1}$ )  
153 under RCP4.5, and between 22–112 cm (5–95% CI range) (mean 71 cm, or 8.5 mm  $yr^{-1}$ ) under RCP8.5 (Fig. 3; SI Table 3).  
154 Larger average increases of  $\sim 63$  cm under RCP4.5 (34–92 cm, 5–95% CI range) and 87 cm (41–132 cm, 5–95% CI range)  
155 under RCP8.5 (Fig. 3; SI Table 3) are predicted for bleaching impacted central IO reefs in the absence of sustained  
156 ecological recovery. The major implications are that whilst 32% of TWA and 45% of IO reefs are predicted to experience  
157 increases of  $> 0.5$  m by 2100 under mean local RCP4.5 scenarios, under RCP8.5 projections 80% of our TWA and 78% of  
158 IO reefs are predicted to experience minimum mean water depth increases above this level. This is an important depth  
159 threshold as recent models suggest that, on average, wave energy regimes will increase especially rapidly once water depth  
160 increases exceed 0.5 m<sup>33</sup>. Of major future concern is that due to the delayed response of processes contributing to SLR,

161 (deep ocean warming, ice sheet and glacier mass loss), these submergence trends are projected to increase towards the  
162 end of the century<sup>16,22,34</sup>. Thus the higher end projections of water depth increases for each scenario may be more realistic  
163 (SI Table 3), rapidly exacerbating the threat to coastal communities and to Small Island Developing States<sup>1,4</sup>.

164

#### 165 **Reef state and submergence trajectories**

166 An especially pressing issue for reef and coastal managers is the question of which reefs are most likely to experience  
167 submergence over the coming decades, and how does this relate to reef state? Percent live coral cover is the most widely-  
168 reported metric of reef state and we thus used our data to examine whether a metric as simple as coral cover had predictive  
169 capacity for projecting changes in sea-level above reefs. Although our data sets span two biogeographic provinces, a range  
170 of depths (2 to 13 m), and a diversity of community structures, coral cover explained up to 62% of the projected increase in  
171 net water depth by the year 2050 (Fig. 4, Extended Data Table 1). Simulations uncover that high coral cover states would  
172 experience little water depth increase with some even extending closer to the surface. However, statistical fits to our data  
173 suggest that coral cover levels of ~40% in the TWA, and ~50% in the IO, are needed to avoid the prospect of net reef  
174 submergence in the next few decades (by 2050) under mean RCP4.5 SLR projections, but that this threshold rises to nearly  
175 60% in the TWA and nearly 70% in the IO under the current emissions trajectory of RCP8.5. Given that coral cover levels  
176 across the sites in our dataset average only  $20.6 \pm 13.9\%$  in the TWA, and  $17.8 \pm 12.6\%$  in the IO region (SI Table 1), there  
177 is thus a high probability that mean water depths above reefs will increase by at least a few tens of centimetres in the  
178 coming decades.

179

#### 180 **Summary**

181 The potential for a high proportion of reefs (>75% across our sites under RCP8.5) to experience water depth increases  
182 greater than 0.5 m by 2100 is of concern, because modelling studies suggest this will be sufficient to open higher wave  
183 energy windows that will increase sediment mobility, shoreline change and island overtopping<sup>1-3,17,18</sup>. We also show that  
184 major climate-driven perturbations, specifically coral bleaching, can drive major declines in reef accretion potential. The most  
185 worrying end-point scenario is that if predictions of increasing bleaching frequency are realised<sup>21,35</sup> and result in more  
186 frequent mortality, reefs may become locked into permanent low accretion rate states, leading to increasing rates of  
187 submergence under all SLR scenarios. Ocean acidification and thermal impacts on calcification represent additional threats  
188 and may negatively impact reef calcification and increase bioerosion<sup>36,37</sup>. These collective threats will be exacerbated by the  
189 low coral cover states that define many reefs, and which our analysis suggests will be insufficient to prevent reef  
190 submergence. Our approach represents a first step in improving our predictive capabilities in these areas, but given the

191 societal relevance and economic costs of SLR along populated tropical coastlines<sup>4</sup>, and that coral reefs have the potential to  
192 play a key role in nature-based defence strategies, these issues should have high priority on the research agenda.

193

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207

208 **Online content** Additional Extended Data display items and Supplementary Files are available in the online version of the  
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210

#### 211 **Author contributions**

212 C.T.P. conceived of the study with support from L.A-F, N.A.J.G, P.S.K and K.M.M.. C.T.P., N.A.J.G., P.S.K., K.M.M., P.J.M.  
213 A.B.A.S. and S.K.W. developed and implemented the analyses. C.T.P. led the manuscript and all other authors contributed  
214 data and made substantive contributions to the text.

215

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316 **Figure captions**

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318 **Fig. 1. Tropical Western Atlantic and Indian Ocean reef carbonate budgets and accretion rates.** (a) Plots showing site  
319 level carbonate budget data ( $\text{kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ ) grouped by country/territory within ecoregions. Box plots depict the median  
320 (horizontal line), box height depicts first and third quartiles, whiskers represent the 95th percentile, and outlier points are  
321 outside the 95th percentile. Bold numbers = country/territory (*italics* = n transects/site); (b) Calculated maximum reef  
322 accretion potential ( $\text{RAP}_{\text{max}}$ ) rates ( $\text{mm yr}^{-1}$ ) for each reef within ecoregions. Numbers in parentheses in each area box  
323 denote the country/territory followed by the mean accretion rate ( $\text{mm yr}^{-1}$ ).

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325 **Fig. 2. Difference between calculated reef accretion potential ( $\text{mm yr}^{-1}$ ) relative to recent (1993-2010) and projected**  
326 **rates of sea-level rise.** Plots showing difference between reef accretion rate and sea-level rise (SLR) rate for (a) Tropical  
327 Western Atlantic (n = 95), and (b) Indian Ocean (n = 107) sites. Recent SLR rates are based on altimetry data for the period  
328 1993 – 2010 (see Methods). Mean RCP4.5 and 8.5 SLR rates (and 5% and 95% CI rates) are based on projections for the  
329 period 2018-2100<sup>22</sup> (see SI Table 2). Dots show individual transect data within each site.

330

331 **Fig. 3 Total predicted water depth increases above reefs by 2100.** Plots for site level data showing predicted water  
332 depth increases against (a) mean RCP4.5, and (b) RCP8.5 sea-level rise projections for the period 2018-2100. Box plots  
333 depict median (horizontal line), box height depicts first and third quartiles, whiskers represent the 95th percentile, and outlier  
334 points are outside the 95th percentile. White bars denote pre-bleaching data. Bottom of grey boxed area shows the 0.5 m  
335 threshold above which significantly increased wave energy regimes are predicted. Site numbers as in Fig. 1.

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337 **Fig. 4. Relationships between mean coral cover (%) and changes in water depth (m) above reefs by 2050.** Model  
338 simulations (100 per site and SLR scenario) showing for (a) Tropical Western Atlantic (n = 95 reefs), and (b) Indian Ocean  
339 sites (n = 104 reefs) predicted changes (y-axis) in mean water depth (m) above reefs as a function of coral cover (x-axis).  
340 Mean change in depth is shown as the centre point. Error bars are standard deviations. Simulations show trends under  
341 lower (5<sup>th</sup> percentile), mean, and upper (95<sup>th</sup> percentile) projections of SLR under RCP4.5 and RCP 8.5 sea-level rise  
342 scenarios.

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356 **Methods**

357 Field data to calculate biological carbonate production and erosion rates, and from which net reef carbonate budgets (G,  
358 where  $G = \text{kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ ) could be calculated were collected from reef sites spanning both the Tropical Western Atlantic  
359 (TWA) and Indian Ocean (IO) regions. All data were collected between 2009 and 2017 (see SI Table 1). At most TWA sites  
360 these data were collected using the ReefBudget methodology<sup>38</sup>, and for IO sites using a previously reported adapted version  
361 of this methodology<sup>12,39</sup> that factors for regional differences in coral assemblages and bioeroding communities. Data were  
362 collected through a number of discrete projects, but in all cases the aim was to capture data from the main shallow water  
363 reef-building zones within a range of sites within each country. Survey depths and habitat types thus reflected this variability,  
364 although were kept as consistent as possible within countries, and replicate transects within sites were always depth-  
365 consistent. In the TWA, data were mostly collected within the 8-10 m depth fore-reef zone but, where field/logistical  
366 conditions allowed, also at shallower (~5 m depth) sites, although the number of locations where data from both depths  
367 could be collected was limited. In the IO region survey depths and habitat zones are more variable reflecting the more  
368 diverse range of reef types and geomorphologies associated with the countries in our dataset. Our data thus provide an  
369 overview of the range in budgetary states, and the resultant accretion potential, of reefs within a country, accepting that not  
370 every reef or setting can be realistically assessed. No budget data were collected from high energy reef crest settings (<2 m  
371 depth) due to physical working constraints, but we note that reported long-term accretion rates for such settings (where  
372 these systems are usually dominated by coralline algae) are generally <1-2 mm yr<sup>-1</sup> <sup>40,41</sup>, rates that are not dissimilar to  
373 those calculated at many sites in this study. The number of replicate transects (see SI Table 1) varied between sites (range  
374 3 to 8) depending on field logistics and weather constraints.

375

376 Following the ReefBudget methodology benthic data were collected using a 10 m transect as a guide line below which a  
377 separate 1 m flexible tape was used to measure the distance within each linear 1 m covered by each category of benthic  
378 cover. All overhangs, vertical surfaces and horizontal surfaces below the line were thus surveyed. Scleractinian corals were  
379 recorded to species level in the TWA, and to genera and morphological level (e.g., *Acropora* branching, *Porites* massive  
380 etc.) in the IO. Substrate rugosity was calculated as total reef surface divided by linear distance (a completely flat surface  
381 would therefore have a rugosity of 1). To calculate rates of coral carbonate production we integrated mean percent cover of  
382 each coral species with species-specific (or nearest equivalent species) measures of skeletal density ( $\text{g cm}^{-3}$ ) and linear  
383 growth rate ( $\text{cm yr}^{-1}$ ), as derived from published sources (see: <http://geography.exeter.ac.uk/reefbudget/>). These data were  
384 then combined with rugosity measures to yield a value for coral carbonate production (G) relative to actual transect surface  
385 area. For several sites in both regions carbonate production rates were calculated slightly differently because community  
386 composition data were based on standard linear intersect methodologies. These were TWA sites in the windward and  
387 leeward Antilles and, in the IO, at Ningaloo and Seychelles. In these cases individual coral colony cover data were scaled up  
388 to derive a 3-d measure of cover by using genera or growth form specific rugosity metrics. For several IO sites (Maldives  
389 and Seychelles) that were known to be severely impacted by the 2016 bleaching event we also report post-bleaching  
390 changes in carbonate production rates, with census data collected using the same methodology as that used pre-bleaching.

391

392 To calculate rates of bioerosion we also undertook census studies to determine abundance and size of parrotfish and  
393 bioeroding urchins (both to species level) per unit area of reef following the methods previously reported for TWA and IO  
394 sites<sup>12,38</sup>. All parrotfish abundance data were collected along replicate 30 x 4 m belt transects, except in Chagos (50 x 5 m  
395 belts), Seychelles (7.5 m radial surveys) and Ningaloo (100 x 10 m belts). To calculate bioerosion rates by each individual

396 fish we used models based on total length and life phase to predict the bite rates (bites hr<sup>-1</sup>) for each species, as reported in  
397 Perry et al.<sup>12,38</sup>. To calculate bioerosion rates by urchins we undertook additional surveys at each site, using either 10 x 2 m  
398 or 10 x 1 m belt transects to determine the species and test sizes of urchins per unit area of reef. Census data were then  
399 combined with published species/test class size erosion rate data<sup>12,38</sup> to yield a measure of erosion rate. Rates of endolithic  
400 bioerosion were estimated for most TWA sites based on a census of endolithic sponge tissue cover per unit area of reef  
401 substrate<sup>38,42</sup>. Exceptions were sites in Bonaire and the Windward Antilles where surveys were not conducted and literature-  
402 derived rates from the TWA were applied. Endolithic bioerosion rates were estimated at all IO sites by applying rates from  
403 the literature to available benthic substrate<sup>12</sup>.

404

405 To calculate maximum reef accretion potential (RAP<sub>max</sub>) rates (mm yr<sup>-1</sup>) at each site we followed a previously used  
406 method<sup>11,12</sup> based on the conversion of measured site specific net carbonate production rates (G) as proposed by Smith &  
407 Kinsey<sup>43</sup>. In this conversion net carbonate production is taken as the sum of calculated gross carbonate production by corals  
408 and coralline algae less erosion rate. We then also factored for variations in accumulating reef framework porosity as a  
409 function of coral community type and for sediment reincorporation<sup>43</sup>. Stacking porosity values ranging from ~80% for  
410 branching coral assemblages to ~20 % for head coral dominated assemblages, with rates of ~50% for mixed assemblages  
411 were proposed in the original work<sup>44</sup>. However, since coral communities are rarely entirely monospecific we used the  
412 following rates in our calculations: 30% for head and massive coral dominated assemblages, 70% for branched and tabular  
413 dominated assemblages, and 50% for mixed coral assemblages (based on data in Kinsey & Hopley<sup>44</sup>) as determined for  
414 each site from benthic coral community data. Sediment reincorporation was factored for by allowing for a proportion of the  
415 bioeroded framework (that is converted to sediment) to be reincorporated back into the accumulating reef structure. This  
416 proportion was calculated as the sum of 50% of the parrotfish-derived sediment (as a highly mobile bioeroder which  
417 defecates randomly over the reef), as well as all sediment produced by urchins and by macrobioerosion. To keep our  
418 estimates conservative we worked on the assumption that only ~50% of this bioerosional sediment yield is actually  
419 incorporated back into the reef (see also ref 45), and excluded any sediment generation by other benthic sediment  
420 producers (e.g., *Halimeda*).

421

422 Due to the absence of empirical data on rates of physical reef framework removal per unit area of reef surface over time we  
423 did not factor for physical loss rates. For the same reason we also did not factor for chemical dissolution of the substrate.  
424 The accretion rates we report, which we consider as current best-estimates of accretion potential across the entire upper  
425 portion of a reef profile (on the basis that accretion can result from both in-situ coral accumulation and the supply of  
426 physically-derived rubble from shallow fore-reef areas to the crest/flat<sup>46</sup>, are thus defined as a rate of maximum reef  
427 accretion potential, or RAP<sub>max</sub>). We thus consider these rates to represent the upper limits of how fast reefs may be  
428 accreting at present, and acknowledge that if physical framework loss and chemical dissolution rates<sup>47</sup> could be  
429 appropriately factored for at the site level our projected rates would likely be lower. How much lower will depend on spatial  
430 variations in physical disturbance regimes and the susceptibility of coral taxa to physical disturbances, and both are likely to  
431 vary markedly at intra-regional scales. Testing the validity of our high end (RAP<sub>max</sub>) rates is thus not simple.

432

433 Evidence from Holocene core records of reef growth, when ecological conditions (in terms of the abundance of high rate  
434 carbonate producing taxa, e.g., *Acropora* spp.) are considered to have been more optimal, suggest that many reefs  
435 exhibited an impressive capacity to either “keep-up” or to “catch-up” during periods of past rapid SLR. Indeed, calculated

436 vertical accretion rates from the early Holocene, when sea-levels were rising rapidly, may have been as high as 12-15 mm  
437 yr<sup>-1</sup> in both the TWA and IO regions<sup>48</sup>. Whilst longer term average accretion rates were lower (e.g., ~3-4 mm yr<sup>-1</sup> in the  
438 TWA<sup>49</sup>; and a little below this in the IO region<sup>48</sup>) these still exceed those estimated for many modern reefs in our dataset,  
439 and fall well below even mean RCP 4.5 SLR scenarios (see SI Table 2). Furthermore, reef core studies that might allow  
440 some assessment of very recent accretion histories on a site-by-site basis i.e., with a focus on the last couple of hundred  
441 years of reef growth, are sparse/absent and would make for inherently problematic comparisons because of the magnitudes  
442 of coral community change that have occurred at most sites over the last few decades.

443

444 However, one useful (albeit sub-area specific) comparator is the recent work of Yates et al. (ref 19) which used historical  
445 bathymetric data from the 1930s to 1980s and Lidar-derived Digital Elevation Models from the late 1990s to 2000s in Florida  
446 to calculate net changes in seafloor elevation. This data integrates for the effects of any physical and chemical losses and  
447 suggests net negative accretion rates in the Upper Florida Keys of around -1.5 mm yr<sup>-1</sup> (over the past 68 years), of -4.5 mm  
448 yr<sup>-1</sup> in the Lower Florida Keys (over the past 66 years) and of -2.7 mm yr<sup>-1</sup> in the US Virgin Islands (over the past 33 years).  
449 Our data from different sites in this region (SE Florida, the upper Florida Keys and the Dry Tortugas) and which do not  
450 include data from lagoon sands and seagrass beds that were integrated within the Yates et al. study, have average  
451 contemporary accretion rates of -0.4, 1.7 and 0.8 mm yr<sup>-1</sup> respectively. Our rates are thus, as expected for the various  
452 reasons outlined above, a little higher but are not markedly higher, suggesting they provide a reasonable estimate of high  
453 end reef accretion potential.

454

455 To test for differences in Net G and calculated accretion rates between sites and countries across our dataset we fitted  
456 generalized linear mixed models (GLMMs) to assess if rates were statistically significantly different between oceans and  
457 regions (n = 885 transects), as well as for the effects of bleaching and the interaction with location (Maldives, Seychelles  
458 recovering and regime shifted) (n = 338 transects), whilst controlling for site depth and the random effect of site. All GLMMs  
459 were fitted using a Gaussian distribution via the lmer function from package lme4<sup>50</sup> in R<sup>51</sup>, with significance assessed using  
460 F-ratio statistics calculated via the Anova function in the CAR<sup>52</sup> package. Model assumptions of normality and homogeneity  
461 of variance were assessed graphically and found to be adequately met. We found a very weak effect of depth on Net G (and  
462 thus RAP<sub>max</sub> rates) across our dataset, with Net G typically being slightly higher on the deeper reefs (p=0.001, r = 0.160).  
463 Although our datasets do not allow a detailed consideration of this issue at the within-region level, the fact that average  
464 accretion rates do not noticeably decline with depth across the upper fore-reef depth internals is consistent with trends  
465 inferred from Holocene core records in the TWA region<sup>49</sup>.

466

467 To assess the capacity of the reefs in our datasets to match recently observed and future projected changes in sea level,  
468 and to estimate magnitudes of water depth increases relative to projected reef accretion by 2100 at each site, we compared  
469 our calculated RAP<sub>max</sub> data against local sea-level change data (SI Table 2). In these comparisons we assume steady state  
470 ecological conditions persisting. For recent observed rates of change we compared our RAP<sub>max</sub> rates against altimetry data  
471 for the period 1993-2010 from combined TOPEX/Poseidon, Jason-1, Jason-2/OSTM and Jason-3 satellite altimetry fields  
472 (downloaded from [http://www.cmar.csiro.au/sealevel/sl\\_data\\_cmar.html](http://www.cmar.csiro.au/sealevel/sl_data_cmar.html) on 22 January 2018). The fields used are monthly  
473 averages on a 1x1° grid with the seasonal (annual and semi-annual) signal removed and include inverse barometer and GIA  
474 corrections. The observed rates were computed by fitting a linear trend to the monthly 1993-2010 time series at the nearest  
475 available ocean grid point to the reef location. For the period 2018-2100 we used sea-level projections under the RCP4.5

476 and RCP8.5 scenarios<sup>22,34</sup>. These regional sea-level projections factor for changes in ocean density and dynamics, changes  
477 in atmospheric pressure, and glacier and ice sheet surface mass balance contributions based on output from 21 CMIP5  
478 atmosphere-ocean coupled climate models (Climate Model Intercomparison Phase 5<sup>53</sup>). In addition, the projections account  
479 for model-based contributions from anthropogenic groundwater extraction, for glacial isostatic adjustment and observation-  
480 based estimates of ice sheet dynamical processes. The regional sea-level patterns of mass redistribution account for  
481 changes in gravitational, deformational and rotational feedbacks. As for the recent observed rates of change, the spatial  
482 resolution of the SLR projections is 1x1° and the closest gridpoint (nearest neighbour) is extracted for comparison to the  
483 coral reef data (SI Table 2).

484

485 To obtain a greater insight into the importance of coral cover on near-future reef submergence, we undertook Monte Carlo  
486 simulations of carbonate budgets, potential accretion rates, and projected increases in depth under sea-level rise. One  
487 hundred simulations were carried out per site during which community structure was sampled randomly from the site-level  
488 statistical distribution of corals, CCAs, and sources of bioerosion (i.e., sampling from the observed mean and standard  
489 deviation of species-specific G or erosion rate at the site). Each simulation was extended to estimate the change in  
490 seawater depth at the year 2050 for six reference rates of sea-level rise (SLR) (as above): the 5th percentile, mean, and  
491 95th percentile of the rate of SLR for each of two Greenhouse Gas (GHG) emission scenarios, RCP4.5 and RCP8.5. For  
492 each site, we obtained the mean and standard deviation for each of the six SLR references. Analyses of differences in  
493 accretion rate, rates of SLR, and increases in depth over reefs were carried out using non-parametric mixed effects models  
494 based on Euclidean distance<sup>54</sup>. This technique is analogous to parametric linear mixed effects models but makes no  
495 assumptions about the statistical distribution of errors. Fixed effects included biogeographic region (TWA vs IO), GHG  
496 emissions scenario (RCP4.5 vs RCP8.5), and coral cover. Country was added as a random effect nested within  
497 biogeographic region. The only exception to this approach was the use of linear mixed effects models in order to estimate  
498 threshold levels of coral cover where the net submergence of reefs was zero. Models were fitted using the same structure as  
499 in PERMANOVA but the predict function was used to estimate model fits for  $y=0$ <sup>55</sup>. Analysis showed that a shift towards  
500 lower GHG emissions (RCP4.5) reduced the degree of reef submergence (Fig. 4, PERMANOVA;  $p<0.001$ ) and emissions  
501 scenario gained in importance when switching from lower to mean to upper (95 percentile) bounds of projected SLR,  
502 explaining 2%, 44%, and 54% of the variance in reef submergence respectively (Extended Data Table 1). Under the upper  
503 bounds of SLR, biogeographic region also became significant (PERMANOVA;  $p=0.005$ ) with submergence being somewhat  
504 greater in the IO (Fig. 4B). Under this pessimistic scenario, threshold levels of coral cover required to avoid net reef  
505 submergence were approximately 13% higher in the IO than the TWA (73% vs 60%) even under RCP4.5. This relative  
506 vulnerability of reefs in the IO was associated with higher rates of SLR (0.94 mm yr<sup>-1</sup> greater, PERMANOVA;  $p=0.02$ ,  
507 Extended Data Tables 2, 3) rather than any biogeographic difference in accretion potential (PERMANOVA;  $p=0.65$ ,  
508 Extended Data Table 4). While IO reefs are generally more resilient than those of the TWA<sup>56</sup>, current ecological trajectories  
509 suggest that few coral reef locations will likely maintain sufficiently high coral cover levels to keep pace with future SLR,  
510 resulting in greater incident wave energy exposure, and changing spectrum of wave processes, along reef-fronted  
511 shorelines<sup>3,6</sup>.

512

513 **Data availability.** Net carbonate budget and reef accretion rate data, and measured and projected sea-level data  
514 supporting the findings of this study are available within the paper and its supplementary information files. Site level coral  
515 cover and carbonate production and bioerosion datasets are available from the authors on request.



516 **Additional references**

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556 **EXTENDED DATA – Figure and table captions**

557

558 **Extended Data Figure 1. Tropical Western Atlantic and Indian Ocean coral carbonate production and bioerosion**  
559 **rates.** Plots showing mean site level coral carbonate production rate (a), and bioerosion rate (b) data (kg CaCO<sub>3</sub> m<sup>2</sup> yr<sup>-1</sup>)  
560 grouped by country/territory within ecoregions for Tropical Western Atlantic and Indian Ocean sites. Box plots depict the  
561 median (horizontal line), box height depicts first and third quartiles, whiskers represent the 95th percentile, and outlier points  
562 are outside the 95th percentile. Country/territory codes as follows: 1. Florida (n = 36), 2. Puerto Rico (n = 6), 3. Grand  
563 Cayman (n = 26), 4. Belize (n = 36), 5. Mexico (n = 64), 6. St. Croix (n = 36), 7. St. Maarten (n = 11), 8. Anguilla (n = 10), 9.  
564 Barbuda (n = 20), 10. Antigua (n = 28), 11. St. Lucia & St. Vincent (n = 37), 12. Bequia (n = 12), 13. Mustique (n = 16), 14.  
565 Canouan & Tobago Cays (n = 20), 15. Union/PSV and Carriacou (n = 20), 16. Bonaire (n = 62), 17. Mozambique (n = 55),  
566 18. Kenya (n = 29), 19. Seychelles (n = 144), 20. Maldives (n = 25), 21. Chagos (n = 111), 22. Ningaloo (n = 34) (n = number  
567 of transects per country/territory).

568

569 **Extended Data Figure 2. Reef accretion pre- and post- the central Indian Ocean 2016 bleaching event.** Calculated  
570 RAP<sub>max</sub> rates (mm yr<sup>-1</sup>) pre- (a, c) and post- (b, d) 2016 bleaching in the Seychelles and the Maldives. e) Plot shows  
571 changes in RAP<sub>max</sub> rates and at "recovered" (n = 96) and "regime-shifted" reefs<sup>38</sup> (n = 72 pre-bleaching, n = 48 post-  
572 bleaching) in the Seychelles, and Maldives (n = 35 pre-bleaching, n = 25 post bleaching). Box plots depict the median  
573 (horizontal line), box height depicts first and third quartiles, whiskers represent the 95th percentile, and outlier points are  
574 outside the 95th percentile.

575

576 **Extended Data Table 1. Effects of biogeography, coral cover, GHG emissions scenario, and range of SLR projection**  
577 **on the future submergence of coral reefs by 2050.** Results of PERMANOVA analyses with coral cover, biogeographic  
578 region (TWA vs. TIO) and GHG emissions scenario (RCP4.5 vs RCP8.5) as fixed effects and country nested within  
579 (biogeographic) region as random effect.

580

581 **Extended Data Table 2: Effect of Biogeographic Region on rates of SLR.** PERMANOVA analysis testing the effect of  
582 biogeographic region on the upper 95% of predicted rates of SLR

583

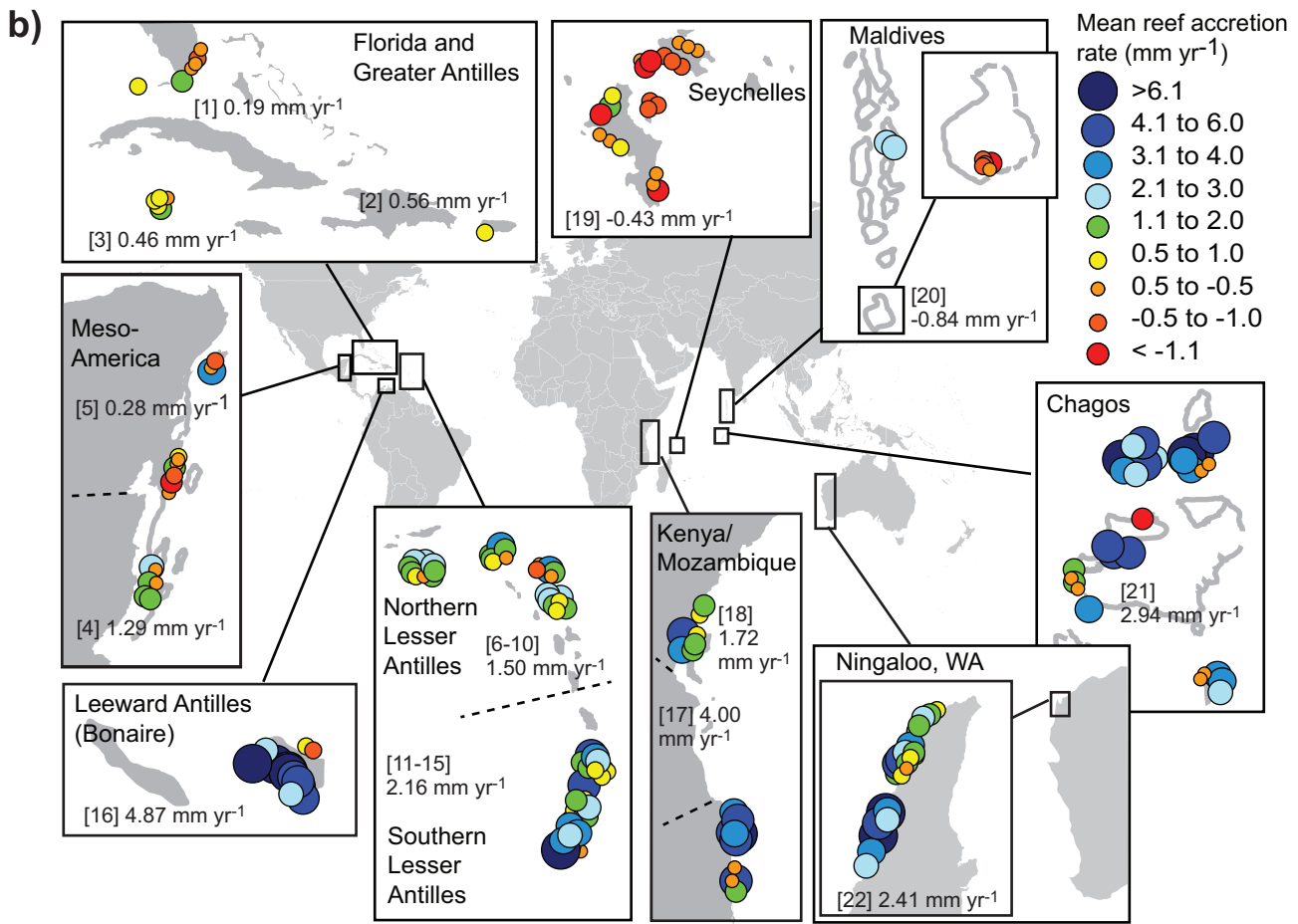
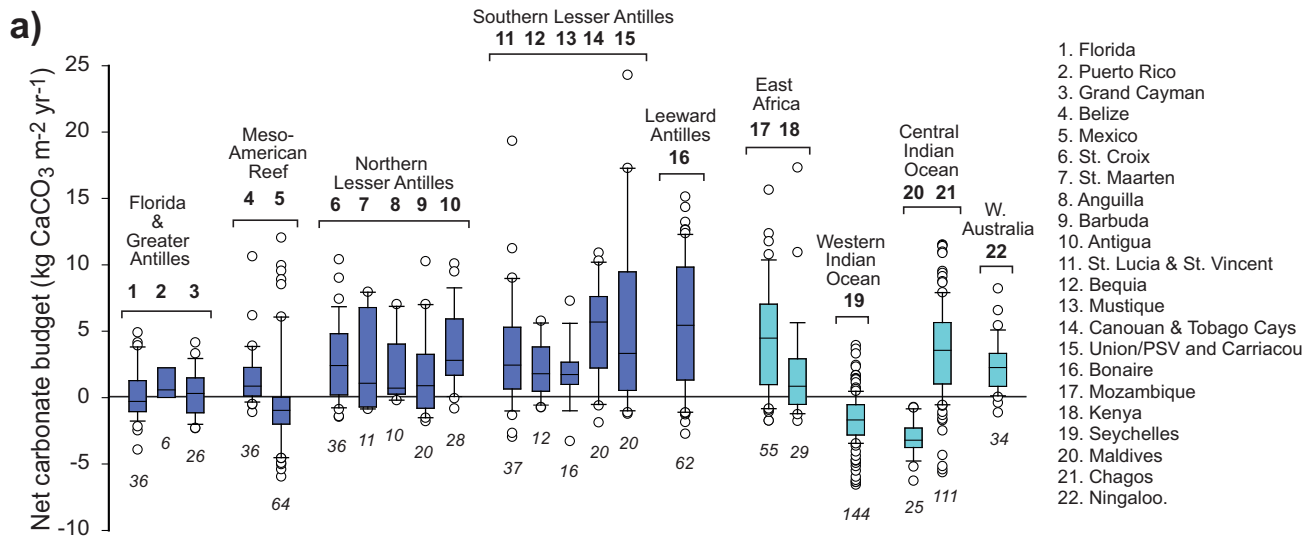
584 **Extended Data Table 3: Differences between SLR rates between biogeographic regions (mm yr<sup>-1</sup>).** The difference in  
585 SLR rates between biogeographic regions (mm yr<sup>-1</sup>) under two GHG emission scenarios and for all three components of  
586 SLR projections. Projections are higher in the Indian Ocean except in RCP4.5 lower percentile (0.03) which was non-  
587 significant.

588

589 **Extended Data Table 4: Variability in potential accretion rate.** Results of PERMANOVA analysis showing local (coral  
590 cover) versus regional (Tropical Western Atlantic vs. Indian Ocean) effects on the variability in potential accretion rate.

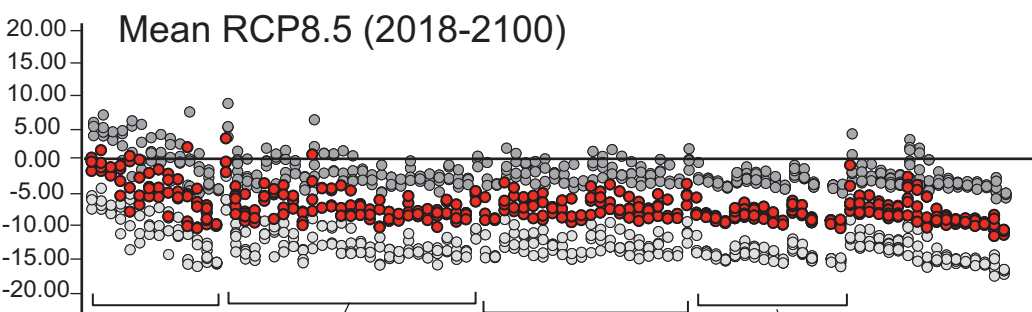
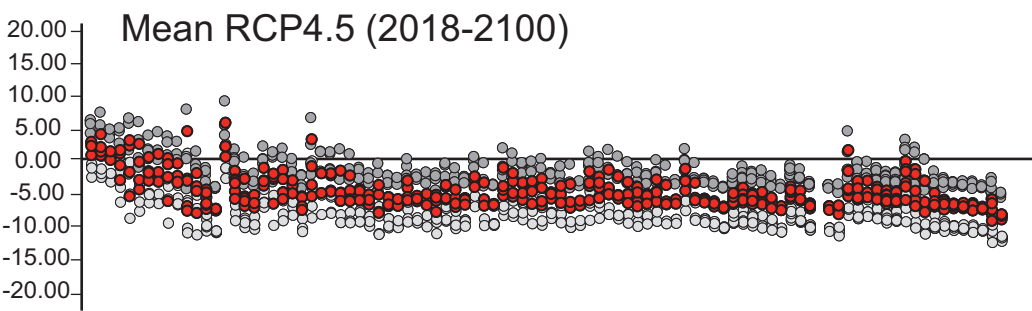
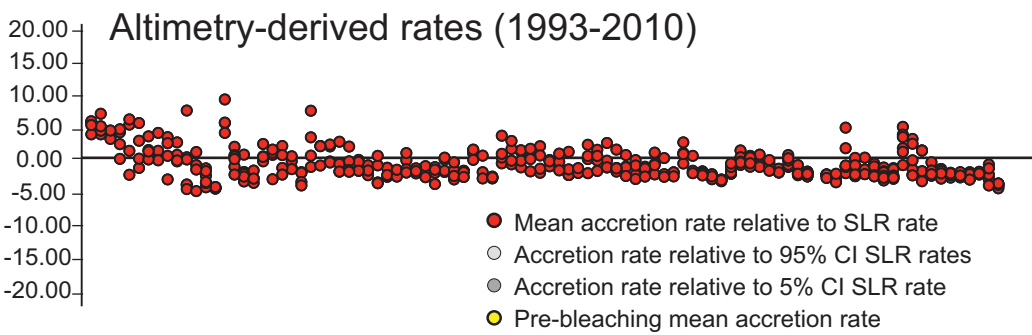
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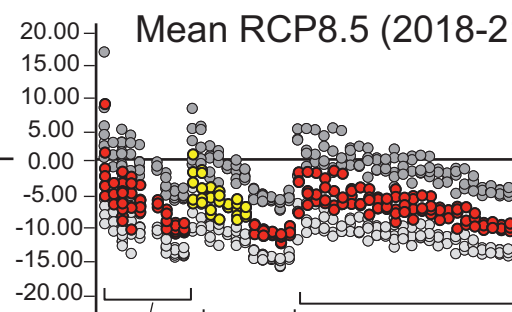
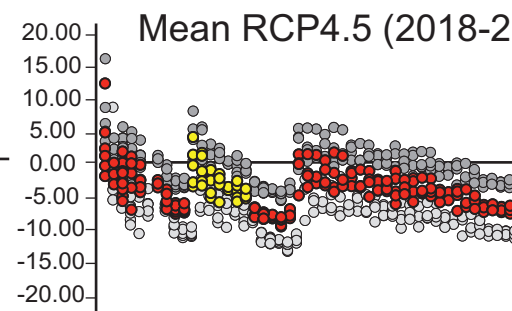
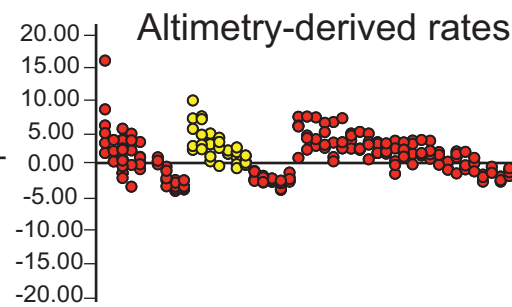
Difference (+ or -) between reef accretion potential rate (mm yr<sup>-1</sup>) and local sea-level rise rate

### a) Tropical Western Atlantic



Leeward Antilles    Northern Lesser Antilles    Southern Lesser Antilles    Florida & Greater Antilles    Meso-American Reef

### b) Indian Ocean



Mozambique    Maldives    Chagos    Ning

