



Supporting Online Material for

Coral Reefs Under Rapid Climate Change and Ocean Acidification

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1. Calculations associated with Fig. 1B.

Temperature and carbonate-ion concentrations were reconstructed for the past 420,000 years using the Vostok Ice Core data (5). Carbonate concentrations were calculated (S1) using CO_2_{atm} and temperature deviations from today's conditions using the Vostok Ice Core data set and assuming constant salinity (34 ppt), mean sea temperature (25°C) and total alkalinity (2300 mmol kg^{-1}). Values of ocean acidity Calculated for the 420,000 yr period varied ± 0.1 pH unit. Present day values (and those of 100 years ago) are also shown, but were derived from other sources (8) given that the Vostok Ice Core data ends 2300 y BP. Surface ocean carbonate ion concentrations during glacial times may have been slightly greater (by 20-25 $\mu\text{mol kg}^{-1}$) than indicated here owing to an elevation of alkalinity during glacial periods linked to glacial ice formation and the dissolution of carbonate minerals that compensated for increased storage of carbon in the deep sea (S2). Furthermore, there is uncertainty with regard to the relationship between Antarctic and tropical paleo-temperatures. Here, we assume that paleo-temperature changes estimated for the Antarctic (8) exceed tropical temperature changes by a factor of 2 (S3). Assuming less polar amplification would yield higher estimates for glacial carbonate-ion concentrations; however, even without any assumed polar amplification of temperature changes, estimated glacial carbon-ion concentrations are greater than modern carbonate-ion concentrations.

2. Calculations associated with Figure 4.

To calculate ocean chemistry changes, we prescribed IPCC SRES A2 emissions (S4) in the University of Victoria (UVic) Earth System Climate Model version 2.8 (S5). Ocean chemistry is computed as per the protocol of Ocean Carbon Model Intercomparison Project (<http://www.ipsl.jussieu.fr/OCMIP>). We add deviations from year 1994 as predicted by the model to ocean chemistry as observed for year 1994 (S6). Reef locations are from ReefBase (S7).

3. Table S1. Feedback Mechanisms Causing Threshold (Catastrophe) Dynamics

Reef ecosystems are particularly susceptible to the emergence of alternative stable states of the ecosystem (S8-11). Stable states are reinforced by ecological feedbacks that 'attract' or drive a reef towards to a particular state and then maintain the ecosystem within a specific state. The following table lists some of the feedback mechanisms that are suspected to occur on coral reefs and highlights how they are exacerbated by climate change. Text highlighted in bold relates to labels on the feedbacks figure (Fig. 4) in the main text.

Feedback mechanism	Exacerbated by climate change
Competitive interactions between macroalgae and corals: Macroalgae pre-empt settlement space (S11) and therefore inhibit coral recruitment thereby constraining coral cover and facilitating further algal colonization (S12)	Frequent mass coral mortality events (bleaching, disease, hurricanes) facilitate algal colonization because grazing intensity decreases (S13). Note, the reverse process also occurs; coral growth and recruitment

	reduce the area available to grazers which intensifies grazing and can reduce macroalgae.
Competitive interactions between macroalgae and corals: algal competition causes increased post-settlement mortality in coral due to reduced light, flow or growth rate (<i>S14, 15</i>)	Frequent mass coral mortality events (bleaching, disease, hurricanes) facilitate algal colonization.
Competitive interactions between macroalgae and corals: Macroalgae overgrow adult corals causing direct reductions in coral fecundity because of absent coral (<i>S6-18</i>) and indirect chronic reductions in fecundity because of competition (<i>S18, 19</i>). Reduced fecundity reduces demographic rates of colonization in corals, reinforcing shift towards algae. Note that rate of algal-coral overgrowth is poorly understood and varies dramatically among the taxa involved (<i>S20</i>)	Frequent mass coral mortality events (bleaching, disease, hurricanes) reduce larval output of reefs further. Calcification rates of corals are slowed by increased ocean acidification. Results in greater competitive effectiveness of macroalgae relative to corals. Thermal stress also reduces fecundity in corals (<i>S20</i>) which may ultimately reduce larval supply and coral recruitment (<i>S21</i>).
Competitive interactions between macroalgae and corals: Macroalgae may act as vectors of organisms that cause coral disease (<i>S22</i>), thereby promoting losses of corals	Coral mortality events promote algal colonization and rising temperature may enhance efficacy of disease organisms (<i>S23</i>).
Competitive interactions between macroalgae and corals: Macroalgae exude polysaccharides that may stimulate bacterial growth near corals causing local hypoxia and coral mortality (<i>S24</i>). Note, mechanism not demonstrated in situ and probably highly dependent on flow regime	Coral mortality events promote algal colonization
Reductions in coral colonization and survival (coral loss) lead to a reduction in reef accretion and therefore a reduction in reef rugosity (structural complexity). This in turn reduces the carrying capacity of reefs for herbivores which require high rugosity to provide shelter from predators and sustain high densities (<i>S25, S26</i>). A reduction in herbivory continues to enhance the colonization of algae (<i>S18, S27</i>)	Rate of rugosity loss may be exacerbated by acidification which leads to elevated rates of bioerosion and physical erosion because coral skeletons become weaker (less densely calcified). Bleaching damage and slower rates of coral recovery will cause habitat loss and increase the average distance among patches of high quality habitat . This may in turn reduce the population connectivity of reef organisms and reduce recruitment (<i>S28</i>).
Certain species of coralline red algae act as inducers to coral settlement (<i>29</i>). Reductions in the cover of encrusting coralline red algae caused by increases in the cover of carpeting macroalgae that trap sediments reduces the availability of settlement substratum for corals, thereby	Acidification increases energetic cost of calcification in coralline algae reducing their growth rate and increasing susceptibility to disease. Increase in macroalgal competitors after coral mortality events exacerbates process further by making the benthos

facilitating proliferation of algae (S30)	increasingly hostile to encrusting corallines
Failure of recovery of the urchin, <i>Diadema antillarum</i> , in much of the Caribbean may be driven by feedbacks. Hostile, macroalgal-dominated reefs possess high densities of microinvertebrates that prey upon settling urchin spat causing a bottleneck in urchin colonization because of high post-settlement mortality (i.e. macroalgae are a predator refuge for juvenile urchins). In contrast, macroalgae are scarce at high densities of adult urchins (S31). Thus, urchins can maintain high-quality habitat for urchin survival but only once grazing levels are high. Modest urchin recovery would enhance the health of many Caribbean reefs (S32).	Acidification may further reduce urchin survival by reducing test strength and / or enhancing vulnerability to disease because of increased energetic requirements of calcification . Reductions in rugosity, which are exacerbated by climate change (above), increase the post-settlement mortality of urchins and increases in macroalgae after bleaching-induced coral mortality also add to density of urchin predators.
Recruitment of corals declines because of Allee effects which reduce fertilization success and reduce levels of larval supply (S33). The problem is then exacerbated because Allee effects may become more severe as coral density declines because of reduced recruitment (and other factors – see main text)	Frequent mass coral mortality events reduce the density of adult corals and enhance the severity of Allee effects further. Chronic stress caused by bleaching also causes reduced fecundity in corals (S20)

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