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Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence

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1 **Climate projections of conditions that increase coral disease**
2 **susceptibility and pathogen virulence**

3
4 Running title: Climate projections of coral disease conditions

5
6
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44 **Rising sea temperatures are likely to increase the frequency of disease outbreaks**
45 **affecting reef-building corals through impacts on coral hosts and pathogens. We**
46 **present and compare climate model projections of temperature conditions that will**
47 **increase 1) coral susceptibility to disease, 2) pathogen abundance, and 3) pathogen**
48 **virulence. A moderate (RCP 4.5) and fossil fuel aggressive (RCP 8.5) emissions**
49 **scenario are examined. We also compare projections for the onset of disease-**
50 **conducive conditions and severe annual coral bleaching, and produce a disease risk**
51 **summary that combines climate and anthropogenic stress. There is great spatial**
52 **variation in the projections both among and within the major ocean basins in**
53 **conditions favouring disease development. Our results indicate disease is as likely to**
54 **cause coral mortality as bleaching in the coming decades. These projections identify**
55 **priority locations to reduce anthropogenic stress and test management interventions**
56 **to reduce disease impacts.**

57

58

59 The 2014 boreal summer was the warmest on record ¹, breaking air temperature records
60 in hundreds of cities and causing unprecedented highs in sea surface temperatures in the
61 North Pacific ². Concurrently, a catastrophic outbreak of starfish wasting disease
62 decimated American west coast populations of ~20 starfish species ³ and outbreaks of
63 eelgrass wasting disease resulted in declines in habitat area as high as 90% in parts of
64 California and Washington (Wyllie-Echeverria pers obs). Pathogens causing these
65 wasting disease outbreaks have been in the environment for at least decades ⁴, although
66 the causative virus for seastar wasting is newly described ³. These recent examples serve
67 as reminders that disease outbreaks can rapidly and extensively devastate populations of
68 keystone species and key habitat builders. Both events also caught the scientific and
69 management communities by surprise, underscoring the importance of developing
70 forecasts and long-term projections of conditions that increase outbreak likelihood.

71

72 Forecasts of conditions conducive to disease onset have been most extensively developed
73 for the agricultural crop sector ^{5,6} because of the economic value of optimising the timing
74 of pesticide application. Studies presenting longer-term, climate-model-based projections

75 of conditions that promote disease onset for other plants and animals are far more rare.
76 To date, climate models driven by Intergovernmental Panel on Climate Change (IPCC)
77 emissions scenarios have only been used to develop projections of conditions related to
78 the causative agents and vectors of human diseases ⁷, such as malaria ⁸⁻¹⁰ and
79 Chikungunya ¹¹. Overall, the science of developing forecasts and projections for wildlife
80 diseases is in its infancy and warrants much greater research focus ⁷, especially in the
81 marine environment where disease outbreaks have been increasing in frequency and
82 severity over recent decades ¹².

83

84 Climate-related diseases have already severely impacted the primary framework builders
85 of coral reef habitats ¹²⁻¹⁵. Of the range of bacterial, fungal, and protozoan diseases
86 known to affect stony corals ¹⁶, many have explicit links to temperature, including black
87 band disease ¹⁷, yellow band disease ^{18,19}, and white syndromes ^{13,20,21}. Here, we apply the
88 climate models used in the IPCC 5th Assessment Report (see Table S1 for list) to project
89 three temperature conditions that increase the susceptibility of coral hosts to disease or
90 increase pathogen abundance or virulence.

91

92 We posit that temperature conditions that increase host susceptibility, pathogen
93 abundance and pathogen virulence will substantially increase the likelihood of disease
94 outbreaks once the set threshold frequencies and stress levels are surpassed. The output
95 from the climate model ensemble for each of these three conditions is a projected year by
96 which the target frequency or stress level is reached. All projections are presented for
97 RCP8.5, the emissions scenario that best characterises current conditions and emission

98 trends, and for RCP4.5, which represents a pathway to stabilisation at 4.5 W/m² (~650
99 ppm CO₂ equivalent) after 2100²². Along with the individual projections, we present
100 maps of the earliest and latest projected year one of these three conditions favourable to
101 disease development is projected to occur. We also present: a) comparisons between the
102 projected timing of these conditions and annual severe coral bleaching, b) a map of a
103 composite metric of anthropogenic stressors that can also increase host susceptibility to
104 disease, and c) a map of disease risk under RCP8.5 that combines climate and
105 anthropogenic stress.

106

107 **Projections of disease conditions**

108 The year in which host susceptibility is projected to exceed the set threshold (i.e., sub-
109 lethal bleaching stress 3 times per decade) varied spatially throughout all reef regions, but
110 with a clear latitudinal trend. Reef locations in the tropics (<23° latitude) suffered thermal
111 stress conducive to disease before sub-tropical reefs (23-32.5° latitude), a pattern that was
112 similar under both RCPs (Fig. 1a and Fig. 2a). There was little variation (<5 years) in the
113 projected timing of this condition among locations in the tropics (Fig. 1a). In contrast,
114 some northern hemisphere sub-tropical reefs, such as in the Red Sea and Persian Gulf,
115 were projected to experience these conditions ~20 years later than sub-tropical reefs in
116 the south of Australia and Madagascar. Overall, under both RCP8.5 and RCP4.5, the
117 median year this threshold will be surpassed was 2011; most (~76% as of 2014) of the
118 world's reefs are already experiencing thermal stress potentially conducive to disease
119 outbreaks. Under both RCP8.5 and 4.5, the metric for increased host-susceptibility will
120 be reached at >90% of reef locations by 2020 (Fig. 2a).

121

122 In contrast to patterns for the host susceptibility metric, there was no clear latitudinal
123 gradient in the projections for increased pathogen abundance (i.e., when cool season
124 temperatures have warmed by $\geq 0.5^{\circ}\text{C}$) (Fig. 1b). Additionally, greater variation in the
125 projected timing of this condition among reefs within both the tropics and sub-tropics
126 was observed, as well as between the RCPs, than was seen for the host susceptibility
127 metric. Under both RCPs, the threshold set for increased cool season temperatures will be
128 reached by 2014 in the southern Red Sea, southern India, the province of Papua in
129 Indonesia, and in the Bahamas (Fig. 1b). In contrast, under RCP8.5, increased cool
130 season temperatures were not projected to occur until the 2030s and 2040s for much of
131 the Coral Triangle, Madagascar and Hawaii, and not until the 2050s and 2060s for
132 locations throughout the far south Pacific, such as French Polynesia (Fig. 1b). The
133 projected years for these locations were all roughly a decade later under RCP4.5 (Fig.
134 1b). The median years for the projections were 2036 (RCP8.5) and 2043 (RCP4.5).
135 Under RCP8.5, the threshold set for increased cool season temperatures is reached at
136 20% of reef locations by 2020 and for 17% after 2050 (remaining 63% fall between
137 2020-2050) (Fig. 2e).

138

139 Spatial patterns for projections of the pathogen virulence metric (i.e., for *Vibrio*
140 *corallilyticus*, when the number of months that temperatures are \geq the MMM is double
141 that observed on average from 2006-2011) were similar to those found for the host
142 susceptibility metric. Reefs in the tropics will experience this condition earlier than sub-
143 tropical reefs (Fig. 1c), with little variation between the two RCPs. The Caribbean was an

144 exception to this latitudinal pattern; the years that sub-tropical reefs in the Caribbean
145 were projected to experience a doubling of months at or above MMM (i.e., 2020) were
146 among the earliest projected under both RCPs. For sub-tropical reefs in the south Pacific
147 and Red Sea, the target stress level will be reached 20 or more years later, in the mid
148 2040s. The median years for this projection were 2031 (RCP8.5) and 2030 (RCP4.5), ~20
149 years later than the median for the host susceptibility metric.

150

151 For most reef locations (~80% for both RCPs), the models projected timing of increased
152 host-susceptibility to occur earliest (Fig. 1a) and for increased pathogen virulence (for
153 *Vibrio corallilyticus*) to occur latest (Fig. 1c). Under RCP8.5 at least one of the three
154 types of temperature conditions favouring disease development were projected to be
155 surpassed at all reef locations by 2031, and 80% of reefs will have experienced one of the
156 conditions by 2020 (Fig. 3a,b; S1a,b).

157

158 There was limited variation between the two RCPs in the projected year that the three
159 conditions favouring disease development would be reached (Fig. 3b and Fig. S1b).

160 Across all reef locations, the average difference in projections between RCP8.5 and
161 RCP4.5 was less than 1 year for the host susceptibility and pathogen virulence thresholds.
162 For the pathogen abundance metric, the average difference between the two RCPs was ~6
163 years. This difference is likely inconsequential given the standard deviation of model
164 outputs is ~6 years for both scenarios (Fig. 2e,h). The minor nature of differences in the
165 projection outputs for the two RCPs reflects the slow divergence of RCP4.5 from RCP8.5
166 over the coming two decades²². Even drastic cuts to emissions outputs and emissions

167 growth required to achieve the CO₂ concentrations characteristic of RCP4.5 do not
168 prevent all of the disease conditions set here from being surpassed at >75% of reef
169 locations by 2090 (Fig. 2 and Fig. S1b).

170

171 **Comparing coral disease and bleaching**

172 The same model ensemble for RCP8.5 was used to project the onset of annual severe
173 bleaching conditions, defined as the year in which 8 DHWs is exceeded annually during
174 the warm season²³. Currently, most corals will bleach once 8 DHWs is reached (Fig. 3),
175 and coral diversity and cover are likely to decline dramatically when temperature stress
176 of this severity begins to recur with insufficient time for recovery²³. We sought to
177 determine whether temperature conditions that favour disease development are projected
178 to occur earlier or later than annual severe coral bleaching. To make this comparison, we
179 calculated the difference in the number of years between the projected timing of any two
180 of the three temperature conditions set here for coral disease and the onset of annual
181 severe bleaching conditions (Fig. 3d). Under RCP8.5, at least two of the three disease-
182 favouring temperature conditions occurred at 96% of reef locations (Fig. 3d) before the
183 onset of annual severe bleaching (98% under RCP4.5, Fig. S1d). All three conditions
184 occur before the onset of annual severe bleaching at 40% of locations. The comparisons
185 of projected timing of disease versus bleaching conditions offered here suggest disease
186 outbreaks will be at least as great a driver of future coral reef condition and community
187 composition as bleaching.

188

189 **Anthropogenic stress patterns and disease risk**

190 Anthropogenic stress is likely to be as important a driver of coral disease dynamics over
191 the coming decades as the temperature conditions presented here²⁴⁻²⁷. The Integrated
192 Local Threat (ILT) Index²⁸ combines four threats that increase disease susceptibility:
193 increased sedimentation and nutrients associated with coastal development^{27,29,30},
194 watershed-based pollution^{26,29-32}, marine-based pollution and damage^{25,33,34}, and injuries
195 associated with fishing activities, particularly destructive fishing¹². The ILT index (500-
196 m resolution) results are resampled here to match the climate model grid used for the
197 temperature projections and the highest threat level within each model pixel is displayed
198 (Fig. 4a). This ensures the global patterns can be seen at the resolution the figure is
199 printed within the article.

200

201 Anthropogenic stress and climate stress are combined here in a disease risk summary, as
202 both are likely to drive future patterns in disease outbreak likelihood. Ecosystem impacts
203 from coral disease have the potential to be equal to or exceed those of severe bleaching
204 stress when two (or all three) of the disease-favouring conditions occur before the onset
205 of annual severe bleaching. Outbreak likelihood is also higher when anthropogenic stress
206 is either high or very high. This logic was applied to produce 5 criteria for relative
207 outbreak likelihood over the coming 20-30 years, which we describe as ‘disease risk’
208 (Fig. 4b). Locations with greater relative risk (#’s 2-5 in Fig. 4b; 22% of locations) were
209 southern Florida, the southern and eastern Caribbean, Brazil, the province of Papua in
210 Indonesia, Philippines, Japan, India, northern Maldives, the Persian Gulf and the Red Sea
211 (Fig. 4b). For the combined disease risk metric, relative risk was considered lower for
212 locations where anthropogenic stress was low or medium, a condition found for 78% (see

213 Fig. 4 caption) of reef locations. Some of these locations included Hawaii, the central and
214 south Pacific, Australia, Thailand and Madagascar (Fig. 4b). The disease risk summary
215 can be seen at the resolution of the anthropogenic stress data (500 m) in a high-resolution
216 image presented in the electronic supplementary material (see Fig. S2). The high-
217 resolution image complements Fig. 4 enabling viewers to zoom into reef locations to
218 interpret disease risk in relation to the actual rather than resampled anthropogenic stress
219 data. The disease risk summary reflects that anthropogenic stress is only high or very
220 high at 22% of locations. However, at almost all reef locations (>95%), 2 of the 3
221 temperature conditions conducive to disease development occurred before the onset of
222 annual severe bleaching. The risk of coral diseases due to climate change (ignoring
223 anthropogenic stress) is high at nearly all reef locations.

224

225 **Future applications and conclusions**

226 These are the first climate-model-based projections of conditions that influence the
227 likelihood of marine disease outbreaks. Some important complexities are necessarily
228 excluded here so that global-scale conservative projections could be produced. The main
229 examples are: 1) variation among and within coral communities and species in host
230 susceptibility due to variation in genetics related to immunity, the expression of
231 immunity genes, and exposure to environmental disturbances and anthropogenic stress, 2)
232 the potential for coral evolution of resistance, which will be highly variable among and
233 even potentially variable within species, 3) the relationships between temperature
234 conditions and the virulence of other pathogens that cause diseases in stony corals, which
235 are not as well known or understood as *Vibrio coralliilyticus* and white syndromes, and

236 4) extreme stochastic events such as extreme climatic events or the evolution of new
237 ‘super’ pathogens, which could invalidate some of the presented conclusions. Other
238 possible conditions that can increase disease susceptibility and pathogen abundance and
239 virulence that are not included here are: sediment runoff and lowered salinity following
240 monsoonal rain events, and coral injuries from cyclones ^{35,36} or predation by coral-
241 feeding gastropods ³⁷, crown-of-thorns starfish ³⁸, and reef fish ^{39,40}. Future scenarios that
242 include ocean acidification projections would also be valuable for understanding
243 conditions that increase coral disease susceptibility and pathogen virulence. Members of
244 the research community can use the data presented here to refine or produce higher-
245 resolution projections for areas for which spatially explicit data on some or all of the
246 information described above becomes available.

247

248 The standard caveats and assumptions related to the use of climate models also apply
249 ^{41,42}, and two are especially pertinent. Firstly, model resolution is coarse and a 1x1° cell
250 can contain many individual coral reefs, a fact related to the computational-intensiveness
251 of climate modeling and to modeling uncertainties (see below). While spatial variation
252 within single model cells is not resolved here, there is considerable variation within reef
253 regions in the projected timing of all three temperature conditions for disease and in
254 anthropogenic stress. Therefore, even at this resolution, the results can be used to target
255 applied research and management actions. Secondly, all climate models have
256 uncertainties and vary greatly in their capacity to project trends in key drivers of climate
257 in the tropics, such as the El Niño Southern Oscillation and its global teleconnections. We
258 include the standard deviation around the ensemble average (the ‘model spread’) for each

259 temperature condition (Fig. 2d-i). The spread in the model results is small (standard
260 deviation of 2-6.5 years), which increases confidence in the major conclusions presented
261 based on the ensemble results and supports use of the ensemble rather than one or more
262 of the individual models. A review of the robustness and uncertainties in the new CMIP5
263 climate model projections (used here) suggests that climate models are improving,
264 representing more climate processes in greater detail, and that the “*uncertainties should*
265 *not stop decisions being made*”⁴¹. For this study, the relevant decisions involve the
266 targeting of actions to reduce anthropogenic stress and trials of the efficacy of
267 interventions that reduce disease impacts and support recovery.

268

269 Currently, the role of disease as a significant driver of future reef community composition
270 is under-appreciated, especially in the Indo-Pacific, and needs to be given greater
271 consideration for at least two reasons. Disease has a tendency to result in greater coral
272 mortality than bleaching^{14,43,44}. Secondly, given the strong links between anthropogenic
273 stress and disease susceptibility^{24,26,29,30}, management actions that reduce anthropogenic
274 stress are probably more likely to reduce the prevalence and severity of coral diseases
275 than reduce the impacts of thermal bleaching. Immediate actions to reduce anthropogenic
276 stress are needed at locations with high or very high anthropogenic stress (Fig. 4a), and
277 are especially urgent at locations also predicted to experience all three temperature
278 conditions set here in the coming two decades (Fig. 4b). These sets of conditions apply to
279 ~20% of the reef locations (Fig. 4b, categories 4 and 5). These locations are priority
280 targets for proactive conservation efforts to reduce anthropogenic stress, such as
281 managing watersheds and coastal development, reducing destructive fishing, and

282 addressing other extractive practices. Furthermore, there is a need for collaborative
283 efforts between researchers and managers to both better understand disease outbreaks and
284 test reactive management interventions that reduce disease transmission rates. Examples
285 include quarantining or culling infected corals, which could be followed by actions that
286 mitigate impacts and support recovery such as managing human activities through
287 temporary closures or other use restrictions. Many of these actions (reviewed in ^{45,46}) are
288 currently experimental and only feasible at small local scales. Trials of the efficacy of
289 these actions can lead to broader implementation in the coming decades.

290

291 There is also a need for researchers and managers to expand upon the currently very
292 limited suite of tools that forecast conditions conducive to coral disease outbreaks ^{20,47}.
293 New early warning systems will need to be built into coral disease response plans. Such
294 plans can help managers consider and justify various decisions and investments in both
295 targeted monitoring and trials/implementation of actions to reduce disease impacts and
296 support recovery. A coral disease response plan framework has been developed for the
297 Great Barrier Reef in Australia ³⁹ and for Hawaii but coral disease response plans have
298 not been as widely adopted as coral bleaching response plans ⁴⁶.

299

300 Perhaps more than any findings to date, the results presented herein indicate that
301 increases in the prevalence and severity of coral diseases will be a major future driver of
302 decline and changes in coral reef community composition, and at least as great a driver as
303 coral bleaching. Elevated temperatures that increase host susceptibility, pathogen
304 abundance or virulence are either already occurring or are projected to occur in the
305 coming decades at almost all reef locations. This is true irrespective of whether nations

306 are able to sufficiently cut emissions such that RCP4.5 better characterizes our emissions
307 trajectory than RCP8.5. There is great spatial variation in the projected timing of the
308 disease-favouring conditions, which is in keeping with much new research highlighting
309 that the impacts of climate change will not be spatially uniform. The spatial variation in
310 the projections we present also emphasises the value for decision-making of developing
311 near real-time early warning systems and seasonal outlooks for marine diseases.

312

313 **Methods**

314

315 **Climate model data:** Monthly sea surface temperature (SST) data were retrieved for
316 each available GCM from the World Climate Research Programme's CMIP5 data set
317 (from <http://www.esg.llnl.gov>) for RCP8.5 (n=33) and RCP4.5 (n=35, see Table S1 for
318 list of models). Methods for matching the start of each model with the observed
319 climatology used (1982-2005), correcting model means, replacing annual cycles, and
320 interpolation routines are all as per⁴⁸. Projections produced are based on model runs that
321 are then averaged, rather than on ensemble means^{23,48}, ensuring variance among models
322 is examined and presented for each projection output (Fig. 2d-i).

323

324 **Temperature conditions that increase disease susceptibility and/or pathogen**

325 **virulence:** Three temperature conditions are examined that increase the susceptibility of
326 coral hosts to disease or increase pathogen abundance or virulence.

327 For all of the projected conditions, results are shown for reef locations only (also as per
328⁴⁸) rasterised to match the climate model grid (n=1748 pixels or 'reef locations').

329 Histograms and plots of the spread in results (average ± 1 stdev) from the climate models

330 are presented for each temperature condition with percentages based on the total number
331 of reef locations.

332

333 **(1) Host susceptibility:** Field studies from all reef regions have shown that coral
334 diseases often follow sub-lethal bleaching, presumably when energy and
335 resources required for the maintenance of disease resistance are reduced ^{14,16,49-51}.
336 For sensitive species globally, thermal stress represented by 4 Degree Heating
337 Weeks (DHWs) is a conservative threshold for predicting the presence of sub-
338 lethal bleaching, since the global optimum predictor of bleaching is slightly
339 higher at ~6 DHWs ⁵². Here, our ‘host susceptibility’ metric identifies when a
340 decade starts in which thermal stress is projected to exceed 4 DHWs at least 3
341 times. This frequency was selected because the return period is so short (~3 years)
342 that corals will likely struggle to recover between bleaching events thus remaining
343 in a weakened and therefore susceptible state.

344 **(2) Pathogen abundance:** Research on diseases affecting agricultural crops indicates
345 that survival rates of both causative agents and disease vectors increase during
346 anomalously warm winters (called ‘overwintering’ ⁶). While many long-term
347 studies of coral diseases detect higher levels of disease prevalence when
348 temperatures peak ¹², a common group of coral diseases, white plague and white
349 syndromes, have been found in higher abundances during warm summers that
350 follow mild winters (neither excessively cool or warm ²⁰). This is likely due to a
351 combination of overwintering and increased host susceptibility because warmer
352 winters provide less of a reprieve for corals between warm seasons. Here, the

353 'pathogen abundance' metric indicates the first year in which the means of the
354 three months centered on the coolest month are $\geq 0.5^{\circ}\text{C}$ above the minimum
355 monthly mean (coolest month) calculated from a 1982-2008 climatology. This
356 roughly equates to the thermal stress associated with mild winters in ²⁰ of 2-6.5
357 $^{\circ}\text{C}$ -weeks, which are calculated from a higher baseline than is used here and
358 which resulted in an increased abundance of white syndromes in Australia during
359 the following summers.

360 **(3) Pathogen virulence:** The model coral pathogen used here, *Vibrio coralliilyticus*,
361 is the causative agent of a number of virulent white syndromes on Indo-Pacific
362 corals, causing progressive tissue loss and ultimately, whole colony mortality. We
363 reviewed experimental studies and related the temperatures at which the virulence
364 and host-seeking motility behaviors (i.e., chemotaxis and chemokinesis) of this
365 pathogen are augmented to the maximum monthly mean (MMM, warmest month)
366 at each sampling location (see Table S2). For each of three strains of *V.*
367 *coralliilyticus*, the pathogen becomes virulent within 2.5 $^{\circ}\text{C}$ of the MMM
368 calculated for the period 1982-2008 at the respective sampling location, so we
369 conservatively set the threshold as MMM (1982-2008). Here, the metric
370 'pathogen virulence' identifies when the number of months in which temperatures
371 exceed the MMM becomes twice that observed, on average, during 2006-2011.
372 This represents the timing of anticipated increases in virulence and in the
373 projected number of months corals are exposed to the virulent pathogen.

374
375 Maps and histograms (standardised to the total number of reef locations) are presented
376 for: a) the earliest year by which at least one disease condition will be met, b) the year by

377 which all three disease conditions will be met, (c) the year from which annual severe
378 bleaching stress is projected, and (d) the difference between the year by which at least
379 two of the three disease conditions are met and the onset of annual severe bleaching (8
380 DHWs).

381

382 A map is also presented of anthropogenic stress using the Integrated Local Threat (ILT)
383 index developed for Reefs at Risk Revisited²⁸, as is described in the paper. We resample
384 these data to our climate model grid by taking the highest level of stress within each
385 model pixel to produce a visual summary interpretable at article-resolution. The disease
386 risk summary presented for RCP8.5 grades risk based on 5 criteria: 1) none of the
387 following criteria apply; 2) two of three climate stressors occur before the onset of annual
388 severe bleaching and anthropogenic stress is high; 3) as for criterion 2 but anthropogenic
389 stress is very high; 4) all three climate stressors occur before the onset of annual severe
390 bleaching and anthropogenic stress is high; and 5) as for criterion 4 but anthropogenic
391 stress is very high. A 500-m resolution image of the disease risk summary is provided as
392 electronic supplementary material enabling readers to zoom into reefs of interest to see
393 which reefs meet the criteria set. The percentage values cited in the paper for reef pixels
394 that meet each of the five criteria are derived at 500-m resolution rather than from the
395 resampled data.

396

397

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551

552 **Author contributions**

553 JM, CDH, CME, SFH, RvH, BW, MG, JL and GW designed the study. RvH compiled
554 and analysed the climate model data in collaboration with JM. MP conducted the spatial
555 analysis required to build the maps upon which Figs. 3 and 4 and Figs. S1 and S2 are
556 based in collaboration with JM. JM, CDH, CME and BW wrote the manuscript with
557 assistance from all other authors.

558 **Competing financial interests statement**

559 The authors declare no competing financial interests.

560 **Supplementary Information**

561 Supplementary Information is linked to the online version of the paper at

562 www.nature.com/nature and includes a table listing the climate models used, a review of

563 experimental studies that examined the effects of temperature on *Vibrio coralliilyticus*, a
564 panel figure for RCP4.5 that matches Fig. 3 here, and a 500-m resolution disease risk
565 summary figure that complements Fig. 4 here.
566

567 **Fig. Legends**

568 **Figure 1. Projections of temperature conditions that increase host susceptibility (a),**
 569 **pathogen abundance (b), and pathogen virulence (c) under RCPs 8.5 and 4.5.** The
 570 conditions and condition thresholds are: (a) *Host susceptibility* – year in which thermal
 571 stress first exceeds 4 DHWs 3x per decade; (b) *Pathogen abundance* – first year in which
 572 the 3 cool season months exceed 0.5 °C above the minimum monthly mean (1982-2008);
 573 (c) *Pathogen virulence* – year in which the number of months of temperatures \geq max
 574 monthly mean (1982-2008) is twice that observed on average from 2006-2011. See Table
 575 S1 for a list of climate models.

576
 577 **Figure 2. Histograms and model means and spreads for the projections of**
 578 **temperature conditions under RCPs 8.5 and 4.5.** For the histograms (top row), bins are
 579 5-year intervals and n=1748 reef locations. For model means and spreads (2 bottom
 580 rows), means are shown as the bold line and spreads are the mean \pm 1 stdev (grey shade).
 581 These data correspond to the model projections shown as maps in Fig. 1. See Table S1
 582 for a list of climate models.

583
 584 **Figure 3. Summaries of projections for disease and bleaching conditions under**
 585 **RCP8.5.** The earliest year (a) is the first year in which at least one of the three
 586 temperature conditions for disease shown in Fig. 1 will be reached. The year in which all
 587 three temperature conditions will be reached is shown in (b). The onset of annual severe
 588 bleaching is shown in (c), defined as temperature stress annually exceeding 8 DHWs
 589 (from ²³). The difference in timing between when at least 2 of the 3 temperature
 590 conditions for disease shown in Fig. 1 will be reached and (c) is shown in (d). Negative
 591 values in (d) mean at least 2 of the 3 temperature conditions for disease are projected to
 592 occur before annual severe bleaching conditions (96% of reef locations).

593
 594 **Figure 4. Anthropogenic stress patterns and disease risk based on exposure to**
 595 **anthropogenic and climate stress.** Anthropogenic stress (a) is a resampling of the Reefs
 596 at Risk Revisited ²⁸ Integrated Local Threat index to the climate model grid used in Figs.
 597 1 and 3; the highest value for stress within each model pixel is retained so that
 598 approximate global patterns can be interpreted at this resolution. Disease risk (b), in
 599 relative terms, relates to whether: 2 or 3 of the temperature conditions (from Fig. 1) occur
 600 before annual severe bleaching (ASB) (see Fig. 3c), and anthropogenic stress is high or
 601 very high. Reef location (model cell) counts and percentages are as follows and are from
 602 the 500-m resolution data, which are presented within Fig. S2: 1 (353485, 78%), 2
 603 (35975, 8%), 3 (23378, 5%), 4 (25184, 6%), 5 (13375, 3%).
 604