

1 **The projected timing of abrupt ecological disruption from climate**
2 **change**

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13 **As anthropogenic climate change continues, the risks to biodiversity will increase**
14 **over time, with future projections indicating a potentially catastrophic loss of global**
15 **biodiversity on the horizon¹⁻³. However, our understanding of how this climate-**
16 **driven disruption of biodiversity will unfold over time is limited because**
17 **biodiversity forecasts typically focus on individual snapshots of the future. Here, we**
18 **use annual projections (1850-2100) of temperature and precipitation across**
19 **>30,000 marine and terrestrial species' ranges to estimate the timing of species**
20 **exposure to potentially dangerous climate conditions. We project that future**
21 **disruption of ecological assemblages from climate change will be abrupt, because**
22 **within any given ecological assemblage the exposure of most species to climate**
23 **conditions beyond their realised niche limits occurs near simultaneously. Under a**
24 **high emissions scenario (RCP8.5), such abrupt exposure events begin before 2030 in**
25 **tropical oceans and spread to tropical forests and higher latitudes by 2050. Below**
26 **2°C global warming, <2% of assemblages globally are projected to undergo abrupt**
27 **exposure events of >20% of their constituent species, but the risk accelerates with**
28 **the magnitude of warming, threatening 15% of assemblages at 4°C, with similar**
29 **levels of risk in protected and unprotected areas. These results highlight the**
30 **impending risk of sudden and severe biodiversity losses from climate change and**
31 **provide a framework for predicting both when and where these events may occur.**
32
33

34 **Introduction**

35 Climate change is projected to become a leading driver of biodiversity loss¹, but when
36 during this century might ecological assemblages suffer such losses, and will the process be
37 gradual or abrupt? Existing biodiversity forecasts typically lack the temporal perspective
38 needed to answer this question because they indicate the number and locations of species
39 threatened by climate change for just a snapshot of the future, often around the end of the
40 century¹⁻³. These snapshots do not account for the temporally dynamic nature of ecological
41 disruption expected due to climate change, often focus at the level of species rather than
42 ecological assemblages, and can seem remote to decision-makers concerned with managing
43 more immediate risks⁴. Indeed, many of the most sudden and severe ecological impacts of
44 climate change can occur when conditions become unsuitable for multiple co-occurring
45 species simultaneously, causing catastrophic die-offs and abrupt 'regime shifts' in
46 ecological assemblages^{5,6}.

47 Forecasting the temporal dynamics of climate-driven disruption of ecological
48 assemblages thus requires quantifying the differences among species in the time at which
49 their climate niche limits may be locally exceeded. Developing advance warnings of the risk
50 of gradual or abrupt ecological disruption is an urgent priority⁷⁻⁹. A temporal perspective is
51 also important for adaptation. Reducing emissions and delaying the onset of exposure to
52 dangerous climate conditions, even by a few decades, could buy valuable time for ecological
53 assemblages to adapt^{10,11}, potentially reducing the magnitude of ecological disruption.
54 However, despite the clear importance of a temporal perspective in understanding and
55 managing climate change threats to biodiversity, we lack a general understanding of the
56 time at which species in ecological assemblages will be exposed to climate conditions
57 beyond their niche limits.

58

59 **The biodiversity climate horizon**

60 To describe the projected timing of exposure of species to climate conditions beyond their
61 niche, we developed an approach based on species historical climate limits and future
62 climate projections. The range of climate conditions, both over space and time, under which
63 a species has been recorded in the wild demarcates the boundaries of its realised niche¹².
64 The projected time in the future at which these bounds are exceeded due to climate change
65 at a site can therefore be thought of as representing a climate horizon, beyond which
66 evidence for the species' ability to persist in the wild is lacking. Over this horizon lies, at
67 best, a sizeable increase in uncertainty about species survival and, at worst, local
68 extinction¹³. For a given species assemblage, the cumulative percentage of species over
69 time that have been locally exposed to climate conditions exceeding their realised niche
70 limits reveals what we term the 'horizon profile' (Fig. 1). The shape of this horizon profile
71 provides information on the potential for climate-driven disruption of species assemblages
72 over time—especially the risk of early or abrupt disruption—that is not evident when
73 focusing on individual climate snapshots.

74 We constructed horizon profiles for species assemblages globally, delimiting
75 assemblages as the species occurring in 100km grid cells based on expert verified
76 geographic range maps for 30,652 species of birds, mammals, reptiles, amphibians, marine
77 fish, benthic marine invertebrates, krill, cephalopods and habitat forming corals and
78 seagrasses¹⁴ (Supplementary Table 1). We used climate projections throughout the 21st
79 century from 22 climate models and three Representative Concentration Pathways (RCPs):

80 strong mitigation (RCP2.6), moderate mitigation (RCP4.5), and a high emissions scenario
81 (RCP8.5)¹⁵ (Supplementary Table 2). Given the importance of temperature as a driver of
82 species metabolism and geographic ranges¹⁶⁻¹⁸, we focus on mean annual temperature as
83 the main proxy for climate. However, because species may be sensitive to other climate
84 variables that may respond differently to greenhouse gas emissions, we also generated
85 horizon profiles using maximum monthly temperatures and terrestrial annual
86 precipitation (see Methods).

87 For each species at a site (i.e., 100km grid cell), we defined the local species
88 exposure time as the year after which projected local temperatures *consistently* exceed, for
89 at least five years, the maximum temperature experienced by the species across its
90 geographic range during historical climate projections (1850–2005) (Supplementary Fig.
91 1). For species that breed annually or near-annually, five years represents a significant
92 number of breeding seasons at temperatures beyond which they have never been recorded
93 (a 20-year window yielded very similar results (Supplementary Figs. 2 and 3)). This
94 approach for quantifying exposure bears similarities to the concept of ‘time of emergence’
95 in climate science, defined as the time at which the signal of anthropogenic climate change
96 at a location emerges from the envelope of historical climate variability^{19,20}. The key
97 distinction is that we define exposure relative to each species’ realised climatic niche limits
98 rather than the historical conditions realised at a single site.

99 The shape of horizon profiles, and the potential ecological disruption they imply, can
100 vary substantially across assemblages (Fig. 1). To summarize each horizon profile, we focus
101 on three key features: (1) timing, the median year for an assemblage when species
102 exposure to unprecedented climate occurs; (2) magnitude, the percentage of species locally
103 exposed; and (3) abruptness, the synchronicity in the timing of exposure among species in
104 an assemblage, measured as the percentage of all species exposure times that occur in the
105 decade of maximum exposure (Fig. 1a).

106 **Timing, magnitude and abruptness of horizon profiles**

108 Under RCP8.5, 81% of terrestrial and 37% of marine assemblages are projected to have at
109 least one species exposed to unprecedented mean annual temperatures (i.e., beyond
110 historical niche limits) before 2100. Despite the lower magnitude of warming, the
111 magnitude of exposure is greatest in the tropics, where narrow historical climate
112 variability²⁰ and shallow thermal gradients²¹, result in many species occurring near their
113 upper realised thermal limits throughout their geographic range. In total, 68% of terrestrial
114 and 39% of tropical marine assemblages are projected to have >20% of their constituent
115 species exposed to unprecedented temperatures by 2100, compared to 7% of terrestrial
116 and 1% of marine assemblages outside the tropics (Fig. 2a). The Amazon, Indian
117 subcontinent and Indo-Pacific regions are most at risk, with >90% of species in any
118 assemblage exposed to unprecedented temperatures by 2100 (Fig. 2a). Horizon profiles for
119 mean annual and maximum monthly temperatures show strong correspondence (Extended
120 Data Figs. 1 and 2). In contrast, few species undergo prolonged exposure to unprecedented
121 high or low annual precipitation before 2100 (Extended Data Figs. 1 and 2), in agreement
122 with greater variability in precipitation projections²². Thus, throughout we focus on
123 exposure to changes in temperature.

124 The most striking feature of horizon profiles for local assemblages is their
125 abruptness (Figs. 1 and 2b). Under RCP8.5, on average 71% (median) of local species

126 exposure times for any given assemblage are projected to occur within a single decade (Fig.
127 3a-b), with the abruptness of exposure higher among marine assemblages (median
128 abruptness = 89%, Fig. 3a) than on land (median abruptness = 61%, Fig. 3b). This pattern
129 of highly synchronized species exposure within assemblages is robust to the choice of
130 climate model (RCP8.5 median abruptness ranges from 60% to 79%, Extended Data Figs. 3
131 and 4), emissions scenario (median abruptness = 83% for RCP2.6 and 72% for RCP4.5),
132 metric of abruptness (Extended Data Fig. 4), and when calculating exposure for maximum
133 monthly (median abruptness = 68%) rather than mean annual temperatures (Extended
134 Data Figs. 1 and 2). The same pattern of abruptness is also evident for horizon profiles
135 constructed separately for each taxonomic group within local assemblages (Extended Data
136 Fig. 4). Marine organisms, especially seagrasses, corals, cephalopods, marine reptiles and
137 mammals exhibit the most abrupt profiles, but it is the consistency of abruptness across
138 groups rather than the differences that is most notable. Similarly, although abruptness for
139 assemblages varies spatially, being greatest in the Amazon, Indian subcontinent, Sahel and
140 Northern Australia, as well as tropical oceans, abrupt horizon profiles are the general rule
141 both within the tropics (median abruptness = 79%) and at higher latitudes (median
142 abruptness = 59%) (Fig. 2b).

143 This pervasive pattern of abrupt exposure arises primarily because co-occurring
144 species often share similar realised thermal limits, rather than abruptness being dependent
145 on higher rates of warming (Extended Data Fig. 5). Clustering of species realised thermal
146 limits can, in part, be explained by shared geographic boundaries or, for tropical species, by
147 the upper limits of temperatures available on Earth^{13,23}. However, even for assemblages
148 where this is not the case because a high percentage of species have warmer temperatures
149 available within 1000km of their range edge, assemblage exposure is still projected to
150 occur abruptly (Extended Data Fig. 5), suggesting that other processes, such as ecological
151 interactions²⁴ or evolutionary conservatism in fundamental niches^{25,26}, lead to similarity in
152 realised niche limits^{16,27} and thus abruptness in the timing of exposure.

153 The synchronicity of species exposure within assemblages means the timing of
154 assemblage-level exposure events is well-described by the median of species exposure
155 times at a site (Extended Data Fig. 6). Under RCP8.5, the global mean year of assemblage-
156 level exposure is 2074 (± 11 years s.d.), but there is considerable variation in the timing of
157 exposure across assemblages (Fig. 2c). In some locations—such as the Caribbean and Coral
158 Triangle—exposure is predicted to be already underway, with these hotspots of exposure
159 expanding in spatial extent over time (Fig. 2c, Extended Data Fig. 7). By 2050, exposure
160 spreads beyond ocean ecosystems to iconic terrestrial ecosystems, such as the Amazon and
161 Congolese rainforests (Fig. 2c, Extended Data Fig. 7). Notably, the timing of these
162 assemblage-level exposure events is not well predicted by the timing of local climate
163 emergence (Spearman's $\rho = 0.29$; Extended Data Fig. 5). And the timing of abrupt exposure
164 events lags behind local climate emergence by 42 years (mean ± 12 years s.d.), indicating the
165 potential time-lag between climate change and ensuing biotic responses.

166 We find that the appearance of a gradual increase in risk to biodiversity globally can
167 result from summarising across local assemblages that differ in their projected timing of
168 abrupt exposure (Figs. 3c-d, Extended Data Fig. 8). Although these global summaries mask
169 the abrupt nature of exposure within local assemblages, they can highlight the importance
170 of increased mitigation efforts in reducing and delaying the onset of unprecedented climate
171 conditions. Compared to RCP8.5, achieving RCP2.6 delays exposure for the most at risk

172 species by circa six decades in the oceans (mean = 58 years, range = 46-65 years, Fig. 3c)
173 and on land (mean = 58 years, range = 49-67 years, Fig. 3d), buying valuable time for
174 species and ecosystems, and human societies that depend upon them, to adapt to a
175 warming climate.

176

177 **The risk of abrupt exposure events**

178 The abruptness of horizon profiles is positively correlated with the magnitude of exposure
179 (Spearman's $\rho = 0.58$; Extended Data Fig. 6), indicating a form of double jeopardy, whereby
180 exposure events involving larger fractions of species are projected to occur more abruptly.
181 This near-simultaneous exposure among multiple species could have sudden and
182 devastating effects on local biodiversity and ecosystem services. Catastrophic, multi-
183 species coral die-offs caused by a record-breaking marine heatwave in 2016 are one recent
184 example⁶. Although it remains uncertain where "safe limits" of species loss for maintaining
185 ecosystem function are located, meta-analyses suggest a 20% decline in species diversity as
186 one possible threshold^{28,29}. We therefore defined assemblages at risk of abrupt ecological
187 disruption as those where at least 20% of species are projected to undergo exposure to
188 unprecedented temperatures within the same decade. Holding warming to $<2^{\circ}\text{C}$ above pre-
189 industrial levels limits such abrupt assemblage exposure events to $<2\%$ of assemblages
190 (Fig. 3e). However, beyond 2°C warming the area projected to undergo abrupt assemblage
191 exposure expands rapidly, encompassing 15% of assemblages globally for 4°C warming.
192 Furthermore, the increase in abrupt exposure does not differ markedly for assemblages
193 afforded high habitat protection ($\geq 20\%$ protected area coverage of a grid cell), indicating
194 that current protected areas are equally at risk from abrupt exposure (Fig. 3e).

195 The risk of abrupt exposure events differs across assemblages globally, with variability
196 across individual climate projections increasing the total area at risk compared to median
197 projections. For instance, even under RCP2.6 (1.75°C mean warming), 9% of assemblages
198 are at some risk of abrupt exposure (Fig. 4a), increasing to 35% of assemblages under
199 RCP8.5 (4.4°C mean warming; Fig. 4b). The risk of abrupt assemblage exposure events is
200 positively correlated with species richness (RCP8.5, Spearman's $\rho = 0.29$ (land) and 0.56
201 (ocean)), highlighting the increased risk of sudden ecological disruption in the world's
202 most biodiverse ecosystems. Moreover, the risk of disruption of ecological function may be
203 underestimated in this analysis because even if particular functional groups (e.g., habitat
204 forming corals) suffer high levels of exposure, this may not be evident at the scale of entire
205 assemblages if other groups are relatively less affected. When abrupt assemblage exposure
206 events are instead defined at the level of major taxonomic groups, the area at risk expands
207 further, encompassing 49% of species assemblages under RCP8.5 (Fig. 4c, Extended Data
208 Fig. 9). Our approach estimates how much of an assemblage's original biodiversity is
209 exposed to potentially dangerous climate conditions over time²⁸. We do not consider the
210 potential for immigration of species from elsewhere to offset local biodiversity losses, but
211 abrupt assemblage-wide exposure is likely to precipitate substantial ecological disruption
212 regardless of the rate at which new species arrive. Furthermore, in tropical lowlands and
213 oceans, where projected exposure is greatest, and warmer adapted species are lacking, net
214 declines in local biodiversity are expected²¹.

215

216 **Crossing the biodiversity climate horizon**

217 While the horizon profile describes the accumulating number of co-occurring species
218 exposed to conditions beyond their realised niche limits, this need not equate with a profile
219 of local extinction. Species may have wider fundamental than realised niche limits^{13,30}, may
220 avoid exposure in microclimatic refugia (but see Extended Data Fig. 10) or via behavioural
221 thermoregulation^{17,31}, or may evolve to tolerate novel conditions¹⁰. In these cases, the
222 timing of abrupt assemblage exposure events could be considered an ‘ignorance horizon’,
223 marking the time beyond which local extinctions are not inevitable but evidence for the
224 ability of species to persist in the wild is largely absent¹³. Thus, at the very least, our results
225 show that within 30 years, continued high emissions will drive a sudden shift across many
226 ecological assemblages to climate conditions under which we have almost no knowledge of
227 the ability of their constituent species to survive. Furthermore, we caution that the timing
228 and magnitude of this exposure may occur earlier and be larger than we anticipate, because
229 our analysis does not consider changes in extreme events⁹, effects of warming on local
230 habitat (e.g. melting sea ice), covariation between climate variables³², or that populations
231 may be locally adapted³³.

232 To the extent that species realised historical thermal limits do reflect fundamental
233 limits to persistence then the occurrence of abrupt exposure events marks the crossing of
234 an ‘ecological horizon’ beyond which catastrophic and coordinated species losses are
235 expected. These abrupt events—projected to spread from ocean (e.g., coral reef) to land
236 (e.g., rainforest) ecosystems by 2050 under high emissions—risk sudden disruption to
237 ecosystems and their capacity to maintain current levels of biodiversity and functioning.
238 Evidence from lab and field-based studies indicates this is a credible risk, particularly for
239 tropical terrestrial ectotherms and for marine organisms for which projected abruptness is
240 most pronounced and for which realised geographic range boundaries most closely match
241 thermal tolerance limits^{16,18,30,34}. Indeed, warming over recent decades has already been
242 associated with drastic population declines and local extinctions^{6,35,36}, even amongst
243 endotherms which are widely assumed to be less sensitive to warming but may be
244 particularly vulnerable to climate driven disruption of trophic interactions^{37,38}. For those
245 ecosystems where exposure is projected within the next few decades, the capacity for
246 species to adapt would appear limited. A priority for future research is to refine estimates
247 of the timing and consequences of exposure, including where factors other than
248 temperature may more strongly constrain species ranges, and where the emergence of
249 novel climates has closest analogues deep in Earth’s history³⁹.

250 Considering the temporal dynamics of biodiversity exposure to climate change
251 provides an early warning system of the potential for abrupt ecological disruption.
252 Averting, or at least delaying, the crossing of this ecological horizon is possible for most
253 assemblages, and requires massive and rapid reductions in greenhouse gas emissions.
254 Elsewhere, our results highlight the urgency of targeted management responses, including
255 establishing monitoring sites in exposed regions, new protected areas in refugia, and the
256 potential for assisted migration and adaptation.

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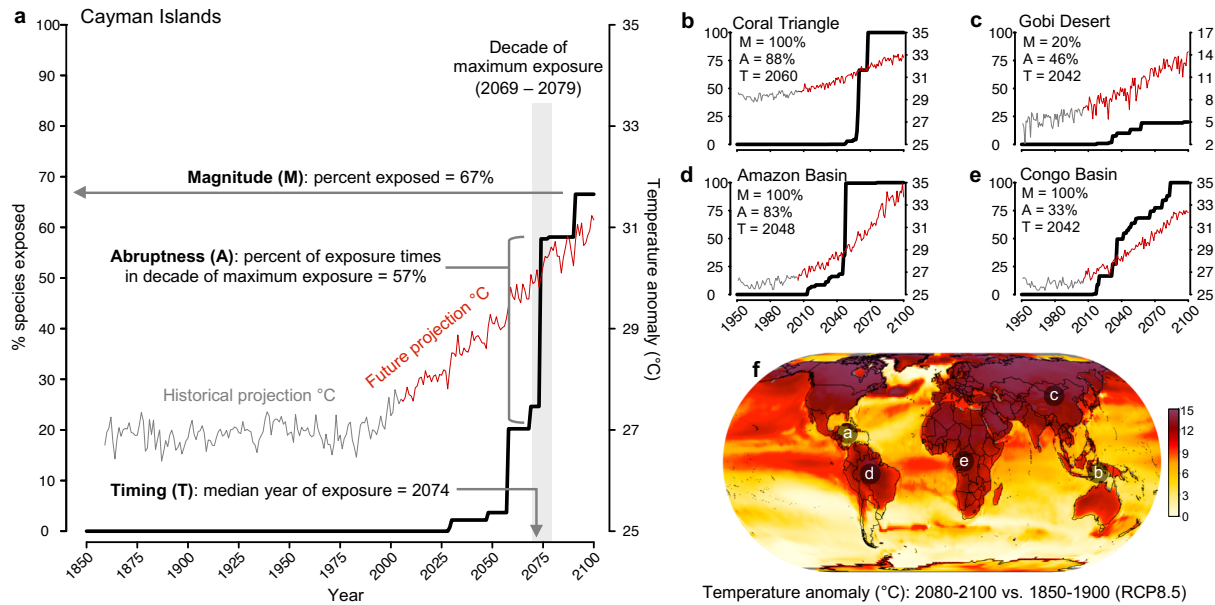
258 **References**

- 259
- 260 1. Urban, M. C. Climate change. Accelerating extinction risk from climate change. *Science* **348**,
- 261 571–573 (2015).
- 262 2. Warren, R., Price, J., Graham, E., Forstenhaeusler, N. & VanDerWal, J. The projected effect on
- 263 insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*
- 264 **360**, 791–795 (2018).
- 265 3. Newbold, T. Future effects of climate and land-use change on terrestrial vertebrate
- 266 community diversity under different scenarios. *Proc. Biol. Sci.* **285**, (2018).
- 267 4. Weber, C. *et al.* Mitigation scenarios must cater to new users. *Nat. Clim. Chang.* **8**, 845–848
- 268 (2018).
- 269 5. Wernberg, T. *et al.* Climate-driven regime shift of a temperate marine ecosystem. *Science*
- 270 **353**, 169–172 (2016).
- 271 6. Hughes, T. P. *et al.* Global warming transforms coral reef assemblages. *Nature* **556**, 492–496
- 272 (2018).
- 273 7. Barnosky, A. D. *et al.* Approaching a state shift in Earth’s biosphere. *Nature* **486**, 52–58
- 274 (2012).
- 275 8. Scheffer, M. *et al.* Early-warning signals for critical transitions. *Nature* **461**, 53–59 (2009).
- 276 9. Harris, R. M. B. *et al.* Biological responses to the press and pulse of climate trends and
- 277 extreme events. *Nature Climate Change* vol. 8 579–587 (2018).
- 278 10. Bay, R. A., Rose, N. H., Logan, C. A. & Palumbi, S. R. Genomic models predict successful coral
- 279 adaptation if future ocean warming rates are reduced. *Sci Adv* **3**, e1701413 (2017).
- 280 11. Chevin, L.-M., Lande, R. & Mace, G. M. Adaptation, Plasticity, and Extinction in a Changing
- 281 Environment: Towards a Predictive Theory. *PLoS Biol.* **8**, e1000357 (2010).
- 282 12. Colwell, R. K. & Rangel, T. F. Hutchinson’s duality: The once and future niche. *Proceedings of*
- 283 *the National Academy of Sciences* **106**, 19651–19658 (2009).
- 284 13. Feeley, K. J. & Silman, M. R. Biotic attrition from tropical forests correcting for truncated
- 285 temperature niches. *Glob. Chang. Biol.* **16**, 1830–1836 (2009).
- 286 14. IUCN. The IUCN Red List of Threatened Species. Version 2017.
- 287 15. van Vuuren, D. P. *et al.* The representative concentration pathways: an overview. *Clim.*
- 288 *Change* **109**, 5–31 (2011).
- 289 16. Stuart-Smith, R. D., Edgar, G. J. & Bates, A. E. Thermal limits to the geographic distributions
- 290 of shallow-water marine species. *Nat Ecol Evol* **1**, 1846–1852 (2017).
- 291 17. Sunday, J. M. *et al.* Thermal-safety margins and the necessity of thermoregulatory behavior
- 292 across latitude and elevation. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 5610–5615 (2014).
- 293 18. Dillon, M. E., Wang, G. & Huey, R. B. Global metabolic impacts of recent climate warming.
- 294 *Nature* **467**, 704–706 (2010).
- 295 19. Hawkins, E. & Sutton, R. Time of emergence of climate signals. *Geophys. Res. Lett.* **39**, (2012).
- 296 20. Mora, C. *et al.* The projected timing of climate departure from recent variability. *Nature* **502**,
- 297 183–187 (2013).
- 298 21. Colwell, R. K., Brehm, G., Cardelús, C. L., Gilman, A. C. & Longino, J. T. Global warming,
- 299 elevational range shifts, and lowland biotic attrition in the wet tropics. *Science* **322**, 258–
- 300 261 (2008).
- 301 22. IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I*
- 302 *to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
- 303 (Cambridge University Press).
- 304 23. Williams, J. W., Jackson, S. T. & Kutzbach, J. E. Projected distributions of novel and
- 305 disappearing climates by 2100 AD. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 5738–5742 (2007).

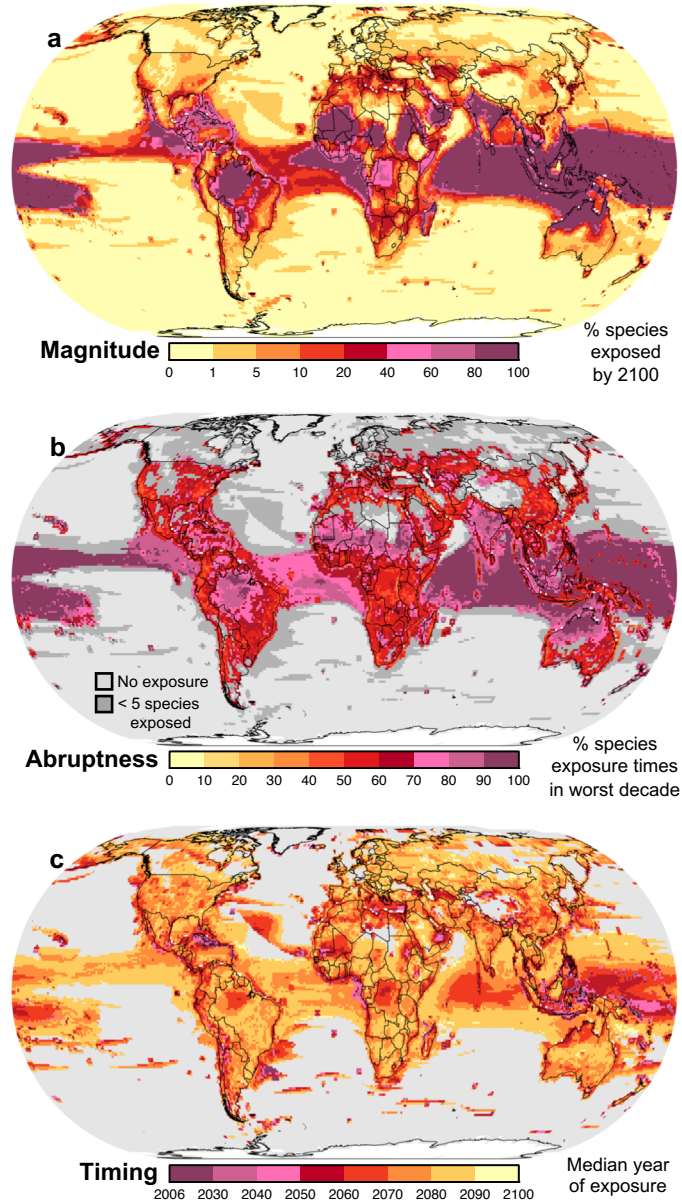
- 306 24. Liataud, K., van Nes, E. H., Barbier, M., Scheffer, M. & Loreau, M. Superorganisms or loose
307 collections of species? A unifying theory of community patterns along environmental
308 gradients. *Ecol. Lett.* **22**, 1243–1252 (2019).
- 309 25. Araújo, M. B. *et al.* Heat freezes niche evolution. *Ecol. Lett.* **16**, 1206–1219 (2013).
- 310 26. Crisp, M. D. *et al.* Phylogenetic biome conservatism on a global scale. *Nature* **458**, 754–756
311 (2009).
- 312 27. White, A. E., Dey, K. K., Mohan, D., Stephens, M. & Price, T. D. Regional influences on
313 community structure across the tropical-temperate divide. *Nat. Commun.* **10**, 2646 (2019).
- 314 28. Newbold, T. *et al.* Has land use pushed terrestrial biodiversity beyond the planetary
315 boundary? A global assessment. *Science* **353**, 288–291 (2016).
- 316 29. Hooper, D. U. *et al.* A global synthesis reveals biodiversity loss as a major driver of
317 ecosystem change. *Nature* **486**, 105–108 (2012).
- 318 30. Sunday, J. M., Bates, A. E. & Dulvy, N. K. Thermal tolerance and the global redistribution of
319 animals. *Nature Climate Change* vol. 2 686–690 (2012).
- 320 31. Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L. & Sunday, J. M. Greater vulnerability
321 to warming of marine versus terrestrial ectotherms. *Nature* **569**, 108–111 (2019).
- 322 32. Mahony, C. R. & Cannon, A. J. Wetter summers can intensify departures from natural
323 variability in a warming climate. *Nature Communications* vol. 9 (2018).
- 324 33. Valladares, F. *et al.* The effects of phenotypic plasticity and local adaptation on forecasts of
325 species range shifts under climate change. *Ecol. Lett.* **17**, 1351–1364 (2014).
- 326 34. Deutsch, C. A. *et al.* Impacts of climate warming on terrestrial ectotherms across latitude.
327 *Proc. Natl. Acad. Sci. U. S. A.* **105**, 6668–6672 (2008).
- 328 35. Sinervo, B. *et al.* Erosion of lizard diversity by climate change and altered thermal niches.
329 *Science* **328**, 894–899 (2010).
- 330 36. Soroye, P., Newbold, T. & Kerr, J. Climate change contributes to widespread declines among
331 bumble bees across continents. *Science* **367**, 685–688 (2020).
- 332 37. Lister, B. C. & Garcia, A. Climate-driven declines in arthropod abundance restructure a
333 rainforest food web. *Proc. Natl. Acad. Sci. U. S. A.* (2018) doi:10.1073/pnas.1722477115.
- 334 38. Spooner, F. E. B., Pearson, R. G. & Freeman, R. Rapid warming is associated with population
335 decline among terrestrial birds and mammals globally. *Glob. Chang. Biol.* **24**, 4521–4531
336 (2018).
- 337 39. Burke, K. D. *et al.* Pliocene and Eocene provide best analogs for near-future climates. *Proc.*
338 *Natl. Acad. Sci. U. S. A.* **115**, 13288–13293 (2018).
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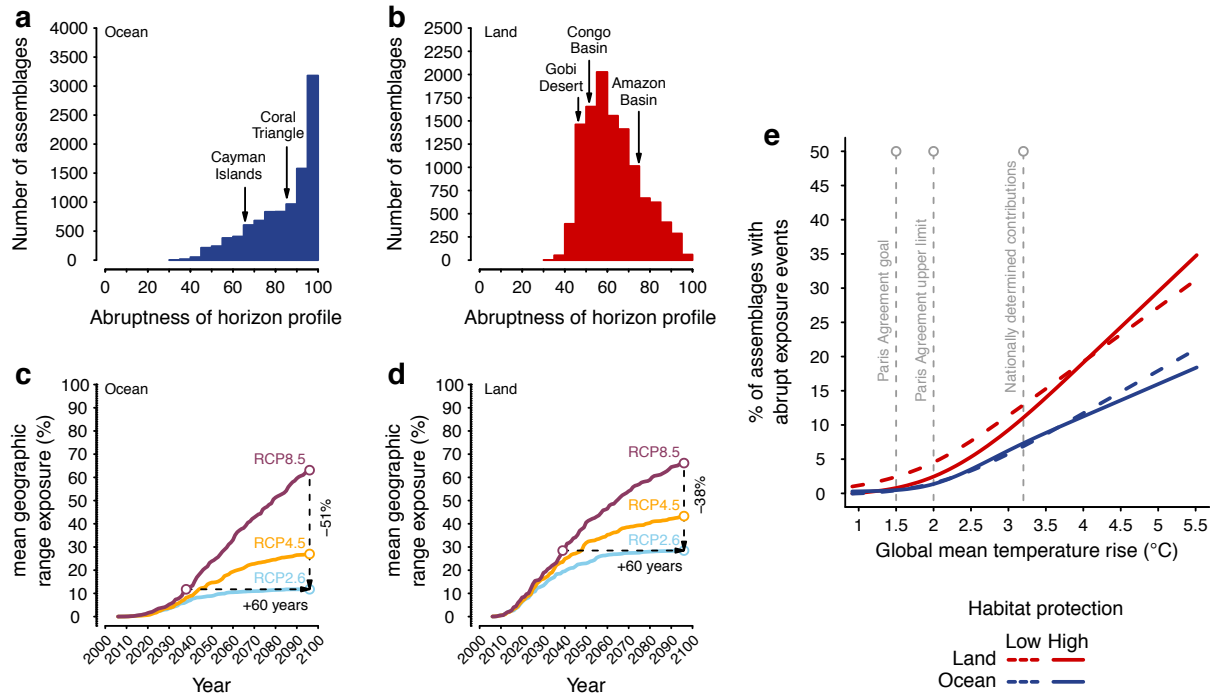


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 343 **Figure 1. Biodiversity climate horizon profiles.** Profiles (solid black lines) indicate the
 344 cumulative percent of species in an assemblage exposed to future temperatures (red line)
 345 beyond their realised thermal niche over time. Iconic ecosystems provide examples of
 346 different profile shapes; **a**, Cayman Islands, **b**, Coral Triangle, **c**, Gobi Desert, **d**, Amazon Basin
 347 and **e**, Congo Basin (see **f**, map of temperature anomalies for locations). Horizon profiles and
 348 temperature trends are shown for a single run of the Hadley Centre Global Environmental
 349 Model (HadGEM2) under a high greenhouse gas emissions scenario (RCP8.5). Timing,
 350 magnitude and abruptness define differences among profiles. Grey line shows historical
 351 temperature projections at a site.

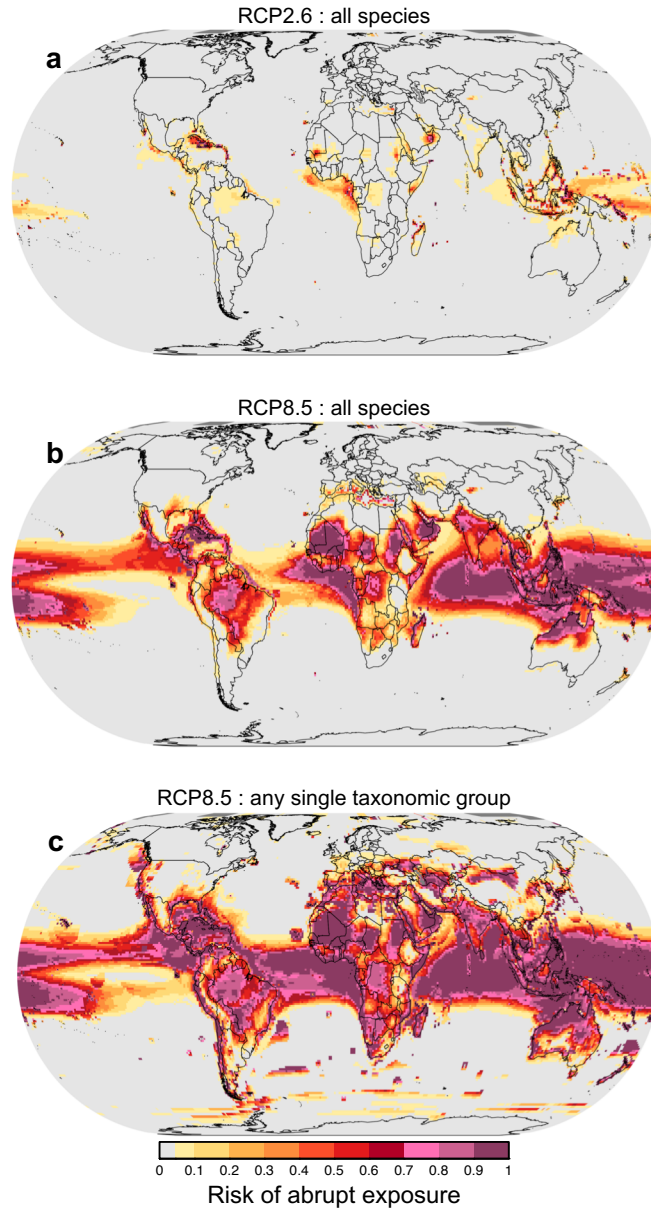


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353 **Figure 2. Global variation in the magnitude, abruptness and timing of horizon**
 354 **profiles. a,** magnitude of exposure indicating the percent of species in 100km resolution
 355 grid cells (i.e., assemblages) exposed to unprecedented temperature (i.e., beyond each
 356 species' realised niche) by 2100. **b,** abruptness quantified as the percent of species
 357 exposure times occurring within the decade of maximum exposure for each assemblage. **c,**
 358 timing quantified as the median year of local species exposure conditional on being
 359 exposed by 2100, the end of the simulation. Maps show the median value across 22 climate
 360 models under RCP8.5 (see Extended Data Fig. 1 for RCPs 2.6 and 4.5).



361
 362 **Figure 3. Abruptness of horizon profiles locally versus globally, and accelerating risk**
 363 **with global warming.** The distribution in the projected abruptness of species exposure to
 364 unprecedented temperatures within marine and terrestrial assemblages (a,b). Selected
 365 assemblages from Fig. 1 are highlighted. Abruptness is quantified as the percent of species
 366 exposure times occurring within the decade of maximum exposure, with results showing the
 367 median across climate models under RCP8.5. Global horizon profiles for oceans and land
 368 (c,d) showing more gradual accumulation of species exposure to unprecedented
 369 temperatures. Dashed lines show how lowering emissions from RCP8.5 to RCP2.6 both
 370 reduces the median magnitude of exposure across climate models and substantially delays
 371 the timing of exposure, buying ~60 years for species and conservation plans to adapt to a
 372 warming climate (see Extended Data Fig. 8 for individual climate models). e, the percent of
 373 species assemblages projected to experience high magnitude and abrupt assemblage
 374 exposure (>20% of species exposed in a single decade) as a function of global warming.
 375 Curves are fitted from model runs ($n = 66$) across RCP2.6, RCP4.5 and RCP8.5.



376

377 **Figure 4. The risk of high magnitude, abrupt assemblage exposure events.** Risk is
 378 calculated as the proportion of 22 climate models where an abrupt exposure event is
 379 projected to occur before 2100. Assemblages avoiding abrupt exposure events across all 22
 380 models are in grey. In **a-b**, abrupt exposure events are defined as >20% of all species in an
 381 assemblage exposed in a single decade. In **c**, abrupt exposure events are defined when any
 382 single organism group (e.g., amphibians) within an assemblage exhibits the exposure of
 383 >20% of its constituent species in a single decade, highlighting the widespread risk of abrupt
 384 ecological disruption.

385

386

387 **Methods**

388 **Biodiversity data.** We used expert verified range maps for 30,652 species from the
389 International Union for Conservation of Nature (IUCN)¹⁴ and BirdLife International⁴⁰,
390 including; birds, mammals, reptiles, amphibians, marine fish, benthic marine invertebrates,
391 and habitat forming corals and seagrasses (Supplementary Table 1). To further increase
392 coverage of open ocean assemblages, our sample includes additional data on krill⁴¹ and
393 cephalopods⁴², reflecting the availability of expert range maps for oceanic species⁴³. We
394 used only breeding ranges for terrestrial species. We excluded marine species restricted to
395 depths greater than 200 meters (the lower limit of the epipelagic zone), as these species
396 are less likely to respond to changes in sea surface temperature. Range maps were
397 converted to 100 km resolution equal-area grid cells, the finest resolution justifiable for
398 these data globally without incurring false presences^{44,45}. Expert range maps provide
399 comprehensive information on species' global geographic distributions⁴⁶, but our results
400 should be interpreted in the context of known data limitations. For some groups, species
401 coverage is incomplete and biased towards commercial species (e.g. cephalopods), while
402 others have been comprehensively assessed for only a subset of clades (e.g. fish) and the
403 species included in our study thus represent a non-random subset of global biodiversity
404 (Supplementary Table 1). For instance, insects and plants may on average be more at risk
405 of geographic range loss due to climate change than terrestrial vertebrates², but we did not
406 assess exposure for these groups because range maps (expert or otherwise) are not
407 available globally. As such, both very short-lived and long-lived terrestrial taxa may be
408 underrepresented in our sample. Furthermore, while many IUCN range maps consider
409 occurrence data from historical records, others may underestimate climate niche limits
410 where longer-term historical records are unavailable and recent geographic range
411 contractions have occurred in part due to reasons other than climate change⁴⁷.

412 Data on marine and terrestrial protected areas were downloaded from the World
413 Database on Protected Areas (<http://protectedplanet.net/>; accessed 21st March 2018). The
414 maps, originally in polygon format, were re-sampled to a 1km resolution prior to further
415 analysis. We considered 100km resolution grid cells highly protected if at least 20% of the
416 grid cell was inside protected areas.

417
418 **Climate model data.** We used temperature and precipitation projections from 22 General
419 Circulation and Earth System Models developed for CMIP5 (Supplementary Table 2). For
420 each model, we downloaded a single projection for mean monthly precipitation (mm),
421 near-surface temperature (K) and sea surface temperature (K) for the historical run
422 (1850–2005), as well as RCP2.6, RCP4.5 and RCP8.5 scenarios for the years 2006–2100 or
423 2006–2300, when available. Model output was downloaded from [https://esgf-](https://esgf-node.llnl.gov/projects/esgf-llnl/)
424 [node.llnl.gov/projects/esgf-llnl/](https://esgf-node.llnl.gov/projects/esgf-llnl/) (accessed 5th June 2017). In our main analysis, we focus
425 on the dynamics of exposure according to mean annual temperature (MAT), calculated by
426 averaging monthly values. However, we also repeated our analysis using the temperature
427 of the hottest month, hereafter 'maximum monthly temperature' [MMT], and for terrestrial
428 assemblages, total annual precipitation (mm), calculated by summing precipitation values
429 across months (see Supplementary Information). Note that the identity of the hottest
430 month can vary both across sites and between years within a site. Given that CMIP5 models
431 use different spatial grids, and to match the resolution of species geographic range data,

432 climate model data were regridded to a 100-km resolution grid using an area-weighted
433 mean interpolation. Climate data interpolation was done in CDO⁴⁸ and R⁴⁹.

434 We calculated species exposure times for each assemblage using individual climate
435 simulations, as opposed to ensembles or multi-model averages, because individual
436 simulation runs include variance in climatic time series due to internal climate variability
437 such as the timing of El Niño–Southern Oscillation events^{22,50}. This internal variability is a
438 key component of the uncertainty in the timing of exposure, and is smoothed out if using
439 multi-model averages as input into the analysis. By calculating species exposure events
440 using individual model simulation runs and then summarising across models, we capture
441 the uncertainty in the timing of exposure due to both internal climate variability and
442 climate model uncertainty (i.e., uncertainty about climate physics across models), in line
443 with ‘time of emergence’ analyses from climate science¹⁹. Throughout, we report multi-
444 model medians in each of our summary metrics.

445
446 **Defining species realised niche limits.** Species experience variability in climatic
447 conditions across both space and time but this temporal variability is ignored when using
448 time-averaged climate conditions (e.g., Worldclim data⁵¹) to estimate species realised
449 niches. To address this, we estimated species realised niche limits using the climate
450 projections from the historical run of each climate model (1850–2005), which includes the
451 influence on climate of observed changes in radiative forcing due to natural factors such as
452 volcanic eruptions, as well as anthropogenic emissions and land use changes⁵². Thus, in the
453 case of MAT, we calculated the maximum MAT experienced across the species geographic
454 range over both space and time ($T_{\max_{\text{MAT}}}$, see Supplementary Information). To prevent
455 estimates of $T_{\max_{\text{MAT}}}$ being inflated by either extreme outliers in the temperature time
456 series or from the overestimation of species ranges⁴⁴, we excluded outlier temperature
457 values within each grid cell, defined as those more than three standard deviations from the
458 mean. Once we had selected the maximum temperature for each cell, we excluded outlier
459 temperature values across each species range, defined as those more than three standard
460 deviations above the mean range value. The $T_{\max_{\text{MAT}}}$ value for each species was then set as
461 the maximum of the remaining values (Supplementary Fig. 1). We used an identical
462 procedure to calculate T_{\max} using MMT ($T_{\max_{\text{MMT}}}$). For precipitation, species may be
463 exposed to either drying or wetting conditions and so we calculated both the minimum
464 (P_{\min}) and maximum (P_{\max}) precipitation value experienced by each species across its
465 geographic range (see Supplementary Information).

466
467 **Estimating species exposure times.** Within each terrestrial ($n = 18560$) and marine ($n =$
468 37333) assemblage (i.e. 100 km grid cell containing any terrestrial or marine species
469 respectively), we defined the time of local species exposure to unprecedented temperature
470 (i.e. the ‘climate horizon’) to be the year after which the MAT (or MMT) of the cell is
471 projected to exceed the species’s $T_{\max_{\text{MAT}}}$ (or $T_{\max_{\text{MMT}}}$) value for at least five consecutive
472 years. We note that using a higher number of consecutive years ($n = 20$ years) had little
473 effect on the magnitude, timing or abruptness of exposure (Supplementary Figs. 2 and 3).

474 For precipitation, we calculated the time of local species exposure as the year after
475 which the precipitation of the cell is projected to be either above or below the species’
476 P_{\max} and P_{\min} values respectively for at least five consecutive years. Annual precipitation
477 values are bounded at zero and this could potentially lead to exposure being

478 underestimated for locations projected to have historically received zero precipitation. To
479 address this, we additionally defined exposure when annual precipitation fell below 15mm
480 for at least five consecutive years. Due to the generally weaker trends and high variability
481 in historical and future projected precipitation, we found that few species were exposed to
482 unprecedented precipitation regardless of how exposure was defined (Extended Data Fig.
483 1). To show the importance of increasing temperatures as the primary driver of exposure,
484 we compared patterns of exposure from MAT alone to those from MAT and precipitation
485 combined, recording the earliest local exposure time of either MAT or precipitation for a
486 species in an assemblage when it was exposed to both variables (Extended Data Fig. 2g-i,
487 see Supplementary Information).

488 We note that by using range-wide estimates of species niche limits, we may
489 underestimate both the magnitude and immediacy of exposure if populations are locally
490 adapted³³. Unfortunately, information on the scale and strength of local adaptation is not
491 generally available across species. Equally, our analysis does not attempt to model adaptive
492 evolution, which may enable species to shift or expand their climatic niche limits over time.
493 Nevertheless, our estimates of the timing of local exposure to unprecedented conditions
494 may be relevant for understanding the potential for evolution to rescue populations from
495 changing climates^{10,11}.

496
497 **Horizon profiles.** Once species exposure times had been calculated for an assemblage we
498 constructed a horizon profile indicating the cumulative percentage of species locally
499 exposed to conditions beyond their realised niche limits. We used the following metrics to
500 summarise the temporal dynamics of biodiversity exposure. First, we calculated the
501 magnitude of exposure as the percent of species in the assemblage exposed over the course
502 of the 21st century. Second the abruptness of exposure for an assemblage was calculated as
503 the percent of all exposure times that occur in the decade of maximum exposure. We
504 identified the decade of maximum exposure using a moving window of ten years. We also
505 calculated an alternative metric of abruptness based on the Shannon-entropy index⁵³,
506 which quantifies the evenness in the distribution of exposure times across all years of the
507 horizon profile (Extended Data Fig. 4). In contrast to our original abruptness metric, lower
508 values of the Shannon-entropy index indicate a more abrupt profile. We therefore rescaled
509 the Shannon-entropy index by the maximum possible entropy value per assemblage,
510 subtracted these values from 1 and then multiplied by 100 to give an index ranging
511 between 0 and 100, where a value of 100 indicates that all exposure times occur in a single
512 decade and a value of 0 corresponds to an equitable distribution of exposure times across
513 years. Abruptness was only calculated for assemblages where five or more species were
514 exposed to avoid idiosyncrasies due to small sample sizes. Third, the timing of exposure for
515 each assemblage was calculated as the median of the times of local species exposure
516 events. Species not exposed before the end of the 21st century were excluded from this
517 calculation. We repeated our analysis using alternative metrics of timing, including the
518 mean year of exposure and the mid-point of the decade of maximum exposure, obtaining
519 very similar results (Extended Data Fig. 6). For each of these exposure metrics we report
520 the median value across the 22 climate models for a given climate scenario, and quantify
521 uncertainty as the standard deviation (Extended Data Fig. 3). The greatest uncertainty in
522 projected impacts involves the magnitude of exposure along the boundaries of the tropics.
523 This arises because of variation among models in the magnitude of warming which alters

524 the spatial extent of regions exposed to unprecedented temperatures. In contrast, variation
525 among models in the timing and abruptness of exposure is relatively small and does not
526 exhibit any clear spatial structure.

527 We compared the median timing of species exposure within assemblages to the
528 timing of local climate emergence, defined as the year after which future local
529 temperatures are projected to exceed the maximum historical (1850-2005) conditions at a
530 site^{19,20}. Timing of emergence was calculated using an identical procedure to the timing of
531 exposure, excluding outlying values from the time series when quantifying the maximum
532 historical temperature at a site and only considering emergence when temperatures
533 exceed the historical maximum for at least five consecutive years. The time of local climate
534 emergence at a site is therefore identical to the time of local exposure for a species
535 occupying a single grid cell. In the absence of perfect adaptation to local climates, a time-lag
536 is therefore expected between local climate emergence and the median timing of exposure,
537 because species typically persist under a broader range of conditions than is present in any
538 single site.

539
540 **Spatial scale.** We modelled species realised niche limits using climate projections at
541 100km grain size, matching the resolution of expert geographic range maps^{44,45}. However,
542 individual grid cells at this resolution may contain (potentially substantial) spatial climatic
543 heterogeneity, thus potentially underestimating variability in species niche limits and
544 potentially overestimating the abruptness of assemblage exposure dynamics. To
545 investigate this possibility, we tested whether the abruptness of horizon profiles across
546 terrestrial assemblages is related to the range in mean annual temperatures within each
547 grid cell, using spatially interpolated weather data for the period 1970-2000 available at
548 1km resolution⁵¹. We found that abruptness is negatively correlated with the spatial
549 heterogeneity in temperature within a cell (Spearman's $\rho = -0.29$), so that assemblages with
550 higher spatial heterogeneity in temperatures (e.g. tropical mountains), exhibit more
551 gradual exposure profiles than those with low heterogeneity in temperatures (e.g. tropical
552 lowlands) (Extended Data Fig. 10). This result has two important implications. First, it
553 suggests that despite the relatively coarse grain size, our analysis still identifies those
554 assemblages where variation in realised niche limits among species is expected to be
555 greatest (i.e. grid cells containing substantial spatial climatic heterogeneity) as having the
556 most gradual exposure profiles. Second, it suggests that while incorporating finer-scale
557 climate data may further reduce the lowest abruptness values estimated across
558 assemblages (i.e. making relatively gradual horizon profiles more gradual), it is unlikely to
559 alter the key conclusion that assemblage exposure to climate warming occurs abruptly,
560 because the most abrupt horizon profiles occur in assemblages where there is little fine-
561 scale climatic heterogeneity (Extended Data Fig. 10). These results support the robustness
562 of our overall conclusions regarding the dynamics of exposure, but it is clear that
563 increasing the spatial resolution at which species niche limits and assemblages are defined
564 would enable a more precise quantification of the timing of species exposure to changing
565 climates and should be a priority for future research.

566 Horizon profiles can be calculated either for a single assemblage or for a set of
567 assemblages combined, such as a biome or the entire globe. In addition to examining the
568 dynamics within assemblages, we generated global horizon profiles, describing the total
569 cumulative exposure of all populations (i.e. species by site combinations) across marine

570 and terrestrial assemblages (Fig. 3c-d). To avoid exposure dynamics being driven by the
571 small number of species with the largest geographic ranges, we weighted each species by
572 the inverse of its geographic range size. This range-size weighted exposure profile ensures
573 that each species contributes equally to exposure dynamics and is mathematically
574 equivalent to calculating the mean % geographic range exposure across species.
575 Unweighted global horizon profiles show qualitatively similar patterns (Extended Data Fig.
576 8).

577
578 **Risk of abrupt exposure events.** We identified those assemblages projected to undergo
579 abrupt and high magnitude exposure events, defined as at least 20% of resident species
580 exposed within a single decade before the end of the 21st century. Across the set of 66
581 climate model runs from the three RCP scenarios, we fit a generalised additive model
582 (GAM) to estimate the % of assemblages projected to undergo abrupt exposure events as a
583 function of mean global warming at the end of the century (2080-2100) relative to pre-
584 industrial conditions (1850-1900). We fit separate models for sites with either low or high
585 (i.e. >20% in protected areas) levels of habitat protection. We forced the regression
586 through the origin, thus assuming no abrupt exposure events would occur if temperatures
587 remained stable at pre-industrial conditions. Because the identity of assemblages projected
588 to undergo abrupt exposure events may vary across model runs, the actual area at risk of
589 abrupt exposure may be substantially greater than expected under any single climate
590 simulation. For each assemblage, we therefore calculated the probability of an abrupt
591 exposure event across the 22 climate models within each emissions scenario. We did this
592 for assemblages consisting of all species, as well as for each organism group separately.

593 594 **References**

- 595
596 40. Birdlife International. Bird species distribution maps of the world. Version 2.0.
597 Cambridge/Arlington, TX: BirdLife International/NatureServe (2012).
598 41. Brinton, E., Ohman, M. D., Townsend, A. W., Knight, M. D. & Bridgeman, A. L. *Euphausiids of*
599 *the World Ocean*. (Springer, 2000).
600 42. Jereb, P. & Roper, C. F. E. *Cephalopods of the World: An Annotated and Illustrated Catalogue*
601 *of Cephalopod Species Known to Date*. (2005).
602 43. Tittensor, D. P. *et al.* Global patterns and predictors of marine biodiversity across taxa.
603 *Nature* **466**, 1098–1101 (2010).
604 44. Hurlbert, A. H. & Jetz, W. Species richness, hotspots, and the scale dependence of range
605 maps in ecology and conservation. *Proc. Natl. Acad. Sci. U. S. A.* **104**, 13384–13389 (2007).
606 45. Jetz, W., Sekercioglu, C. H. & Watson, J. E. M. Ecological correlates and conservation
607 implications of overestimating species geographic ranges. *Conserv. Biol.* **22**, 110–119
608 (2008).
609 46. Meyer, C., Kreft, H., Guralnick, R. & Jetz, W. Global priorities for an effective information
610 basis of biodiversity distributions. *Nat. Commun.* **6**, 8221 (2015).
611 47. Faurby, S. & Araújo, M. B. Anthropogenic range contractions bias species climate change
612 forecasts. *Nature Climate Change* vol. 8 252–256 (2018).
613 48. Schulzweida, U. CDO User Guide (Version 1.9.6). URL
614 <http://doi.org/10.5281/zenodo.2558193>. (2019, February 6).
615 49. R Core Team. R: A language and environment for statistical computing. R Foundation for
616 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>. (2019).

- 617 50. Kay, J. E. *et al.* The Community Earth System Model (CESM) Large Ensemble Project: A
618 Community Resource for Studying Climate Change in the Presence of Internal Climate
619 Variability. *Bull. Am. Meteorol. Soc.* **96**, 1333–1349 (2015).
620 51. Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. Very high resolution
621 interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**, 1965–1978 (2005).
622 52. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the Experiment Design.
623 *Bull. Am. Meteorol. Soc.* **93**, 485–498 (2012).
624 53. Shannon, C. E. A Mathematical Theory of Communication. *Bell System Technical Journal* vol.
625 27 623–656 (1948).

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654

655 **Contributions**

656 A.L.P, C.H.T, C.M. conceived the study, processed the species and climate data, performed
657 the analysis and wrote the manuscript. All authors read and approved the final manuscript.

658

659 **Competing interests**

660 The authors declare no competing financial interests.

661

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665

666 **Reprints and permissions**

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668

669 **Data availability**

670 All datasets used here are publicly available. Expert verified range maps are available from

671 <https://www.iucnredlist.org/resources/spatial-data-download> and

672 <http://datazone.birdlife.org/species/requestdis>. Climate change projections for RCPs 8.5,
673 4.5, and 2.6 for the Coupled Model Intercomparison Project 5 (CMIP5) are available from
674 <https://esgf-node.llnl.gov/search/cmip5/>. Computer code used in the analysis is available
675 on request from the authors. Code and results data to make figures 2-4 is available at
676 figshare (10.6084/m9.figshare.11814633).

677 **Extended Data figure 1. Spatial distribution of the magnitude, abruptness and timing,**
678 **of assemblage exposure for alternative climate variables.** Results show the median
679 value across 22 CMIP5 climate models for mean annual temperature, maximum monthly
680 temperature, and precipitation under RCP2.6, RCP4.5 and RCP8.5.

681 **Extended Data figure 2. Comparing the magnitude, timing and abruptness of**
682 **assemblage exposure across alternative climate variables.** **a-f**, patterns of exposure to
683 unprecedented temperatures show both similarities and differences depending on whether
684 temperature is quantified using mean annual temperature (MAT) or maximum monthly
685 temperatures (MMT). More species are exposed and exposure occurs earlier for MAT
686 compared to MMT, but spatial variation in the magnitude (**a, d**) and timing (**b, e**) of
687 exposure are strongly correlated between temperature variables. Variation in the
688 abruptness of assemblage exposure is less strongly correlated between MAT and MMT (**c**),
689 but both variables confirm the abruptness of projected exposure (**f**). **g-i**, patterns of
690 exposure to both MAT and precipitation combined are very similar to patterns of exposure
691 to only MAT, highlighting the primacy of changes in temperature in driving exposure.
692 Values are the median across 22 CMIP5 climate models under RCP8.5, with hotter colors
693 indicating a higher density of points. In (**a-c**) and (**g-i**) points falling along the dashed 1:1
694 line indicate a perfect correspondence between metrics. The correlation between metrics
695 (Spearman's ρ), and the mean difference in the timing of exposure (years), is shown.

696 **Extended Data figure 3.** Uncertainty (standard deviation, SD) in species local exposure
697 metrics across 22 CMIP5 climate models under RCP8.5. Uncertainty in the magnitude of
698 exposure is greatest around the boundaries of the tropics with little geographic variation in
699 uncertainty in timing or abruptness.

700 **Extended Data figure 4. Abruptness of horizon profiles.** Density plots show the
701 distribution of abruptness values for different CMIP5 climate models ($n = 22$, lines) and
702 representative concentration pathways (RCPs) on land (red) and in the ocean (blue).
703 Histograms show the median abruptness across climate models under RCP8.5 for each
704 organism group. Abruptness is calculated as the percent of exposure times occurring
705 within the decadal window of maximum exposure (colors). Abruptness is also shown for an
706 alternative metric based on the Shannon-entropy index (grey) with values scaled between
707 0 and 100, indicating the most gradual and abrupt distribution of exposure times possible
708 for a given assemblage respectively. Exposure is consistently abrupt across climate models,
709 RCP scenarios, metrics and organism groups.

710 **Extended Data figure 5. Predicting the timing, magnitude and abruptness of local**
711 **species exposure.** On land (left) and in the ocean (right) the (**a-b**) median timing of
712 exposure is weakly correlated (Spearman's ρ) with the timing of local climate emergence.
713 The magnitude of exposure (**c-d**) is weakly correlated with the magnitude of warming
714 between the start (2000-2020) and the end (2090-2100) of the 21st Century. The
715 abruptness of exposure (% of local species exposure times occurring in the decade of
716 maximum exposure) is only partly correlated with (**e-f**) the maximum rate of warming
717 (maximum difference in mean temperature between successive decades) or (**g-h**) the % of
718 species with nowhere warmer within 1000km of their range. Values are the median across
719 22 CMIP5 climate models under RCP8.5. Hotter colors indicating a higher density of points.

720 **Extended Data figure 6. The different dimensions of climate risk to species**
721 **assemblages. a-c**, Bivariate plots showing the strong correlation among alternative
722 metrics for the timing of local assemblage exposure: the median year of local species
723 exposure, the mean year of local species exposure and the mid-point of the decadal window
724 of worst (i.e. maximum) local species exposure. **d-f**, Bivariate plots showing the weaker
725 correlation between the magnitude, abruptness and timing of exposure across
726 assemblages. Values are the median across 22 CMIP5 climate models under RCP8.5, with
727 hotter colors indicating a higher density of points. In **(a-c)** points falling along the dashed
728 1:1 line indicate a perfect correspondence between metrics. The correlation between
729 metrics (Spearman's ρ) is shown, as well as for **(a-c)** the mean difference in the timing of
730 exposure (years).

731
732 **Extended Data figure 7. Accumulation of exposure to unprecedented temperatures at**
733 **decadal time snapshots from 2030 to 2100.** Light grey indicates zero local species
734 exposure. Maps show the median across 22 CMIP5 climate models under RCP8.5,
735 highlighting the immediate onset of exposure in the tropics that spreads to higher latitudes
736 later in the century.

737 **Extended Data figure 8. The global biodiversity horizon profile.** The cumulative
738 exposure to unprecedented temperatures of all local species populations (i.e. species X site
739 aggregated across all sites) increases smoothly over time at the global scale. Global horizon
740 profiles are shown when **(a-b)** species are weighted by the inverse of their geographic
741 range size (equivalent to the mean % geographic range exposed) or **(d-f)** are given
742 equivalent weighting. In **(d-f)**, dynamics are dominated by species with many local
743 populations (i.e. large geographic ranges). Variability in exposure across 22 climate models
744 (thin lines) is shown for each RCP scenario (median, thick line).

745 **Extended Data figure 9. The global distribution in the risk of high-magnitude and**
746 **abrupt assemblage exposure events under different representative concentration**
747 **pathways.** Maps show the probability of abrupt exposure calculated across 22 CMIP5
748 climate models. The risk of abrupt exposure was calculated based on all species in an
749 assemblage (left column) and for each organism group separately (right column). Maps
750 highlight the greater risk of abrupt exposure events under intermediate (RCP4.5), and
751 especially high (RCP8.5) emission pathways, and when considering taxonomic groups
752 separately

753 **Extended Data figure 10. Abruptness of horizon profiles for terrestrial vertebrates in**
754 **100km grid cells with low (red, 1st quantile) or high (grey, 4th quantile) spatial**
755 **temperature heterogeneity.** Abruptness is calculated as the % of species exposure times
756 in the decade of maximum exposure. Temperature heterogeneity is the range in
757 temperatures at 1km resolution within each 100km cell. Assemblages with abrupt exposure
758 have lower temperature heterogeneity suggesting that quantifying species niches at finer
759 spatial resolutions is unlikely to alter the abrupt nature of assemblage exposure dynamics.

760
761