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LETTERS

Climate sensitivity constrained by CO_2 concentrations over the past 420 million years

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A firm understanding of the relationship between atmospheric carbon dioxide concentration and temperature is critical for interpreting past climate change and for predicting future climate change[1]. A recent synthesis[2] suggests that the increase in global-mean surface temperature in response to a doubling of the atmospheric carbon dioxide concentration, termed 'climate sensitivity', is between 1.5 and 6.2 °C (5–95 per cent likelihood range), but some evidence is inconsistent with this range[1–5]. Moreover, most estimates of climate sensitivity are based on records of climate change over the past few decades to thousands of years, when carbon dioxide concentrations and global temperatures were similar to or lower than today[1,6], so such calculations tend to underestimate the magnitude of large climate-change events[7] and may not be applicable to climate change under warmer conditions in the future. Here we estimate long-term equilibrium climate sensitivity by modelling carbon dioxide concentrations over the past 420 million years and comparing our calculations with a proxy record. Our estimates are broadly consistent with estimates based on short-term climate records, and indicate that a weak radiative forcing by carbon dioxide is highly unlikely on multi-million-year timescales. We conclude that a climate sensitivity greater than 1.5 °C has probably been a robust feature of the Earth's climate system over the past 420 million years, regardless of temporal scaling.

In an effort to reduce the uncertainty of climate sensitivity, $\Delta T(2\times)$, we turned to the Phanerozoic record (the past 542 Myr), an interval that includes times when the Earth was both colder and substantially warmer than the present day[8]. Phanerozoic records generally show a positive coupling between CO_2 and temperature[9,10], but determining $\Delta T(2\times)$ quantitatively has proved difficult because there are no convenient proxies for global-mean surface temperature. The GEOCARB and GEOCARBSULF long-term carbon cycle models[11,12] have been used to calculate multi-million-year patterns of Phanerozoic CO_2. Importantly, a critical factor in this approach is the effect of atmospheric CO_2 level on the rate of CO_2 uptake by weathering of calcium and magnesium silicate minerals. A rise in temperature, accompanying a rise in CO_2, increases the rate of silicate weathering, which in turn accelerates atmospheric CO_2 consumption, forming a negative feedback loop.

Here, using the logarithmic relation between temperature change and CO_2, we examine how different values of $\Delta T(2\times)$ affect calculated Phanerozoic CO_2 levels for best estimates, and physically reasonable ranges, of all other factors affecting CO_2 in the long-term carbon cycle. Such factors include solar evolution, changes in palaeogeography, palaeolithology, palaeohydrology, global degassing, organic and carbonate burial rates, and land plant population[11]. Calculating $\Delta T(2\times)$ in this manner differs from most existing approaches in that it does not involve independent estimates of temperature, incorporates information from times when the Earth was substantially warmer than today, and reflects an equilibrium sensitivity that integrates over millions of years.

We amended the GEOCARBSULF[12] model to include a well-defined temperature coefficient for the weathering of calcium and magnesium silicates[13], and held this and all other parameters in GEOCARBSULF fixed except for the CO_2-doubling response, $\Delta T(2\times)$. We then compared model calculations against an independent proxy data set[9] for atmospheric CO_2 over the Phanerozoic (Fig. 1). The best fit between the standard version of the model and proxies occurs for $\Delta T(2\times) = 2.8$ °C (blue curve in Fig. 2a), which parallels the most probable values suggested by climate models (2.3–3.0 °C)[2,5] (Fig. 2b). For $\Delta T(2\times) < 1.5$ °C, unreasonably high levels of atmospheric CO_2 are required to maintain the necessary feedback effect. In the opposite extreme, if $\Delta T(2\times)$ is too large (>6 °C), the silicate weathering feedback prevents atmospheric CO_2 levels from reaching the high past values indicated by proxy data (Fig. 1).

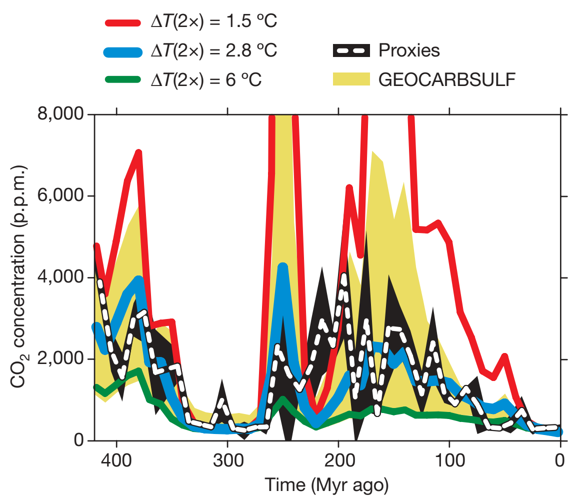

Figure 1 | Comparison of CO_2 calculated by GEOCARBSULF for varying $\Delta T(2\times)$ to an independent CO_2 record from proxies. For the GEOCARBSULF calculations (red, blue and green lines), standard parameters from GEOCARB[11] and GEOCARBSULF[12] were used except for an activation energy for Ca and Mg silicate weathering of 42 kJ mol^{-1} (ref. 13). The proxy record (dashed white line) was compiled from 47 published studies using five independent methods[9] ($n = 490$ data points). All curves are displayed in 10 Myr time-steps. The proxy error envelope (black) represents ±1 s.d. of each time-step. The GEOCARBSULF error envelope (yellow) is based on a combined sensitivity analysis (10% and 90% percentile levels) of four factors used in the model (see Methods).

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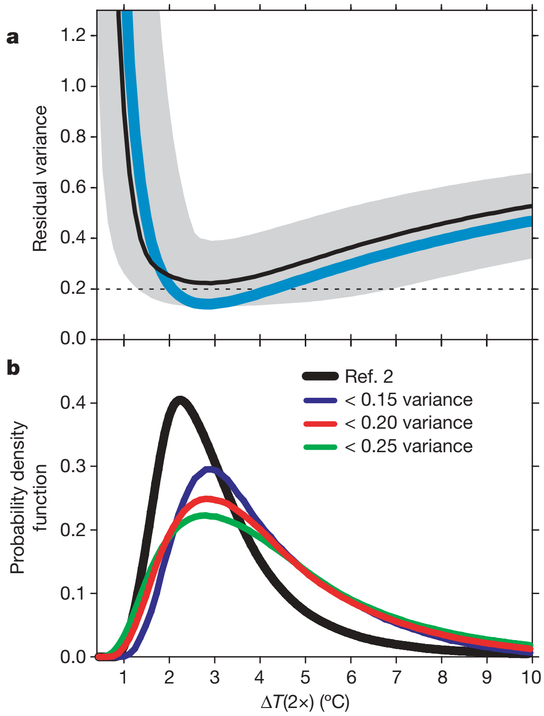

Figure 2 | Calculation of the long-term equilibrium climate sensitivity to CO_2. a, Statistical fit between the proxy and model data sets for varying $\Delta T(2\times)$. The blue curve represents the fit when standard values for all factors[11,12] are used. The thin black curve corresponds to the median fit when four factors are varied simultaneously in a sensitivity analysis (see Methods); the grey region encompasses the 10–90% percentile levels. The residual variance (y axis) represents the relative misfit of GEOCARBSULF to departures of the 10-Myr-averaged proxy-CO_2 data from present-day values. The dashed line corresponds to a residual variance of 0.2, which is roughly twice the residual variance of the best-fit GEOCARBSULF solution. **b**, Bayesian probability density function for three levels of residual variance from **a**. For comparison, the probability density function of ref. 2, which synthesizes calculations of $\Delta T(2\times)$ from climate models and decadal to millennial observations, is also shown.

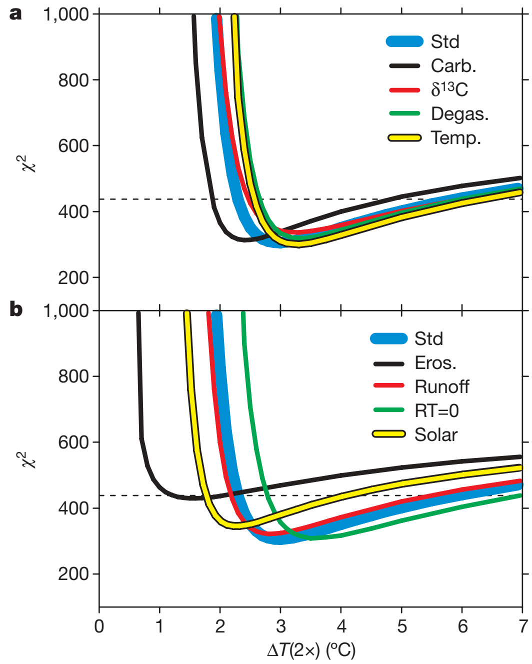

Figure 3 | Sensitivity analysis for the effect of nine additional parameters in the GEOCARBSULF carbon cycle model on the fit between model-derived and proxy CO_2 values for varying $\Delta T(2\times)$. In all cases, the thick blue curve represents the standard formulation (Std; blue curve in Fig. 2a). Values of χ^2 (489 degrees of freedom) below the dashed line correspond to a >95% likelihood that the model and proxy data sets are statistically indistinguishable. **a**, Effect on $\Delta T(2\times)$ of holding constant and equal to present values: the area of land underlain by carbonates undergoing weathering (Carb.), $\delta^{13}C$ of carbonates and $\delta^{13}C$ of organic matter undergoing deposition ($\delta^{13}C$), rates of CO_2 degassing (Degas.), and land temperature (Temp.). **b**, Effect on $\Delta T(2\times)$ of holding constant and equal to present values: global physical erosion (Eros.), river runoff (Runoff) and solar radiation (Solar), and the effect of ignoring the influence of changing global mean temperature on river runoff (RT = 0).

Many factors influence the calculations of CO_2 in GEOCARBSULF, as discussed above and elsewhere[11,12]. It is important, then, to test the sensitivity of CO_2 to variations of $\Delta T(2\times)$ for different values of these other factors (Figs 2 and 3; Supplementary Fig. 1; Methods). Critically, sensitivity analyses demonstrate that physically reasonable variations of the values representing these factors, either singly (Fig. 3; Supplementary Fig. 1) or in combination (Fig. 2), support our overall conclusion that values of $\Delta T(2\times) < 1.5\,^{\circ}C$ lead to a poor fit between the model and the proxies. Owing to trade-offs in the carbon cycle, a handful of extreme parameter choices can combine with $\Delta T(2\times) < 1.5\,^{\circ}C$ to model the proxy data adequately; for example, a small response of weathering rate to a rise in CO_2, due to an unusually low $\Delta T(2\times)$, can be compensated if increasing CO_2 levels fertilize nearly all terrestrial plant life optimally (no nutrient, water or light limitation) and thereby greatly enhance plant-assisted weathering. If we take a bayesian assumption that all GEOCARBSULF parameters are equally probable a priori within the specified ranges, a larger parameter range at $\Delta T(2\times) > 1.5\,^{\circ}C$ for successful modelling translates into a higher probability for this case (Fig. 2). Overall, the largest ranges of GEOCARBSULF parameters that fit proxy data well fall within the range of $1.6\,^{\circ}C < \Delta T(2\times) < 5.5\,^{\circ}C$ (Fig. 3; Supplementary Fig. 1), a range that is consistent with most climate model studies[1–5]. The factor with the lowest best-fit $\Delta T(2\times)$, shown as the curve 'Eros.' in Fig. 3b, is based on the extreme assumption that global physical erosion rates have not changed through time.

Our results pertain most directly to the long-term (multi-million-year) radiative forcing by CO_2; this includes, for example, periods of greatly varying continental ice cover and thus varying ice-albedo feedback, so that our best-fit $\Delta T(2\times)$ gives a mean state for the past 420 Myr. GEOCARBSULF simulations cannot exclude the possibility of a high climate sensitivity (Figs 2, 3) because of the logarithmic behaviour of the forcing and the current error constraints of the modelling[11] and proxy[9] approaches. However, these limitations notwithstanding, our results demonstrate that a weak, long-term radiative forcing by CO_2 ($\Delta T(2\times) < 1.5\,^{\circ}C$) is highly unlikely. This conclusion is consistent with decadal to millennial records from the recent past[1–5] and with millennial records from the ancient past, such as the Palaeocene–Eocene thermal maximum[14,15]. Combined, these data suggest that a $\Delta T(2\times)$ of at least $1.5\,^{\circ}C$ has been a robust feature of the Earth's climate system over the past 420 Myr, regardless of temporal scaling.

METHODS

Sensitivity analyses. We tested the combined influence of the following four factors on $\Delta T(2\times)$ (Fig. 2): varying the activation energy for the dissolution of primary calcium and magnesium silicates during continental weathering from 20 to 83 kJ mol^{-1} (refs 11, 13, 16); varying the CO_2 fertilization of plant-assisted weathering from 15% to 75% of plants affected globally by CO_2 fertilization[11]; varying the weathering rate ratio of early Palaeozoic algal/bryophytic biota to that of modern trees (mainly angiosperms) from 0.125 to 0.5 (refs 11, 17); and varying the weathering rate ratio of gymnosperms to angiosperms from 0.5 to 1.2 (ref. 11). We sampled parameter space at 10 values of each parameter, giving a total of 10,000 GEOCARBSULF simulations for each value of $\Delta T(2\times)$. The success of each simulation was quantified in two ways: with an uncertainty-weighted χ^2 criterion for fitting individual CO_2-concentration estimates, and by a residual-variance criterion that measures the extent to which a simulation explains past departures of CO_2 concentrations from present-day values (for example, a residual variance of 0.1 implies that 90% of the logarithmic departure of past CO_2 from present-day values is explained by the model). For the second criterion, we fit GEOCARBSULF simulations to a 10 Myr uncertainty-weighted moving average of CO_2 proxy data. We performed averages and quantified model fits in the logarithmic domain because the greenhouse effect scales with the logarithm of CO_2 concentration, and proxy CO_2 estimates (and their reported uncertainties) range over more than an order of magnitude.

Ranges of values for the remaining factors cannot be simply estimated, so to demonstrate their effects the extreme situation of no change with time in each factor was examined (Fig. 3). This includes the effect on silicate weathering of physical erosion, land temperature, palaeogeography and global mean temperature as they affect river runoff, and the area of land underlain by carbonates versus silicates. Additional consideration was given to the effects on $\Delta T(2\times)$ of holding constant: rates of global CO_2 degassing, solar radiation, and $\delta^{13}C$ of carbonates and organic matter undergoing deposition.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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