1    **Chance played a role in determining whether Earth stayed habitable**

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8

9    **Abstract**

10    **Earth's climate has remained continuously habitable throughout 3 or 4 billion years. This presents**

11    **a puzzle (the 'habitability problem') because loss of habitability appears to have been more likely.**

12    **Solar luminosity has increased by 30% over this time, which would, if not counteracted, have**

13    **caused sterility. Furthermore, Earth's climate is precariously balanced, potentially able to**

14    **deteriorate to deep-frozen conditions within as little as 1 million years. Here I present results from**

15    **a novel simulation in which thousands of planets were assigned randomly generated climate**

16    **feedbacks. Each planetary set-up was tested to see if it remained habitable over a period of 3**

17    **billion years. The conventional view attributes Earth's extended habitability solely to stabilising**

18    **mechanisms. The simulation results shown here reveal instead that chance also plays a role in**

19    **habitability outcomes. Earth's long-lasting habitability was therefore most likely a contingent**

20    **rather than an inevitable outcome.**

21

## Introduction

The evolution of intelligent life on a planet requires not only that planetary conditions are conducive to life at the start, as it first evolves, but also that the planet remains habitable subsequently, without interruption. This is because there has to be enough time to allow life to increase in complexity from simple cells to more sophisticated single cells to multicellular life and eventually to intelligent life. On Earth this development took something like 3 or 4 By[1-3], throughout which time liquid water appears to have been present somewhere on Earth's surface[4], implying temperatures between its freezing and boiling points.

Conditions remained habitable, and on first consideration this may not seem surprising. However, observations and deductions have accumulated to show that such a long duration of habitability is in fact a puzzling phenomenon requiring explanation. The principles governing the internal dynamics and temporal evolution of stars were worked out in the 1950s[5,6] – when applied to the Sun, they revealed that solar heating of today's Earth is about 30% more intense than of the early Earth[5]. Sagan & Mullen[7] realised that, if all else had remained constant, the early Earth would have been totally frozen under the dimmer early Sun. Or, conversely, given that the early Earth was not frozen, if the rest of the climate system had remained unaltered then the oceans would now be boiling under today's brighter Sun. Evidently neither occurred, for reasons that are still debated[8-12]; although plausible solutions exist, in particular when combining multiple processes[13], as yet there is no firm consensus as to how in reality the 'Faint Young Sun Paradox' was overcome[14].

Probes sent to land on Earth's neighbours in the 1970s provided more evidence that Earth's thermal habitability requires explanation. Venus, with its strong greenhouse and closer to the Sun, was found to be too hot (average surface temperature >460°C [15]) and Mars, with its thin atmosphere and further from the Sun, too cold (average <-50°C [16]). Moreover, subsequent observations point to

48    Mars having once been warm enough to have liquid water on its surface[17,18]; if correct then the

49    history of Mars shows that a planet can lose habitability – that once obtained it is not guaranteed to

50    persist.

51

52    That habitability may be precarious was also emphasized in the 1990s by theoretical calculations[19]

53    showing Earth's considerable potential for climate volatility. A sustained imbalance of 25% between

54    rates of input and output of carbon would, it was pointed out, lead to the oceans freezing within a

55    few million years (if loss of atmospheric $CO_2$ exceeds gain) or boiling away within a few tens of

56    millions of years (if gain exceeds loss). The reason for this predicted susceptibility to rapid climate

57    deterioration is the short residence time with respect to geological fluxes of carbon in the surficial

58    Earth system (ocean, atmosphere, soils and biota) – about 100 ky[19].

59

60    After the realisation that neither Mars nor Venus presently have temperatures conducive to life, and

61    that Earth's carbon dioxide greenhouse is potentially unstable, two main classes of solution were

62    advanced to try and answer the 'habitability problem'[20] for Earth. The first class involves stabilising

63    mechanisms. It was argued[19,21] that the duration of continued habitability (3 to 4 By) so greatly

64    exceeds the potential time to climate failure (~0.001 to 0.01 By) that destabilising tendencies must

65    have been actively opposed by strong negative feedbacks throughout. Earth must possess an inbuilt

66    thermostat and have possessed it since its early history. Otherwise climate would have followed a

67    random walk with, they argued, an impossibly small likelihood of remaining within habitable bounds.

68

69    One proposal in this class, the Gaia hypothesis[22], suggested that once life becomes established on a

70    planet then it intervenes in climate regulation to keep conditions stable and habitable. However, the

71    Gaia hypothesis lacks a clear mechanistic basis and is not consistent with the most recent scientific

72    evidence[23]. Another proposal in this class suggests that silicate weathering contributes to a

73    thermostat by removing carbon dioxide more rapidly under warmer climates[12, 24-30]. Controls on

74    continental silicate weathering rate remain somewhat uncertain, however, with field studies

75    suggesting a strong influence from the rate of supply of newly-exposed (easily weathered) rock[31,32],

76    as well as from climate[28]. Proxy evidence also casts some doubt on whether silicate weathering

77    effectively countered climate changes during Earth's history[33,34] for instance, its rate appears not to

78    have decreased as climate cooled gradually through the Cenozoic[33,35] and climate recovery following

79    the intense warming of the Paleocene Eocene Thermal Maximum has been attributed to organic

80    carbon burial rather than silicate weathering[36,37]. As questions have arisen about whether silicate

81    weathering on the continents provides Earth's thermostat, new proposals have suggested that

82    silicate weathering in other locations is key: either islands[27] or the sea floor[12,29].

83

84    A second, very different, class of solution has also been put forward, based on the principle of

85    observer selection (the weak anthropic principle)[38]. Logically, we can only ever observe facts that are

86    consistent with our own existence. This has been extended to the scenario where a prolonged

87    duration of planetary habitability occurs only extremely infrequently amongst a large population of

88    planets but does happens sometimes by chance. According to observer selection, in this scenario we

89    are bound to find ourselves on one of the lucky planets[39,40], however scarce they might be. This view

90    presupposes a large number of potentially habitable planets if there is to be any likelihood of even

91    one planet surviving due to good fortune alone. There is, however, no shortage of planets. In our

92    galaxy alone there are estimated to be billions of small, rocky planets orbiting within the habitable

93    zones of their parent stars[41,42].

94

95    The most widely held view at this time is that "Earth has been a habitable planet for [billions] of

96    years because of the existence of stabilizing feedbacks in the global carbon and silicon cycles."[12].

97    Although there are a few exceptions[39,40,23], the possible role of chance is typically not even

98    mentioned[12,30,43-45]. Here I describe a new model of habitability and report its results. The results

99    suggest strongly that chance also played a role.

4

# Results

## Approach

The model used here (see Methods for details) is a conceptual (simplest) representation of planetary climate regulation. It includes the fundamentals necessary for simulating climate feedbacks and habitability tendencies and purposefully excludes any other details deemed to be non-essential, even those that can be incorporated accurately. In contrast to previous modelling studies of Earth habitability, it allows for evaluation of observer selection effects by taking a multi-planet perspective. For this reason, the model is not in any way a model of Earth specifically but rather is of potentially habitable planets in general. Because of the difficulty in directly observing exoplanets, there is a lack of data and consequently a high degree of uncertainty about how to model some aspects. However, sensitivity analyses, described below, show that the exact parameter values and assumptions chosen do not affect the main results presented here.

The model is described in detail in the Methods but a brief outline is given here. The model has only one state variable, planetary surface temperature ($T$). Other environmental conditions are not modelled and therefore habitability in this paper refers to thermal habitability only. At the outset, each planet is allocated its own distinct set of positive and negative feedbacks using random numbers. These feedbacks have random signs and magnitudes and are made to vary as a function of temperature in a random way.

In addition to using random numbers to generate a diverse collection of planets, each with different feedbacks, random numbers are also used to determine challenges to habitability. Planets are made to experience a random number of perturbations to temperature, occurring at random times and with random signs and magnitudes. In addition, each planet experiences a randomly-determined

126    long-term climate forcing, to represent drivers that vary with time such as the luminosity of the

127    parent star.

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129    **Example Planet Runs**

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131    It is now shown how these modelling procedures work in practice. Four examples were chosen to

132    illustrate the procedures used. The left-hand side of Figure 1 displays four example planets

133    generated automatically by this scheme. The right-hand side of figure 1 shows an individual run for

134    each of these planets, starting from a random initial temperature and faced with a random set of

135    perturbations.

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137    Figure 1a shows a planet that ended up with a single basin of attraction (zone of negative feedback),

138    on the warmer side of the habitable range. An attractor (a value which the system tends to converge

139    towards) occurs where the horizontal axis ($dT/dt$ = 0) is crossed with a negative slope, or in other

140    words where the planet cools at temperatures slightly above the attractor value and warms at

141    temperatures slightly below it. An attractor is a stable equilibrium point. Zero-crossing points of

142    positive slope are, conversely, unstable equilibrium points that occur at the edges of basins of

143    attraction. This first planet has a region of runaway cooling within which temperatures decrease

144    inexorably until too cold for habitability. In the run shown in Figure 1b, the planet happened to start

145    within this runaway feedback zone and hence immediately became uninhabitable.

146    A second planet (Figure 1c) ended up with five attractors and a small zone of runaway warming. This

147    time the random starting temperature was within the middle (third) basin of attraction. The planet

148    again failed rapidly (Figure 1d), this time because, coincidentally, the three cooler attractor points

149    are all situated very close to the lower boundaries of their respective basins of attraction. As a result,

150    random perturbations soon knocked the system from the first basin of attraction into the one to its

151    left, and this repeated until departure from the habitable range.

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The third planet (Figure 1e) has two basins of attraction and started off in the warmer one. Habitable

conditions were maintained for over 500 My (figure 1f), with jumps between two basins of

attraction, before a perturbation knocked the temperature to above the upper limit. A strong long-

term forcing ($\emptyset$ = -45.2 (°C ky$^{-1}$) By$^{-1}$) would anyway have prevented equable temperatures persisting

for 3 By.

158

Some planets can stay habitable for the full 3 By. The planet in Figure 1g has only one basin of

attraction, spanning nearly the whole of the habitable range. A long-term forcing ($\emptyset$ = -24.6 (°C ky$^{-1}$)

By$^{-1}$) caused the attractor to move slowly further away from the upper limit. Despite a large

perturbation at about 200 My, the planet stayed habitable for the full 3 By (Figure 1h).

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These examples illustrate how the "habitability problem", stabilising mechanisms and chance are

incorporated in this approach. Next, I present results obtained with this approach and consider their

implications.

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**Neither Pure Chance nor Pure Mechanism: Results for Artificial Planets**

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As a first step, some particular planets were each run 1000 times in order to test two hypotheses

based on the classes of solution: (a) that planetary habitability is a matter of good fortune alone,

with a planet's properties having no effect on the likelihood of habitability (henceforth referred to as

Hypothesis 1, or just H1); and (b) that planetary characteristics, such as possession or lack of

stabilising feedbacks, either guarantee or rule out habitability from the outset, with no influence of

random events such as asteroid impacts (Hypothesis 2, or just H2). For these tests, each rerun had a

177     different (random) initial temperature and perturbations each time, there were no long-term

178     forcings ($\emptyset = 0$) and perturbations were at the lower end of severity.

179

180     A planet with unfavourable feedbacks (the second one in Figure 1) went uninhabitable every time,

181     consistent with H2. A purposefully-created planet with no feedbacks (*dT/dt* = 0 for all *T*) also had 0

182     successes out of 1000, consistent with H2 and the contention[19] that pure chance alone (in the form

183     of a random walk driven by random perturbations) leads to an extremely small probability of

184     remaining habitable over such an immense duration.  An optimal planet (*dT/dt* = +300 °C ky$^{-1}$ for

185     $T < T_{\mathrm{mid}}$, -300 °C ky$^{-1}$ for $T > T_{\mathrm{mid}}$) stayed habitable on all 1000 occasions, again consistent with

186     H2.

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188

189     **Results for Populations of Randomly Generated Planets**

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191     The results of a much larger simulation are now reported. In this, the habitability tendencies of

192     100,000 planets were evaluated. The planets were generated by allocating random rather than

193     purposefully designed climate feedbacks, using the procedure described in Methods. The 100,000

194     distinct planets were each run 100 times, with different chance factors (different random sets of

195     perturbations and initial temperatures) for each of the 100 repeats. The results show probabilistic

196     relationships between success rate and inherent planetary characteristics that agree with expected

197     behaviour (Supplementary Fig. 1). It can be seen that, as found in a previous study[46], climate

198     stabilisation can arise occasionally out of randomness – a proportion of the planets generated by the

199     random assembly procedure had some propensity for long-term temperature regulation.

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201

The results were analysed to give further insights into the roles of destiny and chance. Figure 2a

shows outcomes for a subset of 200 planets: 15 of them remained habitable on 1 or more runs and

the other 185 had no successes. The most successful planet stayed habitable on 60 out of 100

repeats. No planet was successful on all of its 100 repeats. Similar results were obtained, on a larger

scale, for the whole simulation (blue line, Figure 2b). Out of a population of 100,000, ~9% of planets

(8,710) were successful at least once, but only 1 planet was successful on all 100 occasions. Success

rates of individual planets were not limited to 0% or 100% but instead spanned the whole spectrum.

Some planets were successful only 1 time in 100, others 2 times, and so on. All degrees of planet

success are seen to occur in the simulation (Figure 2b).

211

Also shown in Figure 2 are the expected distributions for hypothetical cases in which there were

exactly the same total number of successes in the 5 million runs, but in which successes were

distributed either completely according to chance (H1: black line and grey shading) or else only

among always-successful planets (H2: red line and shading). The frequency distribution of run

durations in the simulation is completely distinct from either H1 or H2 (Figure 2c). Furthermore, a

runs test[47] carried out on the simulation results presented planet by planet (the first 100 being those

for planet 1, the second 100 for planet 2, etc) conclusively rejects random order (p « 0.001), again

ruling out H1.

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In terms of the question addressed in this paper, the answer from the simulation results is

unambiguous: in the simulation, the distribution of planet successes is very different from that

expected from either H1 or H2 and is intermediate between them; in the simulation, both

mechanism and chance play a role in determining whether, for each run of each planet, habitability

lasts as long as 3 By. When considering whether habitability persistence is determined in the same

way in reality, however, it is of course necessary to take into account the limitations of the model.

227    The simplifications and uncertainties in the model design mean that it must be unrealistic in some

228    respects. Caution is therefore required in extrapolating from model results to reality. However, it

229    should also be noted that extensive sensitivity analyses (37 in total, addressing a wide range of

230    biological, geophysical, geochemical, biogeochemical and astronomical uncertainties – see Table 1,

231    Supplementary Methods and Supplementary Tables 1 and 2) find the result put forward here to be

232    remarkably robust to model uncertainties (simulation results between H1 and H2 for all 37 model

233    variants tested). In other words, while overall success rates (for instance) differ greatly between

234    model variants, the shared nature of the control over habitability durations does not. For this

235    reason, the complete set of model results, including sensitivity analyses, gives confidence in the

236    overall conclusion. Taken as a whole, the model results suggest strongly that the occurrence of long-

237    term habitability in the real universe is also a function of both mechanism and chance.

238    Independently conceived models should, however, also be applied to this problem, to see if similar

239    results are obtained.

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241

242    **Rerunning the Tape**

243

244    It was a precondition for the coming-into-existence of *Homo sapiens* that Earth had remained

245    habitable over geological timescales, and the results just described give some insight into how it

246    might have occurred. Additional analysis was carried out to further investigate the possibility that

247    Earth's long and unbroken duration of habitability was not inevitable from the outset. A set of 1,000

248    planets were each run twice, with the perturbations and initial temperatures differing between the

249    two runs. Stephen Jay Gould introduced the idea of re-winding the tape of Earth's history to see if

250    biological evolution would yield the same results on a repeat run[48]; here the same idea was

251    investigated for climate evolution. As shown in Figure 3, 15 out of the 1000 planets stayed habitable

252    on the first run and 10 on the second. 6 planets stayed habitable both times. In other words, 6 of the

253     15 that were successful on the first run were also among the 10 that were successful on the second

254     run. More detailed analysis of a larger set of results found there to be a 39% overlap; in other words,

255     if a planet stayed habitable on an initial run then, on average, there was a 39% chance that it would

256     stay habitable on a second run and a 61% chance that it would not. The overall success rates of the

257     more than 1,400 out of 100,000 planets that stayed habitable for 3 By on their first run are shown in

258     Figure 2b (green line). This is the most appropriate comparison to Earth, which stayed habitable on

259     its one 'run' but for which the overall success probability is not known. This distribution differs from

260     that of planets that were successful on any run (blue line, Figure 2b) but again is seen to be

261     controlled by a mixture of both destiny and chance.

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263

264     **Discussion**

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266     The obvious implication from these results is that Earth's success was not an inevitable outcome but

267     rather was contingent — it could have gone either way. If Earth's climate system had been

268     subjected, for instance, to different magnitudes of volcanic supereruptions or different timings of

269     impacting asteroids then the outcome could have been different. A role for chance in the eventual

270     outcome is, arguably, also supported by Earth's geological record, which includes evidence of

271     extreme climate perturbations that may have come very close to extinguishing all life (for instance

272     the Snowball Earth episodes of the PaleoProterozoic[49] and NeoProterozoic[50]).

273

274     The initial prospects for Earth staying habitable could have been poor. If so, this suggests that

275     elsewhere in the Universe there are Earth-like planets which had similar initial prospects but which,

276     due to chance events, at one point became too hot or too cold and consequently lost the life upon

277     them. As techniques to investigate exoplanets improve and what seem at first to be 'twin Earths' are

278     discovered and analysed, it seems likely that most will be found to be uninhabitable.

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## Methods

**Motivation and underlying principles**

The overall goal is to investigate how long-term planetary habitability (necessary for intelligent life to evolve) can occur in the universe. To address this, it is helpful to have a model that can run for billions of years and be capable of simulating many very different planets. Billion-year runs of complex climate models are not feasible because of excessive run times. An alternative approach is attempted here: a simplest possible representation of climate feedbacks and climate regulation.

The first design principle of this idealised model is to aim for simplicity. Details are avoided wherever possible, retaining only those fundamentals that are deemed essential for addressing the overall goal. The focus is exclusively on the most important aspects (climate feedbacks and the possibility of stabilisation). The second principle is to make the model general, not specific. It is definitely not a model of Earth. It is instead a model intended to be equally capable of representing any potentially habitable planet, whether inside or outside the solar system and whether inside or outside conventionally defined habitable zones[44,51]. The third design principle, following from the second, is to avoid assumptions wherever possible. Where there is any doubt about its universal applicability then an assumption is usually not made. The use here of random numbers to generate multiple and diverse instances of planets allows ranges rather than precise values to be specified for each parameter, removing the need to assume exact values. Where assumptions did have to be made during model design, sensitivity analyses (see Supplementary Methods) were used to explore the consequences of alternative assumptions (signalled below by (*SA*)).

The model has only one state variable, planetary surface temperature (*T*), and consists of one sole ordinary differential equation:

$$\frac{dT}{dt} = f(T) + \phi . t \qquad (1)$$

307

308 where $t$ is time, $dT/dt$ is the rate of change of temperature with time (positive values corresponding

309 to planetary warming and negative values to cooling), and $\emptyset$ is a long-term climate forcing, summing

310 over drivers that vary with time such as the luminosity of the parent star. Time ($t$) is the time elapsed

311 since life first evolved (i.e. since life appeared anywhere on Earth; it is not, for instance, the time

312 since the Earth formed or the time since life first appeared on land). The overall sum feedback

313 response is represented by $f(T)$ and varies as a function of temperature $T$. In other words, at any

314 planetary temperature $T$, $f(T)$ is the net rate of warming or cooling that results from all processes

315 operating in combination. Unlike in standard climate models, individual climate feedbacks (such as

316 ice-albedo feedbacks) or processes (such as the interception of outgoing infrared radiation by

317 greenhouse gases) are not separately represented. An advantage of this parsimonious approach is

318 that few assumptions are made, maximising the variety of different types of system that can be

319 represented. A disadvantage is loss of realism, if an important aspect of system behaviour is lost

320 through oversimplification and the omission affects the results obtained.

321

322 Feedbacks are set as follows. First, a random number generator is used to determine the number of

323 climate nodes for the planet ($\sim U_i(2,20)$, where $U_i$ is a uniform distribution). These are then

324 distributed evenly across the habitable temperature range (-10 to +60 °C). Random numbers are

325 then used again to set the value of $f(T)$ for each node, with positive and negative values being

326 equally probable ($\sim N(0,100)$ °C ky$^{-1}$, where $N$ is a Gaussian distribution). $f(T)$ values between nodes

327 are linearly interpolated (*SA*). Each planet is also allocated a random long-term forcing ($\emptyset$), which can

328 be either positive or negative with equal probability ($\sim N(0,50)$ (°C ky$^{-1}$) By$^{-1}$).

329

330 The ability of planets to stay habitable is tested by calculating their temperature evolutions when

331 subject to random perturbations and a long-term forcing. Each run is started at a random initial

332     temperature and is simulated from time zero (origin of life) until 3 By (evolution of intelligence) or

333     until temperature leaves the habitable range. Random temperature perturbations occur at random

334     times (red triangles in figure 1), representing climate-altering events such as eruptions of

335     supervolcanoes and asteroid impacts. There are three size classes of perturbation ($\sim N(2,1)$,

336     $\sim N(8,4)$, and $\sim N(32,16)$ °C), with larger size classes occurring less frequently. Chance is defined

337     here as consisting of the perturbations and the initial temperatures; these are varied for each rerun

338     of the same planet whereas inherent characteristics (feedbacks and forcing) are not.

339

340     The model executes rapidly. Runs take a few minutes for 3 billion years, allowing the habitability

341     propensities of thousands of different planets to be investigated.

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343

344     **Habitable temperature range**

345

346     The model has only one state variable, planetary surface temperature ($T$, in °C, converted to kelvin

347     where necessary; neither vertical atmospheric temperature gradients nor top-of-the-atmosphere

348     temperature are represented; surface environmental conditions other than temperature are also

349     not represented (*SA*)). It is assumed here that life on other planets requires liquid water, as it does

350     on Earth. The lower limit to habitability is set to -10°C (*SA*), somewhat below the freezing point of

351     salt water. More complex (eukaryotic) life on Earth is mostly unable to survive above about 50°C, at

352     which point DNA and other proteins start to denature unless protected. While simple microbes can

353     grow at temperatures up to 122°C (ref. 52), it seems unlikely that more complex (intelligent) life

354     could survive at such temperatures[23]. The pressure-dependent boiling point of water also sets a

355     higher limit but it is assumed here that the most critical factor is enzyme stability, and the upper

356     limit is therefore set to +60°C (*SA*). It is likely that climate needs to stay within narrower bounds

357     during the later stages of the evolution of intelligence, although this was not included in the

358   standard simulation (*SA*). Geographical variability implies that more extreme average global surface

359   temperatures might be required to force extinction everywhere (*SA*). Microbial life can potentially

360   survive periods of inhospitable surface conditions within refuges, such as in subsurface rocks or deep

361   in an ice-covered ocean at hydrothermal vents, emerging later to recolonise the surface; evidence

362   from Neoproterozoic Snowball Earth events suggests however that eukaryotic photosynthetic algae

363   persisted through the events and therefore that surface habitability was maintained at some

364   locations[53]. Other environmental conditions can affect habitability, but only temperature (and

365   therefore water availability) are considered here (*SA*).

366

367

368   **Randomly configured feedbacks**

369

370   It is assumed that there is no inherent bias in the climate systems of planets as a whole towards

371   either negative (stabilising) or positive (destabilising) feedbacks (*SA*). In other words, it is assumed

372   here that the feedback systems of planets are the end result of a set of processes which do not in

373   aggregate contain any overall inherent predisposition either towards or against habitability. Planets

374   are randomly configured such that some end up being more prone to climate stability and others do

375   not, but without any inbuilt bias either way (*SA*). This assumption could be incorrect. For instance, all

376   planets are subject to the Stefan-Boltzmann Law whereby the total heat energy radiated outwards

377   (the black body radiation) increases in proportion to the fourth power of its temperature in kelvin[20].

378   In the absence of systematic effects of temperature on other energy fluxes, this would impart an

379   overall bias towards temperature stability. But other factors may also change in a systematic way

380   with temperature. For instance, all planets with water oceans are also subject to potentially

381   destabilising ice-albedo[54] and temperature-water vapour[55,56] positive feedbacks with the potential to

382   lead to a runaway icehouse or greenhouse[53].

383

16

384    When a new planet is generated in the simulation it is given a random set of feedbacks using the

385    following procedure. First, each planet is allocated a number of nodes ($N_N$), where $N_N$ is equally likely

386    to be set to any number between 2 and $N_N^{max}$, the maximum number of nodes (20 in the default

387    model (*SA*)):

388

$$N_N \sim U_i(2, N_N^{max})$$
(2)

389

390    where $U_i(2, N_N^{max})$ denotes an integer between 2 and $N_N^{max}$, chosen randomly from a uniform

391    distribution (i.e. equal probability of any number).

392

393    After setting the number of nodes, the properties of each node are then calculated. The first node is

394    positioned at the lowest (coldest) temperature ($T_{min}$) and the last node at the highest (hottest)

395    temperature ($T_{max}$) in the habitable range. Feedback strengths outside the habitable range are not

396    considered because a planet is deemed to have 'failed' as soon as it has left the habitable range (*SA*).

397    The temperatures ($T_i$) of the remaining nodes (if $N_N > 2$) are then set so as to distribute them evenly

398    (*SA*) across the habitable temperature range:

399

$$T_i = T_{min} + (i - 1) * \frac{(T_{max} - T_{min})}{(N_N - 1)}$$
(3)

400

401

402    Finally, each node is also given a random feedback strength ($f_i$). The term 'feedback strength' is used

403    here to refer to the rate at which the planet tends to cool down or heat up at a particular

404    temperature, as a result of feedbacks. Each value of $f_i$ is determined by choosing a number randomly

405    from a Gaussian (normal) statistical distribution of mean 0 and standard deviation $\sigma_f$ (in units of

406    degrees C per thousand years):

$$f_i \sim N(0, \sigma_{\mathrm{f}}) \tag{4}$$

408

409 $\sigma_{\mathrm{f}}$ is given a value of 100 °C ky$^{-1}$ (*SA*). As a result, 99.7% of feedbacks calculated using equation 6

410 have an absolute magnitude less than or equal to 300 °C ky$^{-1}$ ($3\sigma_{\mathrm{f}}$).

411

412 It is difficult to be certain about the most realistic value for $\sigma_{\mathrm{f}}$. Some estimated potential heating and

413 cooling rates are shown for Earth in Supplementary Table 3, for comparison. However, because

414 Earth has remained habitable for 3 or 4 By, observer selection means that these cannot be

415 considered representative of planets as a whole. Different rates of temperature change can be

416 expected on other planets, if, for instance, they receive less or more intense radiation from their

417 parent stars or have different amounts of ocean (different heat capacities).

418

419 Feedback strengths at intervening temperatures are calculated by linear interpolation (*SA*) between

420 values at nodes. Some example results of this procedure for randomly determining climate

421 feedbacks are seen on the left-hand side of figure 1 of the paper. The procedure generates a

422 heterogeneous mixture of planets. This is consistent with conclusions, derived from observations

423 from Kepler and other missions, of considerable exoplanet diversity. It is also consistent with

424 theoretical exoplanet studies that have started to investigate the possible climate system

425 consequences of this exoplanet diversity, for instance of planets with much deeper oceans[57] or

426 tidally locked about their parent stars[58] or with different rotation rates[59]. Diversity of planets is thus

427 supported by exoplanet studies; universality of Earth-like feedbacks is not.

428

429

430 **Gradual Changes over Time**

431

432    Various climate-relevant factors can change over geological time. Most notably, a planet in an

433    unchanging orbit around a single star does not receive an unvarying heat input from that star,

434    because stellar luminosities change over time.  Stars are most stable while on the main sequence,

435    but even while on the main sequence their rate of output of radiation increases with age (hence the

436    Faint Young Sun paradox for Earth). The Sun, a G-type star, has increased its output at a faster rate

437    (30% increase over the last 3 By)[14] than most other potentially life-supporting stars. The rate of heat

438    output of the more numerous M-dwarf stars increases more slowly during their longer (> 10 By)

439    lifetimes on the main sequence.

440

441    There are other factors that can also change gradually over the lifetime of a planet[60]. Some of them

442    will amplify or counteract the effects of stellar brightening; they could even outweigh it, leading to a

443    net change in the opposite direction, tending to make the planet get progressively cooler over time.

444    Factors tending to promote long-term cooling include: (1) a gradual increase in continental area over

445    time[61], producing an increase in albedo (land has a higher albedo than water); (2) declining

446    geothermal heating due to decay of radioactive elements in a planet's interior, with the stock of

447    radioactive elements dwindling over time (this is a small factor in the radiation budget of Earth –

448    Supplementary Table 3 – but is probably a larger factor for some other planets and moons); (3)

449    progressive leakage out to space of low molecular mass gases including hydrogen, facilitating

450    oxygenation of the atmosphere and removal of methane and other greenhouse gases[62]. Another

451    potential source of long-term change is the life on the planet itself. As life increases in complexity

452    over time through evolution, the intensity with which it draws resources (including greenhouse

453    gases such as $CO_2$) from the environment may also increase[63].

454

455    From the foregoing, it seems likely that some planets experience a drift towards more negative

456    *dT/dt* values over time, even as the heat received from their host star increases.  For this reason, no

457    bias either way is coded into the model (*SA*). Instead, the overall sum forcing for each planet (Ø) is

458    set randomly from a Gaussian distribution, with equal probabilities of it being either positive or

459    negative:

460

$$\emptyset \sim N(0, \sigma_\emptyset) \tag{5}$$

461

462    where $\sigma_\emptyset$ is set to 50 (°C ky$^{-1}$) By$^{-1}$ (*SA*). 99.7% of forcings in the simulation therefore lie between

463    -150 and +150 (°C ky$^{-1}$) By$^{-1}$.

464

465    By way of comparison, the Sun has increased its rate of energy output by about 30% over the last 3

466    billion years, with the area-averaged solar flux received by the Earth increasing from about 270 W m$^{-2}$

467    to 340 W m$^{-2}$ (ref. 14). This would correspond to a rate of change of $\emptyset$ of (+70/3) W m$^{-2}$ By$^{-1} \approx$ +70

468    (°C ky$^{-1}$) By$^{-1}$ if no other radiative fluxes also changed over the same interval[64].

469

470

471    **Instantaneous Perturbations**

472

473    Planetary climates are also subject to occasional short-lived external perturbations, of varying

474    magnitude and frequency of occurrence. On Earth, volcanic eruptions and super-eruptions (such as

475    Toba) produce aerosols that block sunlight and cool the planet. Careful comparison of climate and

476    volcanic ash records over the last 2,500 years has confirmed that temperatures on the surface of the

477    Earth are depressed for up to 10 years in the aftermath of eruptions[65]. Other sources[66,67] of relatively

478    short-term perturbations to a planet's temperature include impacts of comets or asteroids, orbital

479    instabilities, carbon dioxide emissions associated with emplacements of large amount of basalt onto

480    the surface of the Earth, stellar flares, and nearby supernovae or other cosmic explosions.

481    Perturbations can also be biological in origin[68]. For instance, extreme glaciations on Earth were

482    triggered by the advent of oxygenic photosynthesis and the spread of the first forests across the

483    land[23]. Some perturbations (e.g. those from nearby supernovae or gamma-ray bursts) could be so

484    severe as to preclude any possibility of survival, whatever feedbacks a planet possesses, although

485    perturbations with enough energy to instantaneously boil all of Earth's oceans (raise temperatures

486    throughout the ocean by 100°C) are calculated to be vanishingly rare[67].

487

488    Three classes of perturbations ($P_S$, $P_M$ and $P_L$: small, medium and large) are used in the simulations,

489    with magnitudes determined as follows:

490

$$P_S = U_i(-1 \ or \ 1) * N(2,1)$$
$$P_M = U_i(-1 \ or \ 1) * N(8,4) \quad\quad (6)$$
$$P_L = U_i(-1 \ or \ 1) * N(32,16)$$

491

492    where $U_i(-1 \ or \ 1)$ makes each perturbation randomly positive or negative and $N([\mu, \sigma])$ is a

493    random number from a normal (Gaussian) distribution with mean μ and standard deviation σ (both

494    in °C). For comparison, temperature effects of different catastrophic events on Earth are shown in

495    Supplementary Table 4, while again keeping in mind that Earth is not likely to be typical because of

496    observer selection bias.

497

498    Different planets are subject to different perturbation probabilities depending on how geologically

499    active they are and where they are. Planets in densely-packed galaxies or regions of a galaxy have a

500    higher risk during the course of 3 By of experiencing large perturbations from nearby supernovae

501    and/or gamma-ray bursts. The centres of galaxies, where stars are more tightly packed, are, for this

502    reason, thought to be less likely locations for the evolution of intelligence[69]. Other known factors

503    include the nature of the parent star (how often and how strongly it flares), the stability of the orbits

504    of other planets in the planetary system, and the number and orbital stability of asteroids and

505    comets in the system.

506

507     It is likely, as seen for volcanic eruptions[65] and asteroids[70], that smaller climate perturbations occur

508     more frequently and larger perturbations less frequently. To reflect this variable exposure to

509     perturbations, random numbers are used to allocate each planet different expected numbers (λ) of

510     perturbations in each class:

511

$$\lambda_S \sim U_r(4000, 20000)$$
$$\lambda_M \sim U_r(40, 400) \tag{7}$$
$$\lambda_L \sim U_r(0, 5)$$

512

513     The actual numbers of perturbations ($N_S$, $N_M$ and $N_L$) during each 3 By simulation rerun of a planet,

514     if it completes, are then calculated randomly as follows:

515

$$N_S \sim P(\lambda_S)$$
$$N_M \sim P(\lambda_M) \tag{8}$$
$$N_L \sim P(\lambda_L)$$

516

517     where $P(\lambda)$ is a random number from a Poisson distribution with an expected (mean) value of λ. The

518     perturbations are made to occur at random times (from a uniform distribution) across the 3 By (*SA*).

519     Some examples of the results of applying these equations are shown on the right of figure 1 of the

520     paper (the red triangles).

521

522

523     **Required Duration of Uninterrupted Habitability**

524

22

525    An enormous duration of continued habitable conditions is required for the evolution of intelligent

526    life. It does not by itself guarantee that complex life will evolve (for instance, life may never emerge

527    in the first place) but evolution of complex life is obviously impossible without prolonged

528    habitability. It is difficult to know whether 3 billion years of habitability is always required, or just the

529    time that it happened to take on Earth. Perhaps intelligent life could develop more rapidly on a

530    planet with a more dynamic environmental history without periods of stagnation such as the so-

531    called 'boring billion' on Earth[71]. A minimum requirement of only 100 million years has been

532    suggested[72]. Alternatively, perhaps longer durations are more typical[73]. In the absence of a detailed

533    understanding of the time required, it was set to 3 billion years in this study (*SA*).

534

535

536    **Numerical Integration**

537

538    Numerical integration of equation 1 was carried out in Matlab (ode23s stiff solver, adaptive

539    timestep), with an initial timestep of 10 years, a maximum timestep of 1 million years, a relative

540    error tolerance of one in ten thousand (0.0001) and an absolute tolerance of 0.05°C.  The large

541    ensemble runs reported here were executed on a parallel computing cluster using MDCS (Matlab

542    Distributed Computing Server).

543

544    The initial temperature ($T_0$) was set equal to a different random value between $T_{min}$ and $T_{max}$

545    (equal probability of any value) at the beginning of each run:

546

$$T_0 \sim U_r(T_{min}, T_{max}) \qquad (9)$$

547

548    Because perturbations are abrupt changes which can lead to integration errors if not properly

549    handle, the model was run from one perturbation to another with the numerical integration

550    restarted after each perturbation. Simulations were continued for each planet until it went sterile

551    (*SA*) (its temperature left the habitable range, at which point it was deemed to have 'failed') or until

552    3 By had elapsed, at which point it was deemed to have 'succeeded' (intelligence to have evolved).

553

554

555    **Multiple runs of the same planet**

556
$$N_S \sim P(\lambda_S)$$

557
$$N_M \sim P(\lambda_M)$$

558
$$N_L \sim P(\lambda_L)$$

559    Because random numbers are used, a statistically robust evaluation of the tendency of a planet to

560    maintain habitable conditions requires multiple runs; the result of a single run is unlikely to be

561    representative. In order to run a planet multiple times, a separation has to be made between factors

562    that are intrinsic to the planet, and are therefore fixed for that planet, and those which are changed

563    for each different run of that planet. This separation defines which factors are categorised as part of

564    chance or hazard, and which as part of a planet's inherent make-up and hence mechanism. In these

565    simulations, the feedbacks ($N_N$ and $f_i$), forcing ($\emptyset$) and expected numbers of perturbations ($\lambda_S$,

566    $\lambda_M$, $\lambda_L$) were kept fixed for each planet, whereas the initial temperatures ($T_0$) and actual numbers

567    ($N_S$, $N_M$, $N_L$) and magnitudes ($P_S$, $P_M$, $P_L$) of perturbations were randomly set to different values for

568    each run of a planet *(SA)*. $\lambda_S$, $\lambda_M$, $\lambda_L$ and $\emptyset$ are properties that depend in part on the planet's

569    location (reflecting the nature of the surrounding planetary system and star, as well as of the

570    adjacent part of the galaxy). Reruns were therefore of the same planet in the same astronomical

571    location, rather than of the same planet in different astronomical locations *(SA)*.

572

573    **Code availability**

574

575  Matlab code for the model and sensitivity analyses is publicly available[74]

576  (http://doi.org/10.5281/zenodo.4081451, doi: 10.5281/zenodo.4081451). Results for this paper

577  were generated using the parallel version of the code. The model is also made available in Octave, a

578  free-to-use alternative to Matlab.

579

580

## Data Availability

582

583  No primary data was generated in this study.

584

585

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823

824

## Author Contribution Statement

826

827    TT carried out all analysis and interpretation and wrote the manuscript.

828

829

830

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832

## Figure Legends

**Figure 1: initial climate feedbacks (left-hand side) and temperature histories (right-hand side) of single runs of several randomly generated planets.** Each row of the figure is a different planet. On the left-hand plots (panels a, c, e and g): black circles are nodes and the thick black line is *f(T)* (see Methods for explanation); light grey shading indicates a region of runaway warming or runaway cooling; red circles show initial positions of attractors; red stippled lines demarcate associated basins of attraction. On the right-hand plots (panels b, d, f and h): blue line shows the evolution of planetary temperature; black shading shows limits to habitability; red circles show positions of attractors; green squares are the randomly determined initial temperatures for each run; red triangles indicate the largest perturbations, with triangle size proportional to perturbation magnitude. (a) & (b) are for example planet 1, (c) & (d) planet 2, (e) & (f) planet 3 and (g) & (h) planet 4. Note the different scale on the time axis of each right-hand panel.

**Figure 2: Dissimilarity between simulations results and expected patterns from H1 and H2.** (a) Success rates of a set of 200 planets, ranked in order of success; (b) success rates of all planets that were successful at least once, ranked in order, from a population of 100,000 planets (unsuccessful planets not shown); (c) histogram of habitability durations. Success rates in (a) and (b) were calculated by running each planet 100 times and counting the number of times it stayed habitable for 3 By. Habitability durations in (c) are the times until temperature departs the habitable range. Blue lines and bars show simulation results; red lines and bars show expected results if planetary properties dictate outcomes absolutely (no influence of chance, i.e. H2); black lines and bars show the expected results if outcomes are caused by chance alone (no influence of a planet's feedbacks, i.e. H1). The green dotted line in (b) shows the spectrum of success rates of only those planets that were successful on the first of their 100 runs. H1 and H2 in (c) are made to have the same proportion (0.0145) of successful planets as the simulation.

865

866 **Figure 3: Repeat runs of a set of planets do not give identical outcomes.** 1,000 different planets

867 were generated randomly. (a) results when each planet was run one time: those planets which

868 remained habitable are shown as green circles and those which did not as black circles; (b) results

869 when the same 1,000 planets were run a second time (same planets but different starting

870 temperatures and perturbations compared to the first run). In this particular example 15 planets

871 stayed habitable on the first occasion, 10 on the second, with 6 remaining habitable on both

872 occasions (additional analysis shows that on average there is a 39% overlap, or in other words there

873 is a 39% chance of a planet being habitable in the repeat set if it was habitable in the original set).

874

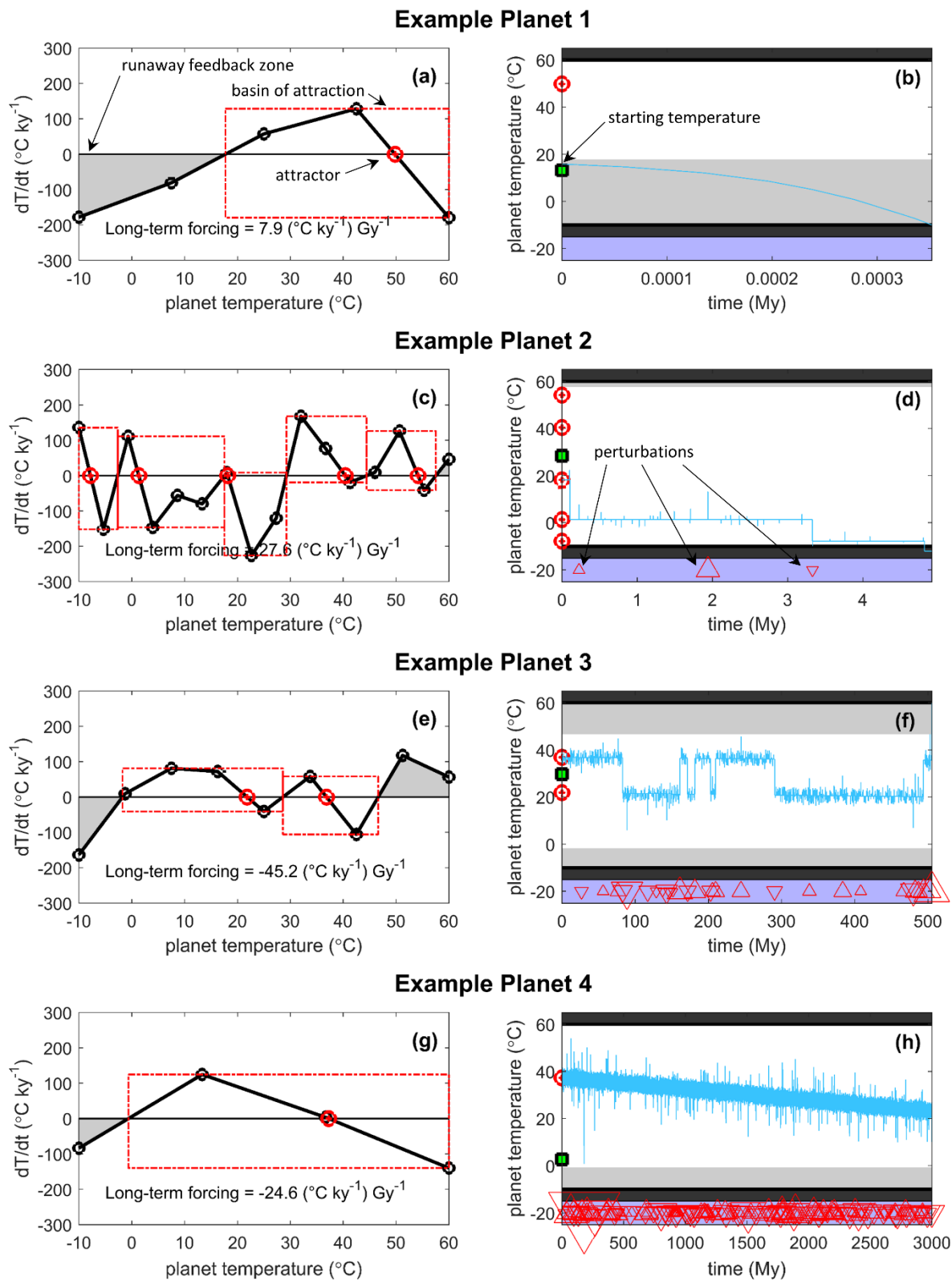| Default assumption | Alternatives tested |
| --- | --- |
| Feedbacks ($f$) $\sim N(0,100)$ °C ky$^{-1}$ with no bias either for or against stabilisation | $f \sim N(0,50)$; $f \sim N(0,200)$; $f \sim U(-100,100)$; bias towards stabilisation (Stefan-Boltzmann Law) |
| $f$ is linearly interpolated between $N_N \sim U_i(2,20)$ evenly-spaced nodes | random node positions; $N_N \sim U_i(2,10)$; $N_N \sim U_i(2,40)$; spline interpolation |
| Feedbacks ($f$) are constant through time | $f$ are subject to random alterations during runs |
| Habitable temperature range ($T_{min}$ to $T_{max}$) = -10 to 60 °C | $T_{min}$ = 0; $T_{min}$ = -50; $T_{max}$ = 50; $T_{max}$ = 100; $T_{min}$ = -70 and $T_{max}$ = 150; $T_{max}$ is pressure-dependent; habitable range narrows over time |
| On average there are 12,000 small perturbations (magnitude ~N(2,1) °C), 220 medium (~N(8,4) °C) and 2.5 large (~N(32,16) °C) ones | Ten times more (all size classes); ten times fewer; all twice as large; all half as large; declining frequency of perturbations over time |
| Positive and negative long-term forcings (∅) are equally likely, increase linearly with time and have magnitudes $\sim N(0,50)$ (°C ky$^{-1}$) By$^{-1}$ | $\emptyset \sim N(0,25)$; $\emptyset \sim N(0,100)$; bias towards warming (due to increasing stellar luminosity): $\emptyset \sim N(+50,50)$; cyclical forcings; non-linear functions of time |
| Time to evolution of intelligence ($t'$) = 3 By | $t'$ = 2; $t'$ = 4; $t' \sim U(0.5,10)$ |

875
876 **Table 1: Assumptions Tested.** The robustness of the main conclusion to various assumptions (see
877 Supplementary Methods for a full list and more complete descriptions, and Supplementary Tables 1
878 and 2 for results) was investigated with sensitivity analyses. The main conclusion, that results agree
879 with neither H1 nor H2 but are intermediate between them, was unaffected by any of the model
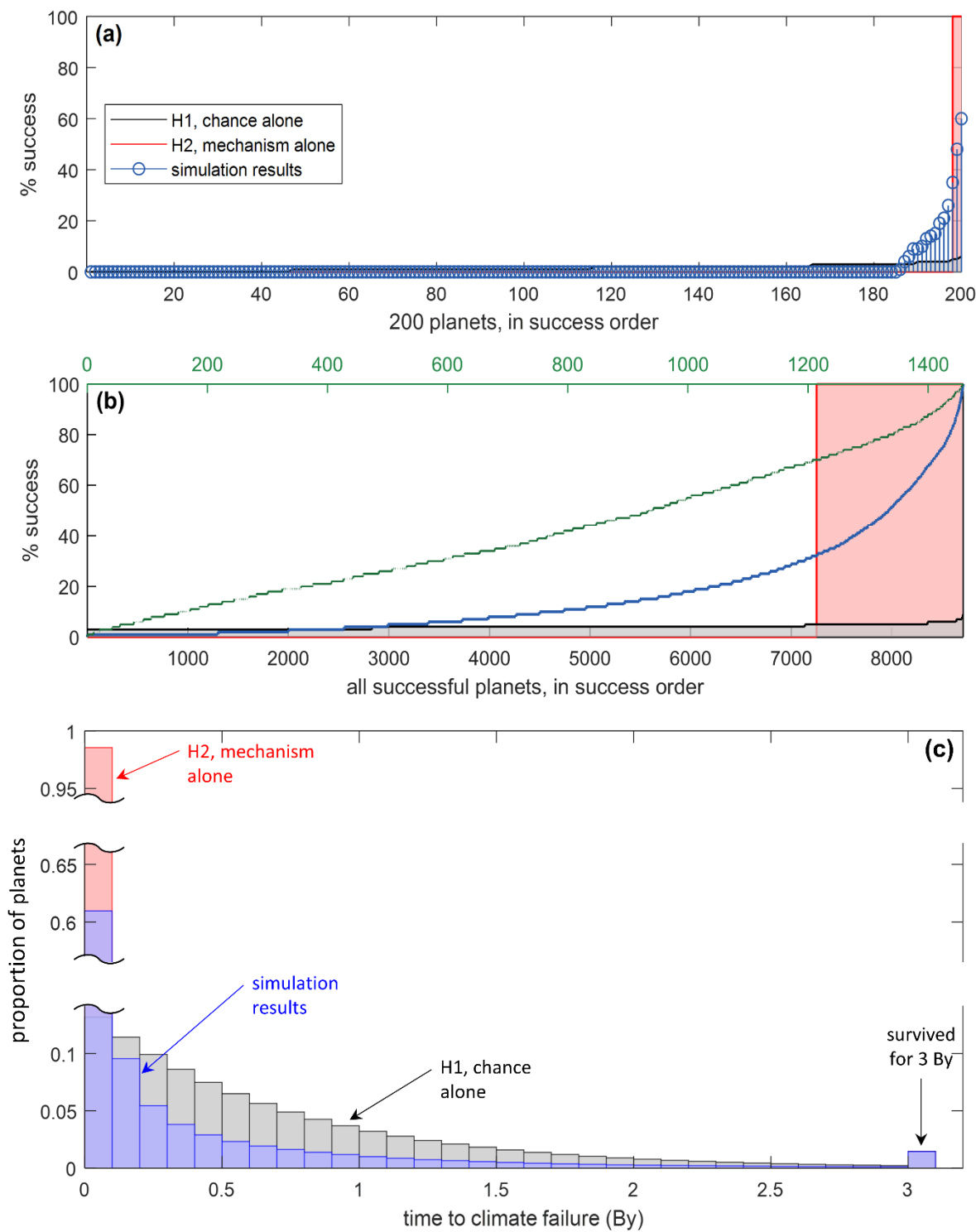880 alterations.
881

882 **Competing Interests**

883

884 The author declares no competing interests

885

Figure 1

## Example Planet 1



## Example Planet 2



## Example Planet 3



## Example Planet 4

889     Figure 2

892    Figure 3

**(a)**



**(b)**



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895 **Supplementary Information**

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900 Accompanying the manuscript "Chance played a role in determining whether Earth

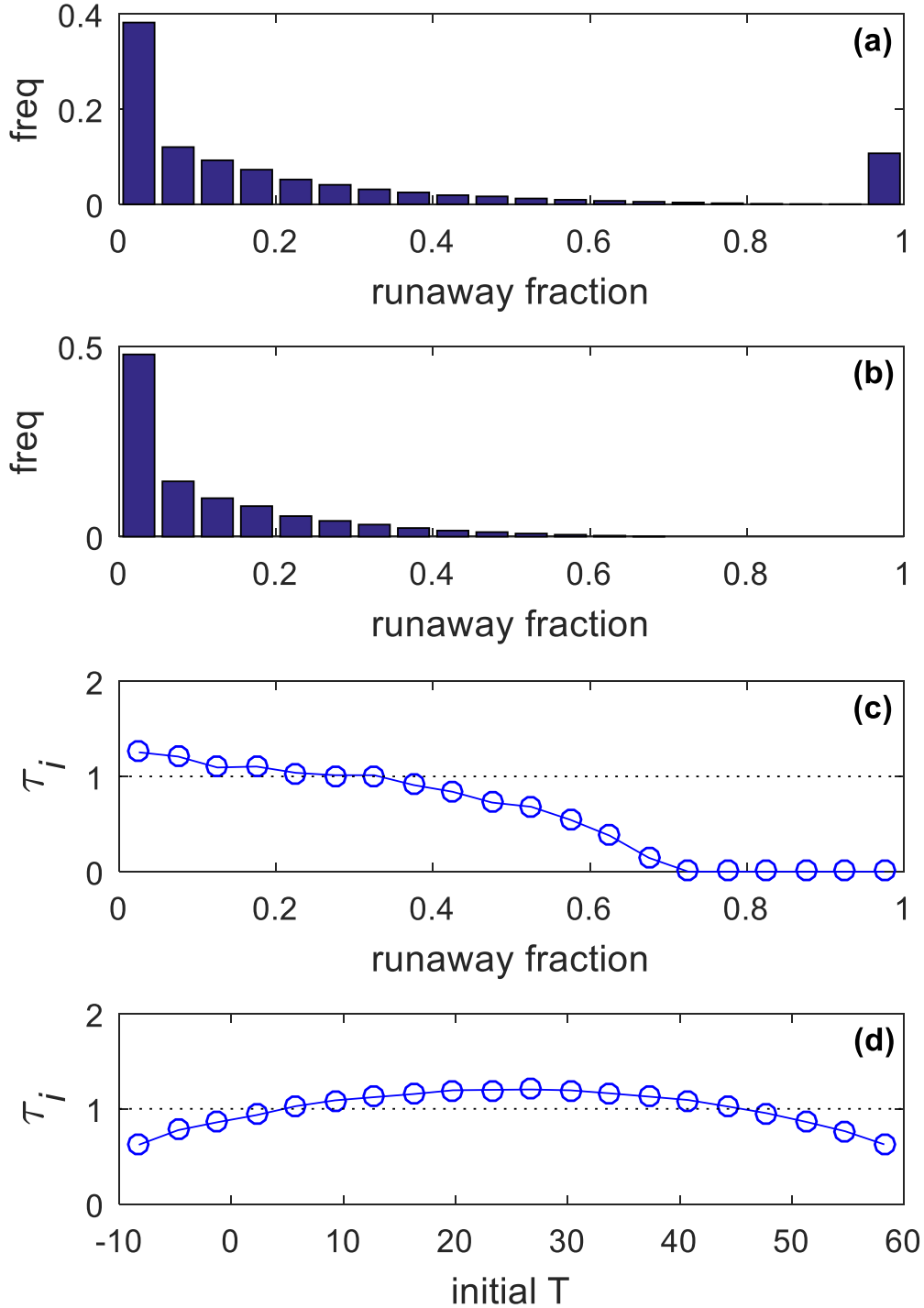901 stayed habitable" by Toby Tyrrell

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**Supplementary Figure 1: Frequencies of occurrence as a function of planet properties, from a simulation of 100,000 randomly different planets.** Checks were made to verify that the model exhibited sensible behaviour in terms of how likelihood of success is influenced by various factors. The method of analysis is shown here, together with results for two factors. (a) histogram of the relative frequencies with which the automated planet-generation process produces planets with different values of $fr_{\text{runaway}}$, the fraction of the habitable range within which temperatures run away to uninhabitable values; (b) histogram of the relative frequencies of successful planets (those staying habitable at least once) with different values of $fr_{\text{runaway}}$; (c) variation of the $\tau_i$ statistic (measure of success) against the value of $fr_{\text{runaway}}$ for the planet; (d) variation of the $\tau_i$ statistic

920    against the starting temperature. In (c) and (d), the $\tau_i$ statistic for each bin is the proportion of
921    successful planets from that bin divided by the proportion of all planets from that bin:

$$\tau_i = \frac{\left[ N_i^s / \left( \sum_{i=1}^{i=nbins} N_i^s \right) \right]}{\left[ N_i^{\text{all}} / \left( \sum_{i=1}^{i=nbins} N_i^{\text{all}} \right) \right]} \tag{10}$$

922    where $i$ is the bin number, $nbins$ is the total number of bins (20), $N_i^{\text{all}}$ is the number of planets for
923    which the value of the planet property is in the $i$th bin's range, and $N_i^s$ is the number of successful
924    planets for which the planet property is in the $i$th bin's range. As expected, (c) shows that increasing
925    extent of runaway feedback zones leads to diminishing probability of planet success; (d) shows that
926    the starting temperature has only a modest impact (runs starting very near to the edges of the
927    habitable range are somewhat less likely on average to stay habitable, presumably because there is a
928    greater probability near the edges of starting within a runaway feedback zone or of being
929    immediately nudged outside the limits by a very early perturbation).
930
931

## Supplementary Methods (Sensitivity Analyses)

Sensitivity analyses were conducted to see if the main conclusion of this paper is critically dependent on particular details of the model or whether it is more robust. The procedure for evaluating the effect of each model detail was to: (1) make a change to that detail in the model (for instance, change a parameter value); (2) execute a parallel but smaller simulation (1,000 planets each rerun 50 times rather than 100,000 planets each rerun 100 times for the standard simulation); then (3) examine the results to see if the major conclusion is again borne out.

**How sensitivity was assessed**

Results were examined in a few different ways to see if the main conclusion held in each altered version of the model.

First, success rates were examined to see if there was a spectrum of different probabilities of success (i.e. if some planets were successful between 1 and 49 times of out of 50, as opposed to all planets being either always successful – 50 out of 50 – or never successful – 0 out of 50).

Second, plots equivalent to Figure 3b were produced for each sensitivity analysis (not shown). In these plots, the distribution of planet success rates was again compared graphically to the distribution of success rates expected according to H1 and H2. If the blue line was again completely separate and distinct from the red and black lines, and positioned somewhere between the two of them, then this was taken as supporting the main conclusion (that both chance and mechanism played a role in whether planets stayed habitable).

Third, the number of sometimes habitable (at least 1 time out of 50) planets for each simulation was compared to the number consistent with destiny (H2) or chance (H1). This check consisted of a quantitative as opposed to a qualitative procedure. If planets are either always successful or always unsuccessful (i.e. H2), with no intermediate possibilities, then the fraction of planets that are habitable must be the same as the fraction of runs that stay habitable, or in other words:

$$N_{\text{occ}}^{\text{p}} = N_{\text{total}}^{\text{p}} * (N_{\text{successful}}^{\text{r}}/N_{\text{total}}^{\text{r}}) \tag{11}$$

On the other hand, if each run of each planet has exactly the same chance of staying habitable regardless of its feedbacks (i.e. H1), then the probability of any one run being successful ($P^r$) must be exactly the same as the fraction of all runs that are successful ($N_{\text{successful}}^{\text{r}}/N_{\text{total}}^{\text{r}}$). The probability ($P^{\text{p}}$) of any one planet being successful at least once (1 or more times out of 50 reruns) would then be given by :

$$P^{\text{p}} = 1.0 - (1.0 - P^r)^{50} \tag{12}$$

$$= 1.0 - \left[1.0 - \left(\frac{N_{\text{successful}}^{\text{r}}}{N_{\text{total}}^{\text{r}}}\right)\right]^{50} \tag{13}$$

The most likely number of successful planets out of 1,000 can then be calculated from the binomial probability distribution. When $((1{,}000 + 1) * P^{\text{p}}))$ is not an integer then $N_{\text{occ}}^{\text{p}}$ is predicted to be given by:

$$N_{\text{occ}}^{\text{p}} = \lfloor (1{,}000 + 1) * P^{\text{p}} \rfloor \tag{14}$$

where $\lfloor \ \rfloor$ is the floor function which rounds a decimal number to the nearest integer below.

975 The predicted values of $N_{occ}^{p}$ according to H2 (equation 12) and H1 (equation 15) were then
976 compared to the observed value of $N_{occ}^{p}$ from the simulation for that sensitivity analysis.

978 As an additional check, the matlab command 'runstest' was used to check for random order of
979 results[1]. When the run durations from all the runs in a sensitivity analysis are placed in a single
980 vector with the first 50 being those from planet 1, the second 50 being those from planet 2, etc then
981 random order would only be expected if H1 is correct. The 'runstest' command returns a value of 1 if
982 the null hypothesis of random order is rejected (refutation of H1), or 0 if it cannot be rejected.

984 As noted in the main text, the frequency of long-term habitability varies greatly (e.g. orders of
985 magnitude variation in $N^{r}$ – see tables below) depending on which assumptions are used. The
986 simulation results are not, therefore, a reliable guide to the frequency of long-term planetary
987 habitability in the universe.

989 **Results (sensitivity to parameter values)**

991 The parameter changes investigated are shown on the left of Table S1 below. After every different
992 parameter change it was found that there was always a spectrum of different probabilities of
993 success. Likewise, in the equivalent of Figure 3b the blue line was always completely separate and
994 distinct from the red and black lines, and was situated somewhere between the two of them. As
995 shown in Table S1, the observed value of $N_{occ}^{p}$ was always much greater than (always more than
996 twice as large as) the value according to H2 and always much less than (always less than half as large
997 as) the values according to H1. Finally, the 'runstest' results were always 1 (p « 0.001), confirming
998 rejection of H1 for all SAs.

1001 **Supplementary Table 1:** Results of sensitivity analyses to examine the effect on the main conclusion
1002 of changing the values of model parameters.

| Parameter [default value] | New value | Number of Successes | | | Number of Habitable Planets | | | 1<2<3? |
|---|---|---|---|---|---|---|---|---|
| | | Planets* | | Runs† | | | | |
| | | $N^p_{occ}$ | $N^p_{always}$ | $N^r$ | 1.Destiny‡ | 2.Simulation | 3.Chance§ | |
| *standard model* | - | *86* | *0* | *923* | *18* | *86* | *606* | ✓ |
| $T_{min}$ [-10] | 0 | 49 | 0 | 376 | 8 | 49 | 314 | ✓ |
| $T_{min}$ [-10] | -50 | 201 | 0 | 2,905 | 58 | 201 | 950 | ✓ |
| $T_{max}$ [60] | 50 | 27 | 0 | 143 | 3 | 27 | 133 | ✓ |
| $T_{max}$ [60] | 100 | 199 | 2 | 2,847 | 57 | 199 | 947 | ✓ |
| $N^{max}_N$ [20] | 40 | 48 | 0 | 384 | 8 | 48 | 320 | ✓ |
| $N^{max}_N$ [20] | 10 | 123 | 0 | 1,151 | 23 | 123 | 688 | ✓ |
| $\sigma_f$ [100] | 50 | 41 | 0 | 309 | 6 | 41 | 266 | ✓ |
| $\sigma_f$ [100] | 200 | 124 | 0 | 1,163 | 23 | 124 | 692 | ✓ |
| $\sigma_\emptyset$ [50] | 25 | 130 | 0 | 1,260 | 25 | 130 | 721 | ✓ |
| $\sigma_\emptyset$ [50] | 100 | 41 | 0 | 396 | 8 | 41 | 328 | ✓ |
| $N_S$ [$10^4$] $N_M$ [200] $N_L$ [4] ‡ | 10x more** | 52 | 0 | 379 | 8 | 52 | 372 | ✓ |
| $N_S$ [$10^4$] $N_M$ [200] $N_L$ [4] ‡ | 10x fewer | 302 | 2 | 4,405 | 88 | 302 | 991 | ✓ |
| $P_S$ [2,1] $P_M$ [5,2.5] $P_L$ [10,5]¶ | all 2x larger** | 22 | 0 | 47 | 1 | 22 | 46 | ✓ |
| $P_S$ [2,1] $P_M$ [5,2.5] $P_L$ [10,5]¶ | all 2x smaller | 315 | 3 | 5,267 | 105 | 315 | 997 | ✓ |
| $t_{max}$ [3By] | 2By | 121 | 0 | 1,122 | 22 | 121 | 679 | ✓ |
| $t_{max}$ [3By] | 4By | 73 | 0 | 689 | 14 | 73 | 500 | ✓ |

1003 * $N^p_{occ}$ is the number of planets out of 1,000 that were successful in at least 1 rerun, $N^p_{always}$ the
1004 number that were successful in all 50 reruns; † $N^r$ is the number of runs out of 50,000 that were
1005 successful; ‡ (from equation 12); § (from equation 15); ¶ for this sensitivity analysis, the numbers
1006 or magnitudes of the three classes of perturbations were all increased or decreased together); **
1007 from 10,000 planets x 50 reruns (10 times more than normal).

**Structural sensitivity analyses**

A second set of sensitivity analyses examined the effect on the simulations results of changing various structural assumptions. The rationale for each structural change is described below, followed by a description (in italics) of how the change was implemented.

1. The stock of asteroids and comets likely to intersect a planet's orbit may become depleted over time (less frequent impact events), planets may cool and stabilise internally over time (less frequent supervolcanoe eruptions), and the population of massive nearby stars (those prone to gravitational collapse to produce supernovae) is likely to become depleted over time. *{Perturbations were made to decline in frequency over time instead of being equally frequent at all times. Each perturbation time $t_\mathrm{p}$ was calculated with: $t_\mathrm{p} = t' * (1 + k) * ((R + 1)^{-8} - k)$ where $k = 2^{-8}$ and $R \sim U(0,1)$ }*

2. Complex life is, on the whole, less tolerant of extreme environmental conditions (prokaryotes can tolerate a wider range of conditions than can eukaryotes, for instance[2]). {*The habitable envelope was made to become narrower over time, instead of remaining of constant width. The habitable range was made to start off 20°C wider than in the default simulation (100°C rather than 80°C) and become progressively narrower, ending up 60°C wide after 3 By}*

3. The feedbacks may possibly vary more smoothly as a function of temperature. {*The value of the feedback f between nodes was calculated using a spline (cubic) rather than linear interpolation}*

4. Alternatively, feedbacks could be quite constant across large temperature intervals but then change quite rapidly across narrow temperature intervals. {*Nodes were given random positions within the habitable range, instead of being positioned at regular intervals across it}*

5. The default model contains no bias either for or against stabilisation but planets as whole may in reality be biased towards stability because of the Stefan-Boltzmann Law (planets with hotter surface temperatures radiate heat more rapidly to space, unless subject to different greenhouse effects)[3]. {*A bias towards stabilisation was implemented by addition of an amount $\vartheta_i$ to all $f_i$, where $\vartheta_i = \left(\sigma_f/2\right) - \left(\left[\sigma_f * (T_i - T_{\min})/(T_{\max} - T_{\min})\right]\right)$ }*

6. Warming or cooling forcings are equally likely in the default model but warming is arguably more likely because stars on the main sequence always become more luminous over time[4]. {*A positive bias was imparted by adding a fixed positive amount (equal to $\sigma_\emptyset$) to the randomly determined forcing in order to make positive values more likely than negative ones, changing equation (7) to: $\emptyset = \{\sim N(0, \sigma_\emptyset) + \sigma_\emptyset\}$}*

7. It is unclear whether feedbacks values should be uniformly or normally distributed. {*Instead of being chosen from a normal distribution centred at zero, values of f are chosen instead from a uniform distribution [ $f \sim U(-\alpha, +\alpha)$ ], where α is chosen so as not to alter the average absolute magnitude of f}*

8. Evolution is a process whose rate appears to vary, progressing more slowly when the environment is more static (for instance the 'boring billion' on Earth)[5] and more quickly during and following periods of environmental change. The time that a planet needs to remain habitable in order for intelligence to evolve may therefore vary greatly between planets rather than always being more or less the same[6]. {*Instead of being fixed at 3 By, $t'$ for each planet is set to a random number between 0.5 and 10 By}*

9. A planet could lose habitability early on, only to recover and remain habitable for 3 By later. *{The range a planet's temperature can vary within is extended to (-200°C to +500°C), while the habitable range remains the same. The maximum number of nodes ($N_\mathrm{N}^{\max}$) is increased proportionately. Each run is simulated for 10 By, regardless of any exits / re-entries to the habitable range during that time. At the end of each run of 10 By, the longest continuous duration of habitability, whenever in the run it occurred, is compared to $t'$}*

1055   10. Because of its simplicity, the model cannot reproduce absolutely all of the behaviours of more
1056   complex models. This extreme simplicity can lead to a shortcoming through the lack of intervening
1057   climate system variables, such as albedo and greenhouse gas concentrations. Because the value of $f$
1058   for each value of $T$ is fixed at the outset for each planet, the standard version of the simulation is not
1059   able to simulate feedbacks that change slowly at a constant planetary temperature. This is not a
1060   significant problem for most such delayed responses that take time to build up (e.g. the waxing or
1061   waning of ice sheets following a change in Earth surface temperature), because their timescales of
1062   readjustment to the prevailing temperature are still very short (e.g. millennia) compared to the
1063   lifespan of a planet. It is, however, more problematic for slower readjustments to temperature. For
1064   instance, the standard model cannot capture the rather slow (over 4 to 30 My [7]) accumulation of
1065   volcanic $CO_2$ in the atmosphere postulated to have brought an end to Proterozoic Snowball Earth
1066   events. {*To enable the possibility of accumulation or depletion of climate-affecting substances at a*
1067   *constant temperature, 3 additional climate-relevant variables ($X_1$, $X_2$ and $X_3$) were added and their*
1068   *behaviour controlled by three additional ODEs of the form $dX_i/dt = f_i(X_i) + \emptyset_i.t + c_i.T$ , where $f_i$*
1069   *are randomly assigned feedbacks as for temperature in the standard model and $\emptyset_i$ are randomly*
1070   *assigned temporal forcings. The ODE for temperature was modified to incorporate the effects of*
1071   *these other factors: $dT/dt = f(T) + \emptyset.t + k_1.X_1 + k_2.X_2 + k_3.X_3$ ; $c_1$, $c_2$ and $c_3$ are random*
1072   *coefficients $\sim U(-1,+1)$ and $k_1$, $k_2$ and $k_3$ are random coefficients $\sim U(-2,+2)$* }

1073   11. In the standard model, the feedbacks are fixed at the beginning and not subsequently altered. It
1074   is possible, however, for significant changes to planetary climate systems to occur later on in their
1075   histories[8], such as occurred on Earth ca. 380 Mya when trees evolved and the first forests spread out
1076   across the land[2]. {*A random number $\sim U_i(0,8)$ of changes were made to f at random times. Each*
1077   *change was of one of four types: (i) addition of the same amount ($\sim N(0, \sigma_f)$) to all $f_i$; (ii) a ramped*
1078   *change with a minimum addition at one edge of the habitable range and a maximum at the other,*
1079   *changing the overall slope of $\delta T/\delta t$ vs T; (iii) addition according to a peaked (triangular) profile; and*
1080   *(iv) addition according to a Gaussian profile with centre randomly placed on the T axis*}

1081   12. As well as being subjected to random instantaneous perturbations, the Earth also experiences
1082   periodic fluctuations in the amount and seasonality of solar heat it receives (Milankovitch cycles),
1083   and most likely is affected also by other longer period cyclic forcings, such as supercontinent
1084   assembly/break-up due to plate tectonics. {*A random number $\sim U_i(1,4)$ of both short period*
1085   *[ $\tau \sim U(0,0.001\text{By})$ ] and long period [ $\tau \sim U(0,0.5\text{By})$ ] extra terms were added to the ODE for*
1086   *planetary temperature. For each one, the term added to the ODE was $(k_i.\sin(2\pi t/\tau))$, where $k_i$ is*
1087   *the randomly-determined magnitude $\sim U(0, (\sigma_f/5))$ of each cyclical forcing and t is time*}

1088   13. The increase over time in the luminosity of the Sun happens to be almost linear[9] but temporal
1089   forcings in general need not be. {*The shape of the temporal forcing was made to be non-linear by*
1090   *multiplying the overall magnitude of the forcing ($\emptyset$) by $(t/t_{max})^\gamma$ where t is time, $t_{max}$ is 3 By and $\gamma$*
1091   *is (50% probability) either $\sim U(1.0,6.0)$ (exponential shape) or $1/\sim U(1.0,6.0)$ (logarithmic shape)*}

1092   14. Early life on Earth was probably thermophilic, perhaps because it first evolved under hot
1093   conditions. Perhaps a hot environment is required for the origin of life[10]. {*This possibility was*
1094   *implemented by choosing the initial temperature from a narrower and hotter range: $T_0 \sim U((T_{max} -$*
1095   *$20), T_{max})$*}

1096   15. The upper limit to thermal habitability is arguably either a function of the boiling point of water
1097   or else of the temperature at which enzymes including DNA denature. The former is assumed in this
1098   model variant, with the boiling point of water made a function of atmospheric pressure rather than
1099   constant as in the standard model. {*An additional environmental variable, atmospheric pressure at*
1100   *sea-level, was added through the addition of an ODE of the form $dX_P/dt = f_P(X_P) + \emptyset_P.t$ , where*
1101   *$f_P$ are randomly assigned feedbacks and $\emptyset_P$ is a randomly assigned temporal forcing. $T_{max}$ (°C) was*
1102   *made to be a function of pressure (P, units of Pa): $T_{max} = [4908/(24.67 - \ln P)] - 273.15$* }

1103   16. Although temperature is the primary factor determining habitability[11], other environmental
1104   variables (such as pH, ionic strength for life in water) also need to stay within habitable limits for
1105   intelligence to be able to evolve. {*Three additional environmental variables ($X_1$, $X_2$ and $X_3$) were*
1106   *added through the addition of three ODEs of the form $dX_i/dt = f_i(X_i) + \emptyset_i.t$ , where $f_i$ are*
1107   *randomly assigned feedbacks as for temperature in the standard model and $\emptyset_i$ are randomly*
1108   *assigned temporal forcings. The planet was deemed to have gone uninhabitable when either*
1109   *temperature (simulated in the normal way) or any other variable left its habitable range (-100 to*
1110   *+100 for the additional variables, in arbitrary units).*}

1111   17. Perhaps life can survive periods of inhospitable conditions within refuges (for instance, the
1112   survival of photosynthetic algae through Snowball Earth episodes lasting for many millions of
1113   years[12,13] may have been within persistent polynyas[14]. If so, then average global conditions may need
1114   to become much more extreme in order for conditions everywhere to be intolerable for life. {*$T_{\min}$*
1115   *and $T_{\max}$ were both changed, to -70°C and +150°C*}

1116   18. There is room for debate about exactly what should be encompassed by the term destiny and
1117   what should be considered as part of luck. In this sensitivity analysis an alternative categorisation is
1118   used, whereby chance is deemed to consist only of perturbations (random events driving sudden
1119   changes in temperature) with all else (including initial temperature) included as part of destiny.
1120   {*Rather than being calculated separately for each rerun of each planet, $T_0$ was calculated only once*
1121   *for each planet, with each rerun of a planet being started from the same initial temperature*}

1122   19. As for the previous sensitivity analysis, the definitions of luck and destiny are altered. This time a
1123   planet's feedbacks (*f*) are considered to be the only factors that might contribute to its destiny, with
1124   all else being considered part of chance and therefore made to vary between reruns of the same
1125   planet. Repeat runs of the same planet can therefore be thought of as taking place in different
1126   locations (in different galaxies or in different regions of the same galaxy, around different stars or in
1127   different planetary systems). {*Rather than being calculated only once for each planet, $\emptyset$, $\lambda_L$, $\lambda_M$ and $\lambda_S$*
1128   *were all recalculated for each and every rerun*}

1129   20. It is necessary to consider whether the results obtained are biased by the degree of hazard built
1130   into the model. It should be considered whether the results would come to resemble H1 (outcomes
1131   controlled only by chance) if the perturbations and forcings were made larger and the feedbacks
1132   smaller. {*Although this was partially addressed in other SAs with changes to individual parameter*
1133   *values, in this SA it was purposefully addressed through a combination of changes: twice as many*
1134   *perturbations, 50% larger perturbations and forcings, and 25% smaller feedbacks*}

1135   21. Conversely, it should also be considered whether the results would come to resemble H2
1136   (outcomes determined only by the nature of the planet's feedbacks) if the perturbations and
1137   forcings were made smaller and the feedbacks larger. {*Again, this question was partially tested in*
1138   *other SAs but was purposefully assessed in this SA through: omitting the larger class of perturbations*
1139   *altogether[63], half the numbers of other perturbations, 25% smaller magnitudes of perturbations and*
1140   *forcings, and feedbacks 50% larger than in the standard version*}
1141
1142   **Results (sensitivity to structural assumptions)**
1143
1144   After each structural change there was always a continuum of success probabilities. In the
1145   equivalent of Figure 2b for each sensitivity analysis the blue line was always separate and distinct
1146   from the red and black lines and somewhere between them. As shown in Table S2, the observed
1147   value of $N_{\mathrm{occ}}^{\mathrm{p}}$ was always much greater than (nearly always more than twice as large as) the value
1148   according to H2, and always much less than (always less than half as large as) the values according to
1149   H1. Finally, 'runstest' results were again always 1 (p « 0.001), confirming rejection of H1 for all SAs.
1150
1151

1152 **Supplementary Table 2:** Results of sensitivity analyses to examine the effect on the main conclusion
1153 of structural changes to the model.

| Sensitivity analysis number | Number of Successes | | | Number of Habitable Planets | | | |
| | Planets* | | Runs† | | | | |
| | $N^{\mathrm{p}}_{\mathrm{occ}}$ | $N^{\mathrm{p}}_{\mathrm{always}}$ | $N^r$ | 1.Destiny‡ | 2.Simulation | 3.Chance§ | 1<2<3? |
|---|---|---|---|---|---|---|---|
| *standard model* | *82* | *0* | *619* | *12* | *82* | *464* | ✓ |
| 1 | 108 | 1 | 1,234 | 25 | 108 | 714 | ✓ |
| 2 | 81 | 0 | 934 | 19 | 81 | 611 | ✓ |
| 3 | 75 | 0 | 749 | 15 | 75 | 530 | ✓ |
| 4 | 75 | 0 | 691 | 14 | 75 | 501 | ✓ |
| 5 | 171 | 0 | 1,850 | 37 | 171 | 849 | ✓ |
| 6 | 60 | 0 | 699 | 14 | 60 | 505 | ✓ |
| 7 | 83 | 0 | 770 | 15 | 83 | 540 | ✓ |
| 8 | 104 | 0 | 604 | 12 | 104 | 455 | ✓ |
| 9 | 94 | 1 | 1,215 | 24 | 94 | 708 | ✓ |
| 10 | 79 | 0 | 267 | 5 | 79 | 235 | ✓ |
| 11 | 163 | 0 | 510 | 10 | 163 | 401 | ✓ |
| 12 | 40 | 0 | 394 | 8 | 40 | 327 | ✓ |
| 13 | 80 | 0 | 690 | 14 | 80 | 690 | ✓ |
| 14 | 71 | 0 | 689 | 14 | 71 | 500 | ✓ |
| 15 | 282 | 4 | 7,424 | 148 | 282 | 1,000 | ✓ |
| 16 | 37 | 0 | 319 | 6 | 37 | 274 | ✓ |
| 17 | 411 | 8 | 10,264 | 205 | 411 | 1,000 | ✓ |
| 18 | 84 | 0 | 967 | 19 | 84 | 623 | ✓ |
| 19 | 215 | 0 | 745 | 15 | 215 | 528 | ✓ |
| 20** | 37 | 0 | 255 | 5 | 37 | 251 | ✓ |
| 21 | 379 | 26 | 8,971 | 179 | 379 | 1,000 | ✓ |

1154
1155 *$N^{\mathrm{p}}_{\mathrm{occ}}$ is the number of planets out of 1,000 that were successful in at least 1 rerun, $N^{\mathrm{p}}_{\mathrm{always}}$ the
1156 number that were successful in all 50 reruns; † $N^r$ is the number of runs out of 50,000 that were
1157 successful; ‡ (from equation 12); § (from equation 15); ** from 10,000 planets x 50 reruns (10
1158 times more than normal).
1159

**Supplementary Table 3: Some heating and cooling fluxes on Earth, and associated potential rates of temperature change.** The upper half of the table shows the rates from individual components of the radiation balance if they were to act in isolation. Net fluxes are likely to be smaller because, in reality, there are always two or more processes acting, some of which oppose each other (stellar heating and outgoing infrared radiation for instance). The lower half of the table shows net fluxes associated with different amounts of energy imbalance.

| Heating or cooling process | Magnitude of energy flux | | Associated (dT/dt) ‡ |
|---|---|---|---|
| | (W m$^{-2}$) * | (10$^{24}$ J y$^{-1}$ = YJ y$^{-1}$) † | (°C ky$^{-1}$) |
| **Solar radiation (sunlight) at the top of the atmosphere** | 340 | 5.5 | 1000 |
| **Reflected sunlight (due to albedo)** | 100 | 1.6 | 300 |
| **Emitted infrared radiation (heat loss to space)** | 240 | 3.9 | 700 |
| **Total greenhouse effect (water vapour, $CO_2$, clouds, $O_3$, $CH_4$, etc)[15]** | 160 | 2.6 | 500 |
| **Heat flow from Earth's interior[16]** | 0.09 | 0.001 | 0.3 |
| **10% energy imbalance at Earth's surface** | 53 | 0.85 | 150 |
| **Greenhouse warming due to $CO_2$ doubling[17]** | 3.4 | 0.055 | 10 |
| **Anthropogenic net climate forcing (since 2005)[15]** | 0.6 | 0.037 | 2 |

* averaged across the whole of the Earth's surface.

† summed over Earth's surface area of 510 x 10$^{12}$ m$^2$; 1 W = 1 J s$^{-1}$; yotta (Y) = 10$^{24}$.

‡ calculated assuming that Earth's long-term heat capacity is the same as the heat capacity of the whole ocean, ~5.6 x 10$^{24}$ J K$^{-1}$ (ref. 18).

1172    **Supplementary Table 4: Estimated temperature changes associated with some catastrophic events**
1173    **(upper half) and times of sudden climate change (lower half) on Earth.**
1174

| Perturbation | Effect on global surface temperature | Literature Source |
|---|---|---|
| **Mount Pinatubo volcanic eruption** | -0.5 °C | 19 |
| **Tambora volcanic eruption** | -1.1 °C | 19 |
| **Toba volcanic supereruption** | -2.0 °C | 19 |
| **Cretaceous/Paleogene boundary (asteroid impact)** | up to -10 °C | 20 |
| **Deccan Traps large igneous province (outpouring of basalts)** | +2 °C | 21 |
| **Paleocene-Eocene boundary (cause uncertain)** | +5 °C | 22 |
| **Eocene-Oligocene Boundary (cause uncertain)** | -3 to -6 °C | 23,24 |
| **Permian-Triassic boundary, largest mass extinction (cause uncertain)** | +8 °C | 25,26 |

1175

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