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Carbonate-silicate cycle predictions of Earth-like planetary climates and testing the habitable zone concept

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In the conventional habitable zone (HZ) concept, a CO2-H2O greenhouse maintains surface liquid water. Through the water-mediated carbonate-silicate weathering cycle, atmospheric CO2 partial pressure (pCO2) responds to changes in surface temperature, stabilizing the climate over geologic timescales. We show that this weathering feedback ought to produce a log-linear relationship between pCO2 and incident flux on Earth-like planets in the HZ. However, this trend has scatter because geophysical and physicochemical parameters can vary, such as land area for weathering and CO2 outgassing fluxes. Using a coupled climate and carbonate-silicate weathering model, we quantify the likely scatter in pCO2 with orbital distance throughout the HZ. From this dispersion, we predict a two-dimensional relationship between incident flux and pCO2 in the HZ and show that it could be detected from at least 83 (2σ) Earth-like exoplanet observations. If fewer Earth-like exoplanets are observed, testing the HZ hypothesis from this relationship could be difficult.
Newton first alluded to the concept of a stellar habitable zone (HZ) in his 1687 Principia² by noting that Earth’s liquid water would vaporize or freeze at the orbits of Mercury and Saturn, respectively. Later, Whewell noted that “the Earth’s orbit is in the temperate zone of the Solar System”¹⁴. Since then, the definition of the stellar HZ has been refined, reaching its modern incarnation based on climate models⁴⁵.

Current HZ calculations⁶ find that around a Sun-like star, an Earth-like planet could remain habitable between 0.97 and 1.70 AU. The inner edge of the HZ is set by loss of surface water and the outer edge is set by the maximum greenhouse of a CO₂ atmosphere where extensive CO₂ condensation and increased Rayleigh scattering prevent any further greenhouse warming from CO₂ (refs. ⁶, ⁷). This definition of the HZ only considers H₂O and CO₂ as greenhouse gases, so Earth-like planets warmed by other greenhouse gases (e.g., H₂ or CH₄) could remain habitable at bigger orbital distances²⁸,²⁹. However, CH₄-rich atmospheres in the HZ may not be possible without life to generate substantial CH₄ (refs. ¹⁰, ¹¹).

In the carbonate–silicate cycle, atmospheric CO₂ dissolves in water and weathers silicates on both the continents and seafloor, which releases cations and anions¹⁶,²²,²⁷. On the continents, the weathering products, including dissolved SiO₂, HCO⁻³, and Ca²⁺, wash into the oceans where the HCO⁻³ combines with cations like Ca²⁺ to create CaCO₃, which precipitates out of solution. The net process converts atmospheric CO₂ into marine carbonate minerals (i.e., CaCO₃). Also, seafloor weathering occurs when seawater releases Ca²⁺ ions from the seafloor basalt and CaCO₃ precipitates in pores and veins. Subsequently, the carbonates within sediments and altered seafloor can be subducted.

Carbon returns to the atmosphere from outgassing. If CO₂ outgassing increases above the steady-state outgassing rate, a planet’s surface temperature rises. This leads to increased rainfall and continental weathering as well as potentially warmer deep-sea temperatures and more seafloor weathering²¹,²²,²⁸. Increased weathering draws down atmospheric CO₂ and stabilizes the climate over ~10⁶-year timescales on habitable, Earth-like planets²⁹.

One- and three-dimensional (1D, 3D) climate calculations of HZ limits⁴⁶,¹⁴ assume that a carbonate–silicate weathering cycle is functioning but do not explicitly include it. The assumed presence of the carbonate–silicate cycle would predict that atmospheric CO₂ of Earth-like planets increases with orbital distance in the HZ⁴,⁶,²⁹. In particular, future telescopic observations, e.g., NASA’s Habitable Exoplanet Imaging Mission (HabEx)³⁰ and Large Ultraviolet Optical Infrared Surveyor (LUVOIR)³¹, could search for the CO₂ trend to test the HZ hypothesis. Previous studies²⁹,³⁵ have suggested the carbonate–silicate weathering cycle could alter predictions of pCO₂ in the HZ, but it is important to know the exact relationship we are looking for. Also, while an increase of pCO₂ with orbital distance in the HZ may be true if all Earth-like exoplanets have the exact same properties as the modern Earth, the trend becomes less certain if HZ planetary characteristics deviate from those of the modern Earth. There could be considerable variability in atmospheric CO₂ throughout the HZ, perhaps even enough to obscure a monotonic trend with orbital distance.

Here, we show that uncertain physicochemical and geophysical parameters in the carbonate–silicate weathering cycle⁹ cause scatter in pCO₂ with orbital distance. We then demonstrate that future telescopes must observe at least 83 (2σ) HZ planetary atmospheres to confidently detect our predicted relationship between atmospheric CO₂ and orbital distance, and confirm the HZ hypothesis.

Results

Stable pCO₂ abundances from our numerical model. We use a coupled climate and carbonate–silicate weathering model (see Methods, subsection “Numerical carbonate–silicate cycle modeling”) to explore pCO₂ on Earth-like planets in the HZ. The model considers numerous planetary properties, listed in Table 1, and their effect on the carbonate–silicate weathering cycle to calculate a planet’s steady-state pCO₂ and surface temperature. If the globally averaged, steady-state surface temperature is below 248 K, we assume the planet is completely frozen and uninhabitable at the surface, as shown by 3D climate models⁵⁶. Similarly, we assume planets are uninhabitable beyond 355 K, above which surface water would be rapidly lost to space³⁷ (see Methods, subsection “Numerical carbonate–silicate cycle modeling” for additional details on these assumed temperature constraints).

We randomly generated 1050 habitable, stable, Earth-like exoplanet climates using uniform distributions of the model parameters in Table 1. A total of 1200 random, initial parameter combinations were considered but we eliminated those that resulted in planets that froze completely or were too hot to retain their surface oceans. As colored dots, Fig. 1 shows habitable, steady-state solutions.

Our model predicts that atmospheric CO₂ abundances should broadly increase and narrow in their spread with orbital distance in the HZ (Fig. 1), consistent with other models of CO₂ in the HZ²⁹,³⁸. As justified next in section “Habitable zone climate theory revisited”, the scatter is about a nominal linear trend between incident flux, S, and log(pCO₂), which is different from a non-linear trend in models that assume a constant surface temperature in the HZ from negative feedbacks³²,³⁴ but do not actually model the carbonate–silicate feedbacks. If future missions are to test the HZ concept by searching for a trend between incident flux, S, and pCO₂ (refs. ³², ³⁴), they could search for the fundamental S–pCO₂ relationship shown in Fig. 1.

Below, we show that a log-linear relationship between pCO₂ and S may be the default in the HZ if Earth-like carbonate–silicate weathering is ubiquitous on habitable planets. In fact, the trend is elucidated by combining climate theory with carbonate–silicate cycle theory in what follows.
the planet to cool. The cooler temperature would lower the CO₂ weathering rate causing CO₂ to accumulate in the atmosphere until the temperature returned to its nominal value of 289 K. Figure 2 shows this scenario with the dotted blue 289 K contour, which gives the pCO₂ value required to maintain a 289-K surface temperature for the modern Earth as it moves about the HZ. The line was calculated from a radiative-convective climate model described in the Methods below, subsection "Habitable zone 1D climate model" (see Eq. (8)).

The constant, 289 K surface temperature contour in Fig. 2 is a non-linear relationship between incident flux, S, and log(pCO₂) but it does not consider the temperature and pCO₂ feedbacks inherent to the carbonate-silicate weathering cycle. We demonstrate that if these feedbacks are taken into account, surface temperature declines with orbital distance, as mentioned in previous work, and the relationship between S and log(pCO₂) is actually approximately linear for Earth-like planets in the HZ.

If Bond albedo is fixed, the surface temperature, Tₛ, for an Earth-like planet in steady state varies approximately linearly with incident flux, S, and log(pCO₂). This linear relationship between Tₛ and S arises from energy balance and from water vapor feedback and can be expressed as

$$F_{\text{SOL}} = F_{\text{OLR}} = \left(1 - \frac{A_B}{4}\right) S = a + bT_s,$$

(1)

where $F_{\text{SOL}}$ is the incoming solar radiation flux, $F_{\text{OLR}}$ the outgoing long-wavelength radiation flux, $A_B$ the Bond albedo, and a and b are empirical constants. From satellite measurements of the modern Earth and radiative calculations, $T_s$ in K, the empirical constants in Eq. (1) are approximately $a = -370$ W m⁻² and $b = 2.2$ W m⁻² K⁻¹ (ref. 43).

Solving for $T_s$ in Eq. (1), the surface temperature is given by

$$T_s = \frac{1 - A_B}{4b} S - \frac{a}{b}$$

(2)

Under the conventional assumption that the HZ is regulated by a CO₂–H₂O greenhouse effect where H₂O concentrations respond to changes in pCO₂, the temperature offset in Eq. (2), $-a/b$, is a function of pCO₂. Thus, surface temperature, as a function of S and pCO₂, is given by

$$T_s(S, pCO_2) = \left(1 - \frac{A_B}{4b}\right) S + f(pCO_2),$$

(3)

where $f(pCO_2)$ is a function that depends on pCO₂. For the modern Earth at 1 AU, $f(pCO_2) = -a/b$. For pCO₂ ≤ 0.1 bar, the CO₂ greenhouse effect is logarithmic in pCO₂, i.e., $f(pCO_2) \propto \ln(pCO_2)^{42,43}$. Above ~0.1 bar, weaker CO₂ absorption features become important and $f(pCO_2)$ deviates from $\propto \ln(pCO_2)^{43,44}$.

As pCO₂ increases for an Earth-like planet moved outward in the HZ, the surface temperature will follow Eq. (3) while the rate at which CO₂ is removed from the atmosphere will adjust according to the carbonate–silicate weathering feedback. Quantitatively, the pCO₂- and $T_s$-dependent flux of CO₂ removal due to the continental weathering flux, $F_w$ (in mol CO₂ per unit time) is described by

$$F_w = \rho \left(\frac{pCO_2}{pCO_2^{\text{mod}}}\right)^\alpha \exp\left(\frac{T_s(S, pCO_2) - T_s^{\text{mod}}}{T_e}\right),$$

(4)

where $\rho$ is a constant determined by the continental weathering properties of the modern Earth, $\alpha$ a dimensionless constant between 0.1 and 0.5 and regulates the pCO₂ dependence of continental silicate weathering, $T_e$ a constant between 10 K and 40 K and represents the e-folding temperature dependence of continental weathering. The range for $T_e$ has been empirically constrained for the surface temperatures relevant to habitable, Earth-like planets from lab measurements and Phanerozoic geologic constraints. Finally, pCO₂^{mod} = 288 × 10⁻⁶ bar and $T_s^{mod} = 289$ K are the modern Earth’s preindustrial pCO₂ and surface temperature, respectively.

The range for $\alpha$ on the Earth was determined empirically from geologic constraints over the past 100 Myr. We assume that this derived range for $\alpha$ applies to the Earth through time and the Earth-like exoplanets modeled here that have a carbonate–silicate cycle. However, better proxy data for the ancient Earth or observing the carbonate–silicate cycle on

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**Table 1 Parameter ranges for our numerical model.**

| Parameter       | Parameter description                                                                 | Range        | Scaling | Units   |
|-----------------|--------------------------------------------------------------------------------------|--------------|---------|---------|
| $F_{\text{out}}$ | Modern CO₂ outgassing flux                                                          | 6–10         |         | Tmol yr⁻¹ |
| $n$             | Carbonate precipitation coefficient                                                  | 1–2.5        |         |         |
| $\chi$          | Modern seafloor dissolution relative to precipitation                               | 0.5–1.5      |         |         |
| $T_s$           | E-folding temperature factor for continental weathering                              | 10–40        |         |         |
| $\alpha$        | Power law exponent for CO₂ dependence of continental silicate weathering            | 0.1–0.5      |         |         |
| $\xi$           | Power law exponent for CO₂ dependence of continental carbonate weathering           | 0.1–0.5      |         |         |
| $I_{\text{land}}$ | Land fraction compared to modern Earth                                              | 0–1          |         |         |
| $S_{\text{sed}}$ | Ocean sediment thickness relative to modern Earth                                    | 0.2–1        |         |         |
| $F_{\text{mod}}$ | Modern continental carbonate weathering                                            | 7–14         | Tmol yr⁻¹ |         |
| $I_{\text{bio}}$ | Biological weathering compared to modern Earth                                     | 0–1          |         |         |
| $\delta$        | Surface to deep ocean temperature gradient scaling                                  | 0.8–1.4      |         |         |
| $\gamma$        | Power law exponent for pH dependence of seafloor dissolution                        | 0–0.5        |         |         |
| $\beta$         | Power law exponent for seafloor spreading rate                                     | 0–0.2        |         |         |
| $m$             | Exponent for outgassing dependence on crustal production                             | 1–2          |         |         |
| $E_{\text{diss}}$ | Seafloor dissolution activation energy                                              | 60–100       | kJ mol⁻¹ |         |
| $n_{\text{heat}}$ | Exponent for internal heat with time                                               | 0–0.73       |         |         |
| $\tau$          | Planet age (see Eq. (10))                                                         | 0–10         |         | Gyr     |
| $S$             | Incident flux relative to modern Earth                                            | 0.35–1.05    |         |         |

*Parameters are dimensionless unless otherwise described. The fourth column shows how scaling parameters impact the model, where $T_s$ is the surface temperature in K and $Q$ is the internal heat of the planet relative to the modern Earth (see Eq. (10) for $Q$). Unless otherwise noted, each parameter range is justified in the original model derivation for the Earth through time.

*The justification for this parameter is given in the Methods, subsection "Numerical carbonate–silicate cycle modeling."
Fig. 1 The expected distribution of stable, Earth-like exoplanet climates from our habitable zone weathering model. The horizontal axis shows incident flux, $S$, normalized to the solar constant ($S_\odot$) and the corresponding orbital distance in Astronomical Units (AU) above the plot. The vertical axis shows the atmospheric CO$_2$ partial pressure (pCO$_2$) in bar. Each point represents a climate in steady state. The black labeled contours show the mean global surface temperature for the given pCO$_2$ and incident flux. The white region below the 248 K contour is where our model assumption of a liquid ocean is no longer plausible so no planets are shown in that region. Above the 355 K contour, Earth-like planets are too hot to retain their liquid oceans for billions of years. Similar to the frozen planets, such hot planets are not considered habitable. Modern Earth and Mars are shown by black squares. The blue histogram at the bottom of the figure shows the number of stable planets in each incident flux bin. The color of each simulated planet shows the relative point density in the plot at that location. The color was calculated using a kernel-density estimate with Gaussian kernels and rescaled from 0 to 1. A color value of 0 represents the location.

Fig. 2 The relationship between incident flux and atmospheric CO$_2$ for Earth-like planets regulated by a carbonate-silicate weathering cycle. The horizontal axis shows incident flux, $S$, normalized to the solar constant ($S_\odot$) and the corresponding orbital distance in Astronomical Units (AU) above the plot. The vertical axis shows the atmospheric CO$_2$ partial pressure (pCO$_2$) in bar. The dotted blue curve labeled 289 K shows the pCO$_2$ value required to maintain a 289 K surface temperature for the given incident flux, $S$. The conventional assumption of CO$_2$ in the HZ stipulates that pCO$_2$ will adjust to maintain a temperate or even constant surface temperature. Under this assumption, moving the modern Earth (labeled black square) outward in the HZ would have the planet approximately follow the dotted blue 289 K contour. The colored points and gray curves show the modern Earth moving outward in the HZ with a functioning carbonate-silicate weathering cycle, calculated from Eq. (6). We consider two temperature and pCO$_2$ dependencies for continental weathering in this plot. The strong temperature dependence contour (labeled Strong T-dep.), uses a temperature and pCO$_2$-dependent weathering factor of $\alpha T_s = 2.3$, which implies a strong temperature feedback on continental weathering compared to the pCO$_2$ feedback (see Eq. (7)). The moderate temperature dependence contour (labeled Moderate T-dep.), uses a temperature and pCO$_2$-dependent weathering factor of $\alpha T_s = 7.5$. These two values for $\alpha T_s$ result in two different paths the Earth can take as it moves outward in the HZ. The planet color shows the mean surface temperature. Log-linear fits to the colored points of the Strong T-dep. and Moderate T-dep. contours have $r^2$ values of 0.959 and 0.999, respectively. Thus, even for a strong temperature dependence of continental weathering, our coupled climate and weathering model predicts an approximately log-linear relationship between incident flux and pCO$_2$ on Earth-like planets in the HZ.

The modern Earth, and all Earth-like planets considered in this work, are assumed to be in steady state, in which the flux of CO$_2$ from volcanic outgassing is equal to the rate of CO$_2$ removal from weathering, $F_w$. If we assume a HZ planet with CO$_2$ outgassing the same as the modern Earth’s, $F_w$ remains constant despite changes in $S$ and pCO$_2$. Setting $T_s(S, pCO_2) = T_s^{\text{mod}}$ and $pCO_2 = pCO_2^{\text{mod}}$ for the modern Earth, from Eq. (4), we see that $F_w = \rho$ and

$$1 = \left( \frac{pCO_2}{pCO_2^{\text{mod}}} \right)^{\alpha} \exp \left( T_s(S, pCO_2) - T_s^{\text{mod}} \right) \left( T_s \right).$$

Equation (5) must hold for a modern Earth within the HZ. If it did not, $F_w$ would not balance CO$_2$ outgassing, which would result in either complete CO$_2$ removal, or CO$_2$ accumulation without bound.
number of observed Earth-like exoplanets. The solid gray curve and this probability is shown on the vertical axis. The horizontal axis shows the regulated by the carbonate

For each $S$, Eq. (8), the polynomial $pCO2 \sim 0.2$ for $S$ and $log(pCO2)$ is the default expectation for Earth-like planets in the HZ.

Observational uncertainty for $pCO2$ in the HZ. In the log-linear fit shown as the solid red line in Fig. 1, which is the expected relationship between $pCO2$ and $S$ that we have derived above, the $r^2$-value is 0.49. Thus, about half the variance in $log(pCO2)$ is described by changes in incident flux. The slope is $3.92 \pm 0.24$ (95%) with units $-log_{10}(pCO2 \text{ [bar]})/(S/S_{⊕})$, so our model predicts a trend of increasing atmospheric $CO2$ with orbital distance, which future missions might detect. However, there is sufficient spread in our simulated planets that confirming the HZ hypothesis from such a trend may be difficult.

This difficulty is readily seen if we consider a log-uniform distribution for $pCO2$ on Earth-like planets in the HZ. If we randomly generate 1050 such planets, where $10^{-4} \leq pCO2 \leq 10$ bar is sampled log-uniformly, 0.35 $\leq S \leq 1.05$ is sampled uniformly, and impose the same constraints on surface temperature for habitability as in Fig. 1, then the log-linear line of best fit through the uniform planet data has a slope of $3.76 \pm 0.465$ (95%) with units $-log_{10}(pCO2 \text{ [bar]})/(S/S_{⊕})$. Thus, measuring just the log-linear trend between $pCO2$ and $S$ in the HZ is unlikely to test the HZ hypothesis as this measurement cannot confidently detect the presence of the carbonate–silicate weathering cycle—it is indistinguishable from that of randomly distributed $pCO2$ between the surface temperature limits for habitability.

The inability to differentiate between the log-linear trends for weathering-mediated and random $pCO2$ vs $S$ in the HZ is due to the assumed surface temperature constraints we impose in our model (between 248 and 355 K for planets in the HZ, see Methods, subsection “Numerical carbonate–silicate cycle modeling”). Such temperature constraints are necessary as the carbonate–silicate weathering cycle can only operate when water, as liquid, is present at the planetary surface. Even without the carbonate–silicate weathering cycle, a minimum surface temperature for habitable planets, which must exist, will result in increasing $pCO2$ with orbital distance, as shown by the constant temperature contours in Fig. 1.

To test the HZ hypothesis, we propose searching for the two-dimensional (2D) distribution of planets in the $S$-$pCO2$ phase space that arises from the carbonate–silicate weathering cycle. This $S$-$log(pCO2)$ relationship is shown by the point density in Fig. 1, where the distribution of habitable, stable planets is not log-uniformly distributed over $pCO2$. Rather, around the best-fit line, there is an abundance of planets in the outer HZ at high $pCO2$, a dearth of low $pCO2$ planets between $-0.9$ and $-0.7 S/S_{⊕}$, and few high-$pCO2$ planets throughout the HZ compared to the log-uniform $pCO2$ case. These differences are expected features of the carbonate–silicate weathering cycle due to the temperature- and $pCO2$-dependent nature of the weathering feedback. Recall from section “Habitable zone climate theory revisited” that, as $S$ decreases, the lowered temperature will reduce weathering causing $pCO2$ to increase. This results in the lack of low-$pCO2$ planets in the middle of the HZ and the high abundance of habitable planets in the outer HZ (purple shaded region in Fig. 1). Similarly, for large $pCO2$, the temperature is warmer and $pCO2$ higher than that of modern Earth so the carbonate–silicate weathering cycle acts to lower $pCO2$, which reduces the number of high-$pCO2$ planets throughout the HZ relative to the outer HZ.

To detect the prevalence of the carbonate–silicate weathering cycle and test the validity of the HZ concept, future observations

dependance of continental weathering while bigger $\alpha$ increases the $pCO2$ dependence of continental weathering (Eq. (4)).

In addition to predicting a linear relationship between $pCO2$ and $S$, the carbonate–silicate cycle implies that moving an Earth-like planet outward in the HZ will cause $T_s (S, pCO2)$ to decrease. For increasing orbital distance, $pCO2$ must increase for $T_s (S, pCO2)$ to increase in the HZ. From Eq. (5), $pCO2$ will be greater than $pCO2^{\text{mod}}$ in such cases so $T_s (S, pCO2)$ must be less than $T_s^{\text{mod}}$. This decrease in $T_s (S, pCO2)$ as $S$ decreases is shown in Fig. 2. Physically, the power law dependence of weathering on $pCO2$ can balance volcanic outgassing at lower surface temperatures in the outer HZ.

Figure 2 shows the approximately log-linear relationship between $pCO2$ and $S$ for the modern Earth moved outward in the HZ. The gray lines and colored circles in Fig. 2 show the expected $pCO2$ value for the given incident flux $S$, calculated from Eq. (6). For each $S$ value in Fig. 2, Eq. (6) was solved for $pCO2$ by using Eq. (8), the polynomial fit for surface temperature based on a 1D climate model (described in the Methods, subsection “Habitable zone 1D climate model”), assuming values of $\alpha T_e$.

The value of $\alpha T_e$ affects the slope of the relationship between $S$ and $pCO2$ due to the carbonate–silicate weathering cycle, shown in Fig. 2. From above, the ranges for $\alpha$ and $T_e$ are $0.1 \leq \alpha \leq 0.5$ and $10 \leq T_e \leq 40$ (ref. 21), so $1 \leq \alpha T_e \leq 20$. If we consider uniform distributions of $\alpha$ and $T_e$, then roughly 95% of $\alpha T_e$ values are greater than 2.3. If $\alpha = 0.23$ and $T_e = 10 K$ then $\alpha T_e = 2.3$, which is used for the Strong $T$-dep. curve in Fig. 2. The mean of each parameter, $\alpha = 0.3$ and $T_e = 25 K$ gives $\alpha T_e = 7.5$, which corresponds to the Moderate $T$-dep. curve in Fig. 2. For $\alpha T_e \leq 2.3$ the colored points and gray curves become increasingly similar to the constant 289 K surface temperature contour in Fig. 2. However, for uniform distributions of $\alpha$ and $T_e$, ~95% of $\alpha T_e$ values are greater than 2.3, so an approximately log-linear relationship between $S$ and $log(pCO2)$ is the default expectation for Earth-like planets in the HZ.
should measure the 2D $S$-$pCO_2$ distribution of habitable, Earth-like exoplanets. This measured distribution can be compared to the distribution of habitable planets we predict in Fig. 1 to determine if Earth-like planets in the HZ are consistent with the $S$-$pCO_2$ predictions of the carbonate–silicate weathering cycle.

A test of the 2D phase space of $S$ and $pCO_2$ in the HZ is shown in Fig. 3, which was produced using a 2D Kolmogorov–Smirnov (KS) test. The 2D KS test compares the statistical similarity of a sample distribution to a reference distribution. For Fig. 3, the reference distribution was comprised of 500 randomly generated planets from the log-uniform distribution for $pCO_2$ described above ($10^{-4} \leq pCO_2 \leq 10$ bar, $0.35 \leq S \leq 1.05S_\oplus$, and surface temperature between 248 and 355 K). The sample distribution was generated by randomly selecting a number of planets from Fig. 1 equal to the number of observed exoplanets. For a given number of observed exoplanets in Fig. 3, the horizontal axis, we ran the KS test 10,000 times then calculated the mean and standard deviation from those runs, shown by the gray contour and shaded region. This resampling is necessary as the 2D KS test is a nonparametric approximation that two data sets come from the same underlying population. We note that below ~20 observed planets and for probabilities above ~0.1, the 2D KS test used here can be unreliable. These limitations do not invalidate the analysis shown in Fig. 3, as we want to know, with 95% confidence, that a log-uniform $pCO_2$ distribution can be ruled out if real exoplanets follow the distribution shown in Fig. 1, which corresponds to the gray line and shaded contour dipping below the 0.05 probability value, shown by the horizontal black line, at 83 observations in Fig. 3.

Thus, confidently detecting the carbonate–silicate weathering cycle will require many exoplanet observations, as shown in Fig. 3. Proposed NASA telescopes, HabEx and LUVOIR, are expected to observe between 3 and 115 Earth-like exoplanets within the HZ, as shown in Fig. 3, which was produced using a 2D Kolmogorov–Smirnov (KS) test. The ranges for each mission concept are shown by the colored circles with error bars in Fig. 3. Only the nominal capability of LUVOIR-A, the variant of the proposed LUVOIR space telescope with a primary mirror diameter of 15 m, would provide sufficient Earth-like exoplanet detections to confidently discriminate between a log-uniform $pCO_2$ distribution in the HZ and a $pCO_2$ distribution regulated by the carbonate–silicate weathering cycle. A caveat is that this calculation does not consider the instrument uncertainty in derived $pCO_2$ measurements for each telescope or that other processes not considered in our model may alter $pCO_2$ in the HZ, as discussed below.

### Discussion

Our model assumes that the full variation and uncertainty in Earth's carbon cycle parameters through time (Table 1) are representative of habitable Earth-like exoplanets generally. This assumption is a reasonable first-order approximation as the bulk composition and geochemistry of rocky exoplanets appear similar to Earth's. However, the validity of this assumption likely depends on the parameter in question. For example, it is probably reasonable to expect habitable exoplanets to have a wide range of land fractions and outgassing fluxes, but it is unclear whether there is as much natural variability in the temperature dependence of silicate weathering. An improved mechanistic understanding of weathering on Earth might reduce these uncertainties.

Other weathering feedbacks have been proposed to operate on the Earth through time, such as reverse weathering. In reverse weathering, cations and dissolved silica released from silicate weathering are sequestered into clay minerals rather than carbonates so that $CO_2$ remains in the atmosphere, warming the climate and reducing ocean pH. Reverse weathering is thought to be strongly pH dependent and as ocean pH decreases, reverse weathering turns off, acting as a climate stabilization mechanism similar to the carbonate–silicate cycle. The importance of reverse weathering is so poorly constrained through Earth's history that it does not make sense to consider it in our model. However, with future constraints from geology and lab measurements, reverse weathering might alter the stable $CO_2$ abundances of our modeled atmospheres shown in Fig. 1.

At both the inner and outer edges of the HZ, our model assumes that abundant liquid water exists at the planetary surface because, without a liquid surface ocean, the carbonate–silicate weathering cycle ceases and $CO_2$ cannot be sequestered after outgassing. Beyond these temperature bounds, other processes must regulate $pCO_2$. This is a caveat to consider in future observations. As we see from Fig. 1, Mars has low atmospheric $CO_2$ and low incident flux. Frozen exoplanets similar to Mars, populating the white area under the 248 K contour in Fig. 1, could exist in exoplanet surveys. Similarly, planets devoid of surface water, such as Venus, might exist at high $pCO_2$ within the HZ. If future observations detect such planets without confirming the existence of a liquid surface or surface temperature, it could introduce additional uncertainties in any relation between orbital distance and atmospheric $CO_2$. Detecting a surface ocean, one of the most important surface features to confirm, is important to interpret trends of $CO_2$ in the HZ.

Because we only consider variations on an Earth-like planet, our model predictions may underestimate the inherent variability in habitable exoplanetary conditions. Planets very different from the modern Earth, such as waterworlds without a carbonate–silicate weathering cycle, or CH4-rich worlds, could introduce additional uncertainty in an observed relationship between $S$ and $pCO_2$ in the HZ. Despite such uncertainties, future missions should measure the relationship between $S$ and $pCO_2$ in the HZ, or possibly a sharp transition in $pCO_2$ at the inner edge of the HZ due to loss of surface water and subsequent shutoff of surface weathering. A more complex model than presented here is necessary to predict such a jump in $pCO_2$ at the inner edge of the HZ. However, if the carbonate–silicate weathering cycle is indeed ubiquitous, as is typically assumed in HZ calculations, then the relationship between incident flux and $pCO_2$ may follow the $S$-$pCO_2$ relationship predicted in Fig. 1. If no such relationship is observed, then the carbonate–silicate weathering cycle may have limited influence on planetary habitability and the limits of the conventional HZ could need revision. Alternatively, the HZ hypothesis could be incorrect and the long-term climate of HZ planets could be set by phenomena beyond those considered here.

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### Methods

**Habitable zone 1D climate model.** We use the Virtual Planetary Laboratory (VPL) 1D radiative-convective climate model to generate surface temperatures for an Earth-like planet at various $pCO_2$ and incident fluxes. We consider incident fluxes between 1.05$S_\oplus$ and 0.35$S_\oplus$, the HZ limits for a Sun-like star, and...
The surface temperatures predicted by the polynomial Eq. (9) is in good agreement with the results of the 1D climate model. The maximum error in predicted surface temperature between the polynomial fit and the 1D climate model is ~3%.

The alkalinity that enters the ocean from weathering will balance a charge-weighted sum of the mol liter\(^{-1}\) of cations produced in weathering, principally Ca\(^{2+}\) and Mg\(^{2+}\). Implicit in our model assumptions is that continental land fraction, \(f_{\text{land}}\), and biological weathering fraction, \(f_{\text{bio}}\), are fixed.

The weathering model balances the flux of outgassed CO\(_2\) against the loss of carbon due to continental and seafloor weathering, which result in precipitation of carbonates in the ocean and seafloor pore space. Quantitatively, for time, \(t\), this is described by time-dependent equations where we normalize to the mass of the ocean, \(M\), (nominally, an Earth ocean, 1.35 \times 10\(^{24}\) kg):

\[
\frac{dC}{dt} = \frac{F_{\text{out}} + F_{\text{carb}} - P_{\text{aq}} - P_{\text{p}}}{M} \label{eq:carbon1}
\]

Here, \(C\) is the non-organic carbon content of the atmosphere–ocean system in mol C kg\(^{-1}\), and \(A\) is the carbonate alkalinity in mol equivalents (mol eq). Carbonate alkalinity (henceforth alkalinity) is the charge-weighted sum of the mol liter\(^{-1}\) concentration of bicarbonate and carbonate anions, [HCO\(_3\)] + 2[CO\(_3\)]\(^2-\). \(F_{\text{out}}\) is the global CO\(_2\) outgassing flux, \(F_{\text{carb}}\) and \(F_{\text{p}}\) are the continental carbonate and silicate weathering fluxes, \(F_{\text{aq}}\) is the rate of seafloor basalt dissolution, and \(P_{\text{aq}}\) and \(P_{\text{p}}\) are the pore and ocean precipitation fluxes. The fluxes on the right-hand side of Eq. (9) \((F_{\text{out}}, F_{\text{carb}}, P_{\text{aq}}, P_{\text{p}}, F_{\text{aq}}\) and \(F_{\text{carb}}\)) are given in mol C yr\(^{-1}\) for \(dC/dt\) and in mol liter\(^{-1}\) for \(dC/dt\).

The alkalinity that enters the ocean from weathering will balance a charge cation (e.g., Ca\(^{2+}\)), which is why a factor of 2 enters in the definition of \(dA/dt\) in Eq. (9). Hence, geochemists often think of alkalinity in terms of the balance of cations produced in weathering, principally Ca\(^{2+}\). This reasoning arises because the weighted sum of carbonate and bicarbonate concentrations must balance the charge of conservative cations minus conservative anions (i.e., 2[Ca\(^{2+}\)] + 2[Mg\(^{2+}\)] + Na\(^{+}\) + \ldots [Cl\(^-\)] \ldots), ignoring minor contributions from weak acid anions and water dissociation. Weathering releases cations and carbon speciation adjustments to ensure charge balance, so that the cation release is effectively equivalent to carbonate alkalinity.

To re-examine the rate of model convergence and range of model inputs over which Eq. (9) converges, we do not consider the seafloor pore space and atmosphere–ocean as separate systems. This differs from previous versions of the model\(^{11}\), which considered the atmosphere–ocean and pore space independently. Rather, we approximate the atmosphere–ocean and pore space as a single entity in Earth-like planets. This simplification does not appreciably change the model output for atmospheric CO\(_2\) because we run the model to steady state in all cases, where the atmosphere–ocean and pore space reach approximate equilibrium. In the next section, we present additional details on our model implementation and discuss the agreement between our no-plateau model and the original, two-box model.

A second modification is the range of incident stellar fluxes over which the model can be run. Previously, the model described here was used to study the Earth through time\(^{21}\) and thus only considered solar fluxes between \(S_\odot\) (the modern solar constant) and early Earth’s 0.75\(S_\odot\) (\(S_\odot = 1360\) W m\(^{-2}\)). We extend that range to include the entire conservative HZ of a Sun-like star, roughly 1.05\(S_\odot\) to 0.35\(S_\odot\). We use Eq. (8), the fourth-order polynomial fit to a 1D climate model, to calculate surface temperatures throughout the HZ. The Bond albedo of the planet is calculated dynamically by the climate model and thus included implicitly in our polynomial fit.

With the coupled climate and weathering model, we generate steady-state, Earth-like planets by randomly sampling plausible initial model inputs. The ranges for each parameter we consider are representative of the Earth through time\(^{21}\) and shown in Table 1. These ranges represent very broad uncertainties of the carbonate–silicate cycle on the Earth through time\(^{21}\). Implicit in our assumed parameter ranges is that continental land fraction, \(f_{\text{land}}\), and biological weathering fraction, \(f_{\text{bio}}\), increase from 0 when the Earth formed to 1 on the modern Earth. Similarly, the relative internal heat, \(Q\), is assumed to be large when the Earth is young and unity for the modern Earth. Therefore, on the modern Earth, we set \(f_{\text{land}} = 1, f_{\text{bio}} = 1, Q = 1\), and the weathering rate is maximized and outgassing rate is relatively small (see Methods, subsection “Validity of carbon cycle parameterizations to exoplanets” for a discussion on the importance of these parameters in our model). This is seen in Fig. 1, where the modern Earth appears near the lower bound for predicted pCO\(_2\) in the HZ. If the continents on an exoplanet were more easily weathered or outgassing much lower than on the modern Earth, such exoplanets could have pCO\(_2\) values well below the modern Earth value shown in Fig. 1. We do not consider such exoplanets in this model, so the results presented here are only applicable to planets similar to the Earth through time.

Our model assumes that each simulated planet is habitable, i.e., it has a stable, liquid surface ocean, a necessity for the carbonate–silicate cycle to operate. For a mean surface temperature below 248 K, Earth-like planets are likely completely frozen\(^{39}\), which we use as a low temperature bound in the model. While 248 K is below the freezing point of water, it is a global mean surface temperature and 3D models show that the range 248–273 K for this parameter does not lead to the existence of a liquid ocean belt near the equator. At the other temperature extreme, a hot, Earth-like planet can rapidly lose its surface oceans due to high atmospheric water vapor concentrations that are photolyzed and subsequently lost to space. This upper temperature bound on habitability occurs at ~353 K\(^\circ\) above 355 K, Earth-like planets are unlikely to remain habitable for any longer and cannot operate a carbonate–silicate cycle over geologic timescales. We use these two temperature bounds, 248 K and 355 K, as the limits for habitability in our model. Any modeled planet with a final surface temperature outside these limits is uninhabitable and removed from our results.

We limit HZ planets to those with pCO\(_2\) below 10 bar. For most Earth-like planets in the HZ, 10 bar of CO\(_2\) results in planets with surface temperatures well above 355 K, which are not habitable on long time scales. If we impose a fixed stratospheric water vapor concentration in the 1D climate model and modify the tropospheric water vapor concentration based on empirical data from the modern Earth, we enable the 1D climate model to accurately model habitable, Earth-like planets through much of the HZ. But in the outer HZ, with more than ~10 bar of CO\(_2\), this assumption overestimates atmospheric water vapor concentrations and leads to artificially warm planets, so we reject such cases. Above ~10 bar of CO\(_2\) in the outer HZ, assuming a saturated troposphere for water vapor, increasing atmospheric CO\(_2\) may not lead to additional warming. Rather, the surface cools in such scenarios because additional CO\(_2\) leads to increased Rayleigh scattering and no additional warming. Because Earth-like planets in the outer HZ would be frozen...
Validity of carbon cycle parameterizations to exoplanets. The parameterization of weathering in our model has been empirically validated for the modern Earth\textsuperscript{16,21,26}. The exponential temperature dependence of continental weathering is a reasonable approximation that agrees with field and lab measurements\textsuperscript{16} and can reproduce the climate results of more complex models\textsuperscript{21,26}. Similarly, the power-law parameterization for the pCO\textsubscript{2}-dependence of continental weathering agrees with data from the modern Earth\textsuperscript{26} and can even be approximately derived from equilibrium chemistry arguments for an Earth-like exoplanet\textsuperscript{38}. The bulk geochemistry of rocky exoplanets may be similar to Earth\textsuperscript{50}, so we expect our weathering parameterization to reasonably approximate Earth-like planets in the HZ. However, uncertainties in how the carbonate-silicate weathering cycle regulates climate on Earth persist\textsuperscript{23}, so the predicted variations in pCO\textsubscript{2} in our model may not capture the true variability of pCO\textsubscript{2} in the HZ. Below, we show that our broad parameterization of the carbonate–silicate weathering cycle may encompass the plausible range of pCO\textsubscript{2} for the Earth through time, but improved understanding of the carbonate–silicate weathering cycle may be necessary to know if such variations are indeed representative of the Earth through time and applicable to Earth-like planets generally.

The rate of weathering depends strongly on the intrinsic features of a planet, such as the CO\textsubscript{2} outgassing rate and the properties of its continents. Changes in continental uplift rate, lithology, and configuration are parameterized in our model through the f\textsubscript{land} and f\textsubscript{bio} terms. The parameters f\textsubscript{land} and f\textsubscript{bio} linearly scale the weathering flux and could analogously be considered a continental weatherability scaling factor. For the ranges of f\textsubscript{land} and f\textsubscript{bio} considered in our model (see Table 1), changes in the continental weatherability alone can generate pCO\textsubscript{2} values spanning ~4 orders of magnitude. This broad parameterization likely encompasses pCO\textsubscript{2} perturbations due to continental weatherability changes caused by large volcanic eruptions or changes in continental configuration. Indeed, the largest, constrained change in pCO\textsubscript{2} due to such events on Earth may be closer to ~1 order of magnitude, coeval with the eruption of the Siberian Traps\textsuperscript{85}.

The importance of continental weatherability (f\textsubscript{land} and f\textsubscript{bio}) on pCO\textsubscript{2} is the simulation for 10 Gyr or until the system reaches steady state. We consider the model to have reached steady state when extrapolation of the rate of change of pCO\textsubscript{2} for 1 Gyr changes pCO\textsubscript{2} by <1%. Typically, the model converges within a few Myr to a few tens of Myr. Rarely (2 of the 1200 planets simulated in this work), parameter combinations will not reach steady state after 10 Gyr. Simulations with combinations of exceptionally high outgassing rates and low CO\textsubscript{2} weathering rates can enter a regime were atmospheric CO\textsubscript{2} builds without bound, never converging. Such model results are beyond the range of validity of our model.
The Supplementary Data.

NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-020-19896-2 ARTICLE

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Author contributions

O.R.L., D.C.C., and J.K.T. all contributed to the theoretical and conceptual aspects of this work and the drafting of the manuscript. O.R.L. implemented the numerical model and generated model data.

Competing interests

The authors declare no competing interests.

Additional information

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