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

2

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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[1,2]. 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[3,4]. This is because reef structure and water depth modulate across-reef and nearshore

55   wave energy regimes[5-7]. 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[4,8]. This is a widely discussed scenario as

57   reef-building species abundance declines globally, limiting reef growth potential[9-14], 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[15]][16]. Even modest depth increases of ~0.5 m above reefs are projected to increase coastal flooding

60   risk, and change nearshore sediment dynamics[3,5,17,18]. However, datasets to support predictions of magnitudes of above-

61   reef submergence and how these may vary geographically under different RCP scenarios are sparse[25]. 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[4].

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[14,20,21]. 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[29]. Fourth, we quantify the relationship between mean coral cover (as the most

77   widely used reef "health" metric[9,10]) 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 = Kg $CaCO_3$ m^{-2} yr^{-1}) of most shallow water (<10 m

82   depth) reefs across the TWA (mean ± SD: 2.55 ± 3.83 G) and IO (mean: 1.41 ± 3.02 G) are currently low (Fig. 1A), and are

83   substantially below optimal rates reported under high coral cover states for both regions (range ~5-10 G[23]). 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 ± SD: 5.75 ± 4.87 G; Fig. 1A), a rate closer to historical optimal rates[23]. The lowest rates were along

87   the Mesoamerican Reef (Mexico mean ± SD: 0.14 ± 3.81 G; Belize: 1.52 ± 2.19 G), in Florida (mean ± SD: 0.16 ± 1.96 G)

88   and Grand Cayman (mean ± SD: 0.28 ± 1.74 G; Fig. 1A; SI Table 1). These trends mirror those in coral cover reported in

89   recent basin-wide analyses[24], and provide compelling evidence that both coral carbonate production (mean 4.22 ± 4.06 G)

90   and bioerosion rates (mean 1.74 ± 1.46 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 ± SD: 8.12 ± 4.60 G and 2.79 ± 1.08 G respectively; see

93   Extended Data Fig 1) that are close to historically estimated regional rates[25,26]. In the IO, highest contemporary budgets

94   were calculated on reefs in Mozambique (mean ± SD: 4.78 ± 5.01 G) and Ningaloo, Australia (mean ± SD: 2.46 ± 2.01 G).

95   The lowest (and net negative) rates were calculated at Seychelles (mean ± SD: -1.51 ± 1.90 G) and Maldives sites (mean ±

96   SD: -2.98 ± 1.30 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 ± 2.16 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 ± SD: 2.16 ± 1.93 mm yr^{-1}) and

101   Leeward Antilles (mean ± SD: 4.87 ± 2.71 mm yr^{-1}; Fig. 1B). Low RAP$_{max}$ rates characterise all reefs examined in Florida

102   and the Greater Antilles (Gd. Cayman 0.46 ± 0.66 mm yr^{-1}, Florida 0.19 ± 0.93 mm yr^{-1}; Fig. 1B) and along the

103   Mesoamerican Reef (Belize mean ± SD: 1.29 ± 0.89 mm yr^{-1}, Mexico 0.28 ± 1.52 mm yr^{-1}; Fig. 1B). These low RAP$_{max}$ 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[13,27,]) that

106   have changed reef ecology.

107

108   In the IO, mean calculated regional RAP$_{max}$ rates are only 2.01 ± 2.33 mm yr^{-1}. Sites in East Africa (Mozambique, mean ±

109   SD: 4.00 ± 2.78 mm yr^{-1}; Kenya, 1.72 ± 1.32 mm yr^{-1}) and Ningaloo, Western Australia (2.41 ± 2.01 mm yr^{-1}) have the

110   highest mean RAP$_{max}$ rates, whilst western and central IO sites are on average net negative (Seychelles, mean ± SD: -0.43

111   ± 0.95 mm yr^{-1}; Maldives, -0.84 ± 0.47 mm yr^{-1}) (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[28]. Chagos

113   corals also suffered high mortality during 2016[29] and although post-event budget assessments have yet to be undertaken it

114   is likely that the relatively high mean RAP$_{max}$ rates we report (2.94 ± 2.06 mm yr^{-1}; 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$_{max}$ (GLMM; p<0.001). Declines were greatest in the Maldives and on "recovering reefs" (sensu Graham

117   et al.[30]) 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[30]; and 2) that models predict the rapid onset of annual bleaching for

121   the central IO, under both RCP4.5 and 8.5 scenarios[21] (i.e., well inside the timescales necessary for reef recovery[31,32]) 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$_{max}$ rates against recent altimetry measured

126   SLR rates for the period 1993–2010 (see Methods) and rates projected under RCP4.5 and 8.5[29] (see Methods; SI Table 2).

127   In both regions only ~45% of reefs have calculated mean RAP$_{max}$ rates close to (within ± 1 mm yr^{-1}) 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$_{max}$ rates for each site to projected mean local RCP4.5 and 8.5 rates for the 21st century[22]. In the Indian

131 Ocean only 2.7% of reefs have mean RAP_{max} rates close to (within ± 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 ± 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 21st 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 ~40 cm, or 4.8 mm yr^{-1}), and between 16–104 cm (5–95% CI range) (mean ~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 ~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[33]. 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[16,22,34]. 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[1,4].

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 ± 13.9% in the TWA, and 17.8 ± 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[1-3,17,18]. 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[21,35] 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[36,37]. 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[4], 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

207

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

209   paper.

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

317

318   **Fig. 1. Tropical Western Atlantic and Indian Ocean reef carbonate budgets and accretion rates.** (a) Plots showing site

319   level carbonate budget data (kg $CaCO_3$ m^{-2} 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 (RAP_{max}) rates (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 (mm yr^{-1}).

324

325   **Fig. 2. Difference between calculated reef accretion potential (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[22] (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.

336

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 (5th percentile), mean, and upper (95th 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 $G = kg\ CaCO_3\ m^{-2}\ yr^{-1}$) 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[38], and for IO sites using a previously reported adapted version

361   of this methodology[12,39] 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 $<1-2\ mm\ yr^{-1}$ [40,41], 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 ($g\ cm^{-3}$) and linear

383   growth rate ($cm\ yr^{-1}$), 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[12,38]. 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⁻¹) for each species, as reported in

397 Perry et al.[12,38]. 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[12,38] 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[38,42]. 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[12].

404

405 To calculate maximum reef accretion potential (RAP$_{max}$) rates (mm yr⁻¹) at each site we followed a previously used

406 method[11,12] based on the conversion of measured site specific net carbonate production rates (G) as proposed by Smith &

407 Kinsey[43]. 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[43]. 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[44]. 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[44]) 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[46], are thus defined as a rate of maximum reef

427 accretion potential, or RAP$_{max}$). 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[47] 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$_{max}$) 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^{-1} in both the TWA and IO regions[48]. Whilst longer term average accretion rates were lower (e.g., ~3-4 mm yr^{-1} in the

438 TWA[49]; and a little below this in the IO region[48]) 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^{-1} (over the past 68 years), of -4.5 mm

448 yr^{-1} in the Lower Florida Keys (over the past 66 years) and of -2.7 mm yr^{-1} 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^{-1} 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[50] in R[51], with significance assessed using

460 F-ratio statistics calculated via the Anova function in the CAR[52] 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$_{max}$ 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[49].

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$_{max}$ 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$_{max}$ 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 on 22 January 2018). The fields used are monthly

473 averages on a 1x1^{o} 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[22,34]. 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 [53]). 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 submersion, 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[54]. 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 [55]. 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^{-1} 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[56], 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[3,6].

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.

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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 $CaCO_3$ m^2 yr^{-1})

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_{max} rates (mm yr^{-1}) pre- (a, c) and post- (b, d) 2016 bleaching in the Seychelles and the Maldives. e) Plot shows

571   changes in RAP_{max} rates and at "recovered" (n= 96) and "regime-shifted" reefs[38] (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^{-1}).** The difference in

585   SLR rates between biogeographic regions (mm yr^{-1}) 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.

591

592

a)

Net carbonate budget (kg CaCO$_3$ m^{-2} yr^{-1})

Southern Lesser Antilles
11 12 13 14 15

Florida & Greater Antilles
1 2 3

Meso-American Reef
4 5

Northern Lesser Antilles
6 7 8 9 10

Leeward Antilles
16

East Africa
17 18

Central Indian Ocean
20 21

Western Indian Ocean
19

W. Australia
22

1. Florida
2. Puerto Rico
3. Grand Cayman
4. Belize
5. Mexico
6. St. Croix
7. St. Maarten
8. Anguilla
9. Barbuda
10. Antigua
11. St. Lucia & St. Vincent
12. Bequia
13. Mustique
14. Canouan & Tobago Cays
15. Union/PSV and Carriacou
16. Bonaire
17. Mozambique
18. Kenya
19. Seychelles
20. Maldives
21. Chagos
22. Ningaloo.

b)

Florida and Greater Antilles
[1] 0.19 mm yr^{-1}
[2] 0.56 mm yr^{-1}
[3] 0.46 mm yr^{-1}

Meso-America
[5] 0.28 mm yr^{-1}
[4] 1.29 mm yr^{-1}

Leeward Antilles (Bonaire)
[16] 4.87 mm yr^{-1}

Northern Lesser Antilles
[6-10] 1.50 mm yr^{-1}
[11-15] 2.16 mm yr^{-1}
Southern Lesser Antilles

Seychelles
[19] -0.43 mm yr^{-1}

Maldives
[20] -0.84 mm yr^{-1}

Kenya/Mozambique
[18] 1.72 mm yr^{-1}
[17] 4.00 mm yr^{-1}

Ningaloo, WA
[22] 2.41 mm yr^{-1}

Chagos
[21] 2.94 mm yr^{-1}

Mean reef accretion rate (mm yr^{-1})
>6.1
4.1 to 6.0
3.1 to 4.0
2.1 to 3.0
1.1 to 2.0
0.5 to 1.0
0.5 to -0.5
-0.5 to -1.0
< -1.1

a) Tropical Western Atlantic

Altimetry-derived rates (1993-2010)

Difference (+ or -) between reef accretion potential rate (mm yr⁻¹) and local sea-level rise rate

- ● Mean accretion rate relative to SLR rate
- ○ Accretion rate relative to 95% CI SLR rates
- ● Accretion rate relative to 5% CI SLR rate
- ● Pre-bleaching mean accretion rate

Mean RCP4.5 (2018-2100)

Mean RCP8.5 (2018-2100)

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

b) Indian Ocean

Altimetry-derived rates

Mean RCP4.5 (2018-2

Mean RCP8.5 (2018-2

Mozambique | Maldives | Chagos | Ninga

a) RCP 4.5

Tropical Western Atlantic

Indian Ocean

b) RCP 8.5

a) Tropical Western Atlantic

b) Indian Ocean