Future climate forcing potentially without precedent in the last 420 million years

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The evolution of Earth’s climate on geological timescales is largely driven by variations in the magnitude of total solar irradiance (TSI) and changes in the greenhouse gas content of the atmosphere. Here we show that the slow \( \sim 50 \text{ W m}^{-2} \) increase in TSI over the last \( \sim 420 \) million years (an increase of \( \sim 9 \text{ W m}^{-2} \) of radiative forcing) was almost completely negated by a long-term decline in atmospheric CO\(_2\). This was likely due to the silicate weathering-negative feedback and the expansion of land plants that together ensured Earth’s long-term habitability. Humanity’s fossil-fuel use, if unabated, risks taking us, by the middle of the twenty-first century, to values of CO\(_2\) not seen since the early Eocene (50 million years ago). If CO\(_2\) continues to rise further into the twenty-third century, then the associated large increase in radiative forcing, and how the Earth system would respond, would likely be without geological precedent in the last half a billion years.

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The primary source of energy in the Earth’s climate system is incoming solar radiation, termed total solar irradiance, or TSI. At equilibrium, because of the requirement of energy conservation, the Earth’s radiative budget must balance such that TSI is equal to outgoing longwave radiation at the top of the atmosphere (a state known as radiative equilibrium). Since the radiation emitted by a body is a function of surface temperature, the Earth’s ‘effective temperature’ \( T_E \) is the temperature at which radiative equilibrium is achieved assuming the Earth acts like a blackbody, and can be calculated (in K) using the following expression:

\[
T_E = \left( \frac{F_t(1 - A)}{4\sigma} \right)^{1/4} = 256 \text{ K} \quad (1)
\]

where \( F_t \) is the TSI (currently \( \sim 1,368 \text{ Wm}^{-2} \)), \( \sigma \) is the Stefan–Boltzmann constant \( (5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4}) \), \( A = 0.29 \) (ref. 1) is the Earth’s average planetary albedo (the fraction of incoming radiation scattered or reflected back out of the atmosphere by clouds, particulates in the atmosphere and the Earth’s surface), and the factor of 4 accounts for the spherical and rotating nature of the Earth. The 31 K difference between \( T_E \) and the observed surface temperature of the Earth (+14.0°C or 287.1 K) is the 1961–1990 mean\(^2\) is almost entirely due to the action of the greenhouse effect (for example, ref. 3).

The majority (~75%) of the greenhouse effect is due to the warming effects of water vapour and clouds, with the non-condensing greenhouse gases (predominantly CO\(_2\) and CH\(_4\)) accounting for the remaining 25% (ref. 3). However, at the temperatures and pressures typical of the Earth’s surface, water vapour and clouds act as feedbacks rather than drivers of the greenhouse effect, with CO\(_2\) and CH\(_4\) and the other non-condensing GHGs (for example, N\(_2\)O) determining the overall strength of the greenhouse effect\(^3\). Given this understanding, and that summarized in equation (1), the climatic evolution of the Earth over geological time is largely a function of the concentration of the non-condensing greenhouse gases, planetary albedo \( (A) \) and the TSI \( (F_t) \) (for example, ref. 4).

Owing to the way the Sun generates energy though the nuclear fusion of hydrogen into helium, over time its luminosity has increased\(^4\). This is a relatively well-understood process and the TSI at any time \( (F_t^s) \) can be approximated by the following function\(^5\):

\[
F_t^s = \frac{1}{1 + \frac{1}{2} (1 - \frac{t}{t_0})} \times F_t \quad (2)
\]

where \( F_t \) is the present day TSI \( (1,368 \text{ Wm}^{-2}) \), \( t \) is the time of interest since the formation of the Earth (Myrs) and \( t_0 \) is the age of the Earth \( (4,567 \text{ Myrs}) \) (ref. 6), although here following ref. 5 we use a \( t_0 = 4,700 \text{ Myrs} \). As a result, there has been an increase in TSI of \( \sim 400 \text{ Wm}^{-2} \) since the formation of the Earth. The following equation relates this change in TSI relative to today to radiative forcing \( (\Delta F_{\text{sol}}) \) assuming a constant planetary albedo \( (A) \) through time:

\[
\Delta F_{\text{sol}} = \frac{(F_t^s - F_t) \times (1 - A)}{4} \text{ Wm}^{-2} \quad (3)
\]

The global mean surface temperature change \( (\Delta T, \text{ in K}) \) for a given change in radiative forcing \( (\Delta F, \text{ in Wm}^{-2}) \) can be described by:

\[
\Delta T = \Delta F \times S \quad (4)
\]

where \( S \) is the sensitivity parameter\(^7\), in \( \text{KW}^{-1}\text{m}^2\). Following ref. 4, and assuming an effective emissivity, \( \varepsilon \), of the Earth of 0.6 (that is, 40% of longwave radiation is absorbed by greenhouse gases in the atmosphere), equation (1) can be used to define the following equation that describes \( S \) for today’s climate (where the surface temperature \( = 287.1 \text{ K} \) in the absence of any climate feedbacks (for example, water vapour, sea-ice etc.), also known as the Planck response (hence the subscript ‘P’)):

\[
\Delta T = \frac{S_p}{4\varepsilon T_s^4} = 0.31 \text{ KW}^{-1}\text{m}^2 \quad (5)
\]

\( S_p \) depends on the overall strength of the greenhouse effect and the surface temperature of the Earth, and so this value is not necessarily applicable throughout Earth’s history; nonetheless, this treatment provides a first-order constraint that the long-term secular increase in TSI of 400 Wm\(^{-2}\) would be associated with a secular warming of at least \( \sim 20 \text{ K} \) over the last 4.5 billion years, if albedo and emissivity remained constant. Since the combined effect of the greenhouse gas and other climate feedbacks (for example, water vapour, lapse rate, sea-ice etc.) is positive\(^6\), this is a minimum estimate of \( S \) and when all climate feedbacks are considered, \( S_s \) (where ‘a’ denotes actuo after ref. 7) is likely in the range of 0.8–1.6 \text{ KW}^{-1}\text{m}^2 (for example, refs 7,9–11).

The actual evolution of Earth’s temperature through geological time is a subject of considerable debate (for example, ref. 12), yet there is a longstanding view that, despite the increase in solar output, Earth’s surface temperature was, for much of geological time, warmer, not colder, than today (for example, refs 13,14). This apparent inconsistency is known as the ‘Faint Young Sun’ paradox and to reconcile the observation of a relatively stable climate in the face of increasing solar output through time requires a parallel change in some other factors that influence Earth’s radiative budget. First and foremost among these factors is thought to be a concomitant reduction in the strength of the greenhouse effect, and in atmospheric CO\(_2\) concentration in particular (for example, refs 15,16). The radiative forcing from changing CO\(_2\) can be estimated using the following formulation\(^17\):

\[
\Delta F_{\text{CO}_2} = 5.32 \ln(C/C_0) + 0.39 \ln(C/C_0)^2 \quad (6)
\]

where \( \Delta F_{\text{CO}_2} \) is the radiative forcing from CO\(_2\) change (in Wm\(^{-2}\)), \( C \) represents the concentration of CO\(_2\) at the time of interest and \( C_0 \) is the pre-industrial concentration of CO\(_2\) = 278 p.m. For the decrease in atmospheric CO\(_2\) to balance the increase in solar output over time, the following equation is required to be true (or at least approximately so):

\[
\Delta F_{\text{sol}} + \Delta F_{\text{CO}_2} \approx 0 \text{ Wm}^2 \quad (7)
\]

In this formulation we are ignoring the other non-condensing greenhouse gases (for example, CH\(_4\), N\(_2\)O). This is partly out of practical necessity since there are currently no proxies for these gases, but is justifiable to a first order because variations in CO\(_2\) accounted for \( \sim 80\% \) of the greenhouse gas forcing on glacial–interglacial timescales\(^1\) and CO\(_2\) was likely the dominant greenhouse gas for the past 500 Myrs (refs 18–20).

Testing whether the apparent stability of surface temperature is a consequence of the relative stability of climate forcing, therefore, requires high-density, high-quality data on past atmospheric CO\(_2\) levels. Consequently, in this study we compile the available CO\(_2\) data for the last 420 Myrs where, although the magnitude in the change of solar output is reduced relative to changes on longer timescales, data availability is sufficient to provide a detailed picture of the evolution of atmospheric CO\(_2\). The relative stability of climate over this interval is constrained by three lines of evidence: (i) the continued presence of complex life, given the thermal limits of metazoans (\(<40–50^\circ\text{C}\); ref. 21) and despite a number of mass extinctions\(^22\); (ii) the continuous presence of liquid water and the occurrence of climate-sensitive sedimentary deposits (for example, coal versus glacial deposits) that indicate warm and cold periods but no evidence of an overall...
long-term secular trend (Fig. 1); and (iii) moderate tropical sea surface temperatures (25–40°C) as recorded by oxygen and clumped isotope analysis of fossil marine carbonates. Our new compilation shows that this climate stability was the result of a long-term decline in atmospheric CO2 that, in terms of radiative forcing, approximately cancelled out the increase in solar output. This long-term view of climate forcing provides a valuable geological context for potential levels of CO2 in our warming future.

Results

A new CO2 compilation. In order to better understand the role of the greenhouse effect in Earth’s climate evolution, we have compiled ~1,500 discrete estimates of atmospheric CO2 from five independent techniques drawn from 112 published studies covering the last 420 Myrs (Supplementary Data 1). We uniformly apply a set of criteria and the latest understanding, described in the supplement, to screen the available CO2 records. By following these criteria, the ages and CO2 values associated with some records are revised (see Methods), and ~1/5 of the published estimates have been excluded (leaving n = 1,241 in our final compilation). This standardization process helps ensure the highest-quality compilation whose individual records can be more cleanly compared to one another.

Our new compilation is shown in Fig. 1 and, compared to older compilations, there is better agreement between the different methods of CO2 reconstruction. In this case, this is largely due to the refinement of the pedogenic carbonate proxy following ref. 29 (see Methods). However, despite our efforts to improve the compilation, there are still relatively large uncertainties at times and disagreements remain between techniques for some time intervals (Fig. 1). It is also apparent that the early parts of the record rely on fewer observations and are characterized by a reduced diversity in proxy type (Supplementary Fig. 1). In order to gain a better appreciation of the multi-million-year evolution of CO2, and in light of these uncertainties and limitations we have followed a probabilistic approach where Monte Carlo resampling is used to generate 1,000 artificial time series of CO2 with each data point randomly perturbed within its age (X) and CO2 (Y) uncertainty. Each realization was then interpolated to a regular 0.5 Myr spacing and a LOESS fit was performed with the degree of smoothing optimized by generalized cross-validation. At each time step the distribution of LOESS fits was evaluated and the maximum probability, hence the most likely value for long-term CO2, and the associated 68 and 95 percentile ranges were determined (Fig. 1 and Supplementary Data 2).

Our new compilation and probabilistic treatment reveals that for the last ~420 Myrs, CO2, on the whole, has been elevated compared to pre-industrial values (278 p.p.m.). The highest CO2 values of ~2,000 p.p.m. were reached during the Devonian (~400 Myrs ago) and Triassic (220–200 Myrs ago), with individual estimates ranging up to a maximum of ~3,700 ± 1,600 p.p.m. at 215 Myrs. In contrast, values close to pre-industrial are found during much of the Carboniferous (~300 Myrs ago) and late Cretaceous (~80 Myrs ago). A linear fit to either the entire CO2 compilation, or a resampling of our LOESS fit to reflect the original data density, reveals that long-term average CO2 has declined over the last 420 Myrs by ~3.4 p.p.m. per Myr (Fig. 1).

Radiative forcing through the last 420 million years. Radiative forcing from CO2 change can be calculated using equation (6). This can then be combined with the radiative forcing from the increase in solar output defined by equation (3) (Fig. 2a); the temporal evolution of the simple sum of these terms (ΔF_CO2,sol) is shown in Fig. 2b. As has been noted elsewhere with prior Phanerozoic CO2 compilations (for example, refs 31,32), there is a good first-order agreement between CO2 levels and the occurrence of greenhouse/icehouse states (Fig. 1); CO2 is high during greenhouse climate states and low during icehouse climates. Our data support previous work suggesting that, when ΔF_CO2,sol is considered, icehouse states generally occur when climate forcing drops below approximately +1–2 W m⁻² (refs 31,32). This treatment also reveals that for the last 420 Myrs, despite a gradual 4% increase in solar luminosity (equivalent to +9 W m⁻² of radiative forcing), there has been very little long-term change in ΔF_CO2,sol (despite shorter-term fluctuations of up to 10 W m⁻²), with a linear fit to all the data suggesting only a slight decrease of 0.004 W m⁻² per Myr (±0.001 s.e.m.; P = 0.0003; red line on Fig. 2b); a linear fit to our LOESS fit resampled with the original data density yields a slightly higher negative slope (−0.008 ± 0.001 s.e.m.; P = 0.0001; black line Fig. 2b). This indicates that the long-term decrease in CO2 over the last 420 Myrs has largely compensated for the increase in solar output over the interval. In terms of shorter-term radiative imbalances, 95% of the ΔF_CO2,sol values are within ±7 W m⁻² and 68% within ±5/−3 W m⁻² (Fig. 3). Thus, even on multi-

Figure 1 | Temporal evolution of climate and atmospheric CO2. Latitudinal extent of continental ice deposits (blue bars) and multi-proxy atmospheric CO2 (in p.p.m.) compiled from the literature (data found in Supplementary Data 1; symbols). CO2 from leaf stomata shown in blue circles, pedogenic carbonate δ¹³C as pink crosses, boron isotopes in foraminifera as green triangles, liverwort δ¹³C as dark blue filled circles and δ¹³C of alkenones as dark blue crosses. The most likely LOESS fit through the data, taking into account X- and Y- uncertainty is shown as the blue line (data found in Supplementary Data 2). 68 and 95% confidence intervals are shown as dark and light grey bands. Red line is a linear best fit (curved due to log-scale for y axis) and 95% confidence interval for least squares regression through the CO2 data (m = 3.4 ± 0.17 s.e.m., R² = 0.26, P < 0.0005). Black line is least squares fit through the LOESS best fit (blue line) resampled to original data density (m = 3.5 ± 0.12 s.e.m., R² = 0.44, P < 0.0005). Dashed line is pre-industrial CO2 (278 p.p.m.). Icehouse time intervals are indicated by a black band and greenhouse intervals by a white band.
The concentration of atmospheric CO$_2$ on multi-million-year timescales depends largely on the balance between the input of CO$_2$ from volcanism, metamorphism and organic carbon weathering and the output of CO$_2$ from silicate weathering and organic carbon burial. Since the magnitude of silicate weathering is climatically sensitive (that is, a function of temperature and precipitation; for example, ref. 33), silicate weathering also buffers the CO$_2$ content of the atmosphere by acting as a negative feedback. However, we note that in many modern settings silicate weathering is supply-limited. Thus, for silicate weathering to operate as a climate feedback, the Earth must be sufficiently tectonically active to ensure an adequate supply of fresh minerals.

The marked 'double-hump' pattern of the CO$_2$ reconstruction (Fig. 1) that is also common to other compilations (for example, refs 28,35) is likely caused by changes in the inputs and outputs of CO$_2$ in response to the supercontinent cycle. For example, the low CO$_2$ during the Carboniferous (~300 Myrs ago) and during the later parts of the Cenozoic (last 65 Myrs) was likely a result of a reduced volcanic flux and/or enhanced silicate weathering, at least in part due to higher continental relief during supercontinent construction phase. During the million-year timescales (and sometimes shorter) the external radiative forcing (not considering the action of additional feedbacks internal to the climate system such as the ice-albedo feedback) has not varied beyond ±2.0% of the total incoming radiation (~340 W m$^{-2}$).

**Discussion**

The concentration of atmospheric CO$_2$ on multi-million-year timescales depends largely on the balance between the input of CO$_2$ from volcanism, metamorphism and organic carbon weathering and the output of CO$_2$ from silicate weathering and organic carbon burial. Since the magnitude of silicate weathering is climatically sensitive (that is, a function of temperature and precipitation; for example, ref. 33), silicate weathering also buffers the CO$_2$ content of the atmosphere by acting as a negative feedback. However, we note that in many modern settings silicate weathering is supply-limited. Thus, for silicate weathering to operate as a climate feedback, the Earth must be sufficiently tectonically active to ensure an adequate supply of fresh minerals.

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climate forcing that has no apparent geological precedent, for at least the last 420 Myrs. We should be aware of course of the limitations of the geological record, and it is debatable whether an extreme climate change event analogous to the Anthropocene, if it existed at all, would leave a detectable signal, given our current CO2 proxies and records43. Nonetheless, prolonged warm greenhouse climate states have occurred in the past, but the rates of climate change in the geological record are on the whole very likely slower than what we are currently experiencing (for example, ref. 44). Unabated fossil fuel use therefore has the potential to push the climate system into a state that has not been seen on Earth in at least the last 420 Myrs.

Methods

Assembling the CO2 compilation. The new CO2 compilation here consists of 1,241 independent estimates coming from five proxy methods and 112 published studies. In putting this compilation together, we applied a uniform set of criteria described next to screen potential CO2 records. By following these criteria, the CO2 values associated with some records are revised, while other records are excluded all together. This standardization process helps ensure a high-quality compilation whose individual records can be more clearly compared to one another. Of course, some of our criteria may be judged at some point to be incorrect. It is in this light, and in the spirit of full transparency, that we describe our criteria. We consider our compilation to be a ‘living document’, not only because in the future new records will be added but because existing records will be interpreted in new ways. The compilation can be found in Supplementary Data 1.

First, we excluded all goethite-based CO2 estimates45–48 due to uncertainties in modelling some of the isotopic fractionation factors49. We also excluded all B/Ca-based estimates50 because the environmental controls on B/Ca are currently not well understood51. The naphlcolite proxy is based on well-described mineral phase equilibria52, but we exclude the published estimates because it is not possible to assign mean values (all values within a defined CO2 interval are equally probable). It is important to note, however, that the range described by these naphlcolite estimates agree well with the other data in our compilation. We do not include the boron-based estimates of Pearson and Palmer53 owing to problems related to potential diagenesis, potential analytical issues, vital effects of extinct species and other limitations of the geological record, and it is debatable whether an uncertainty bounds in estimated CO2. Owing to the ad hoc nature of these functions, CO2 estimates from stomatal ratios should be considered semi-quantitatively only. We modify many of the stomatal-based estimates of Retallack54. First, we only use estimates associated with five or more cuticle fragments, as this is the minimum sampling required in most cases for robust estimates65. We use the quantitative transfer function of Royer66 for estimates coming from Ginkgo as these other groups are too distantly related to Ginkgo and have not been calibrated correctly67.

A recent development that we have incorporated is the lowering of CO2 estimates from the pedogenic carbonate method58. This is because one of the key input parameters, the concentration of biologically derived CO2 in the soil (S(z)), had been overestimated in most paleosols by a factor of two or more68. Here we adjust most CO2 estimates assuming a S(z) of 2,000 p.p.m. (ref. 68). This is a simple correction that masks variability in S(z)69, but it is nonetheless a useful place to start and in most cases represents an improvement over previous estimates70. This is an area where we anticipate substantial revision in the near future. Along these lines, several proxies for S(z) have been proposed69–71, and we use estimates of S(z) derived from these methods when available. We also replace some of the pedogenic carbonate-based estimates of ref. 73 with those based on the same sediments72,73 because these newer studies provide better constraints on organic matter δ13C. Lastly, we collapse the high-resolution stomatal-based record of ref. 76 into one estimate calculated from the mean of the individual estimates.

Uncertainties in paleo-CO2 estimates have been assessed in different ways. Most earlier uncertainties associated with the pedogenic carbonate method, for example, only incorporate uncertainty in S(z); potential uncertainties in other input variables are ignored. In addition, errors associated with stomatal-based methods that involve quantitative regression equations usually only reflect uncertainty in the regressions; uncertainties in the fossil measurements are ignored. This means that error bars can convey different meanings, which hinders comparisons across methods. In recent years, Monte Carlo simulations for propagating uncertainty in multiple input variables have been developed for all five proxy systems41,55,59,77. So long as the reported percentile ranges are identical, these simulations facilitate better cross-method comparisons.
We attempt here to standardize reported uncertainties so that they incorporate uncertainty in all input variables; we also standardize the percentile levels (16 and 84; equivalent to ± 1 s.d. for a normally distributed population). For uncertainties derived from Monte Carlo simulations that propagate uncertainties in most or all input variables (this covers most estimates from the alkenone, boron and seawater proxy), we adjust the reported 16 and 84 percentiles to a 5% level; for example, if the 2.5 and 97.5 percentiles are reported, we assume the population has a normal distribution and cut the uncertainties in half. Because most paleo-CO2 estimates have a right-skewed distribution, this means that we are overestimating the magnitude of the upper uncertainty and underestimating the magnitude of the lower uncertainty. For uncertainties with the pedogenic carbonate method derived by varying only S(z), we adopt for the 16 and 84 percentiles the generic recommendation of +100%/−50% of the median value calculated from multifactorial Monte Carlo simulations37; these uncertainties are larger and probably more representative than the reported uncertainties. Similarly, for stomatal estimates whose uncertainties only take into account variance in the transfer function, we assume 16 and 84 percentiles equal to +100%/−40% of the median value, a range that takes into account representative uncertainty in both the transfer function and the fossil measurements77.

All ages have been updated to the 2012 Geologic Time Scale79. Many CO2 estimates in bioturbational proxies have biostratigraphic (for example, ‘Maasrichtian’), magnetostratigraphic or chronostatigraphic constraints. For records with biostratigraphic or magnetostratigraphic constraints, we update their ages following the new Time Scale. Many CO2 estimates have no reported age uncertainties. In almost all cases, these estimates have excellent age control, the most common example being UVST estimates from marine sediment cores (for example, all boron- and alkenone-based estimates). Some terrestrial-based data fall under this category too, for example, the Triassic–Jurassic sediments in the Newark Supergroup80. When no age uncertainty is reported we take the 1 s.d. to be 0.001 Myr for marine records and 4% for terrestrial records.

Monte Carlo sampling and LOESS fitting. Monte Carlo approach was used to generate 1,000 realizations of the multiproxy CO2 time series with each data point randomly perturbed within its age and CO2 uncertainty as given in Supplementary Data 1. For CO2 estimates with asymmetric uncertainties, we force symmetry by assuming ± 1 s.d. is equal to the average offset between the median and the 16 and 84 percentiles. Each realization of the time series was then interpolated to a regular 0.5 Myr spacing. We fitted each interpolated realization using the programme R81. The optimal degree of smoothing was determined for each interpolated realization using generalized cross-validation82. At each 0.5 Myr time step the distribution of LOESS curves was evaluated and the probability distribution was determined. From this probability distribution the most likely value (or probability maximum) and the upper and lower limits corresponding to 68 and 95% confidence limits were identified. These variables are given in Supplementary Data 2.

Owing to the nature of the proxies used the make-up and coverage of our new CO2 compilation varies considerably as a function of time. By grouping the data into 2.5 million year bins following the new Time Scale, many CO2 estimates have no reported age uncertainties. In almost all cases, these estimates have excellent age control, the most common example being estimates from marine sediment cores (for example, all boron- and alkenone-based estimates). Some terrestrial-based data fall under this category too, for example, the Triassic–Jurassic sediments in the Newark Supergroup80. When no age uncertainty is reported we take the 1 s.d. to be 0.001 Myr for marine records and 4% for terrestrial records.

Data availability. The authors declare that all data supporting the findings of this study are available within the Supplementary Information files associated with this manuscript.

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