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On the absence of solar evolution-driven warming through the Phanerozoic

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ABSTRACT

Reconstructed temperatures through the Phanerozoic indicate a gradual cooling or, at best, no significant temperature trend, despite a 4.4% increase in solar heating. It is possible that an underlying warming trend has simply been swamped by 'noise' due to significant data-errors and/or natural fluctuations. Alternatively, the lack of warming may indicate cooling by biological and/or geological processes, which happen to have the right amplitude to cancel the effects of solar warming. This paper demonstrates that the absence of Phanerozoic warming cannot be explained as a warming trend hidden by noise. It also shows that, given widely accepted estimates of climate sensitivity, it cannot be explained as cancellation by negative feedback in the climate system. The Gaia hypothesis, anthropic selection or some other unconventional mechanism may therefore have to be invoked to explain the absence of long-term warming through the Phanerozoic.

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Introduction

Reconstructions of tropical sea-surface temperatures (SSTs) through the Phanerozoic show a long-term cooling with time (e.g. Royer *et al.*, 2004) or no clear trend (e.g. Veizer *et al.*, 2000), despite a 4.4% increase in solar heating (Bahcall *et al.*, 2001). This paper investigates whether, given the inevitable uncertainties in this data, this can be explained by conventional models or whether additional, unconventional, climate mechanisms are required.

There are two possible reasons why the expected long-term warming trend might not be detected. Firstly, there may be a warming trend, which is reduced by negative feedback [e.g. the silicate-weathering cycle (Walker *et al.*, 1981)], with the remaining moderate warming being obscured by stochastic fluctuations. This "noise" could result from two distinct mechanisms:

1 Data errors resulting from inaccurate measurement, incomplete data reduction, diagenetic overprinting or spatial variations in SSTs.
2 Natural long-term fluctuations in the Earth's climate system produced by plate tectonics (Goddéris *et al.*, 2012) and biological evolution (Berner, 1993).

An alternative explanation for the absence of warming is that geological and/or biological evolution reduces the concentration of greenhouse gasses and/or increases albedo through time. Unlike in point (2) above, this involves a directional trend rather than random fluctuations. For example, the evolution of organisms which are increasingly efficient at colonizing and weathering continents has led to a biologically mediated fall in greenhouse gas concentrations (Schwartzman, 1999). A cooling trend is then a consequence of geological and biological evolution in the same way that warming is a consequence of solar evolution. This paper investigates this possibility by examining whether the absence of a warming trend through the Phanerozoic is statistically significant given the observed fluctuations. The approach taken is to remove the effects of solar evolution and feedback processes from palaeo-temperature estimates to leave a time-varying quantity which characterizes the climatic influence of biogeochemical evolution. Statistical analysis then shows that the resulting climate-function exhibits a long-term trend rather than the random drift associated with a stochastic process.

Phanerozoic sea-surface temperatures

Robust statistical analysis of time-series trends requires data that are spread reasonably uniformly through a period of time substantially longer than the duration of typical fluctuations. Furthermore, the measurements should ideally be determined using a standardized procedure.

Given this, the best available data set is that of δ^{18}O-based, Phanerozoic sea-surface temperatures (SSTs) from Veizer *et al.* (1999). Problems do arise when using such oxygen-isotope ratios [see Royer (2006) for a discussion], but the results are broadly confirmed by other techniques. For example, δ^{13}C excursions throughout the Phanerozoic exhibit similar trends suggesting a climate control on both isotope systems (Stanley, 2010), whereas the latitudinal distribution of ice-drafted debris deposits (Frakes and Francis, 1988) broadens substantially during periods of high δ^{18}O. Organic carbon-based proxies [i.e. Tex$_{86}$, Schouten *et al.* (2002)] are another useful SST proxy and, although analyses are currently restricted in time coverage, results confirm the general picture from oxygen data [e.g. warm conditions in the Mesozoic (Jenkyns *et al.*, 2012)]. Computer models of long-term climate based on CO$_2$ proxies (e.g. Goddéris *et al.*, 2012) also produce comparable results in terms of general trends, especially the long-term downwards drift in temperatures, which is of particular interest here.

In a little more detail, deviations of equatorial SSTs from the modern value may be estimated using δ^{18}O measurements of calcite and

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aragonite shells (Veizer *et al.*, 1999, 2000) as both the concentration of ^{18}O in the oceans and its rate of uptake by carbonate-forming organisms are enhanced when the Earth is relatively cold. However, there is significant disagreement over how to treat long-term trends in these data. Veizer *et al.* (2000) completely removed the long-term trend before calculating palaeo-temperatures on the assumption that trends are produced by tectonic processes. Royer *et al.* (2004), on the other hand, interpreted the trend as resulting from seawater pH-variations driven by changes in atmospheric CO_2 levels. After correcting for these, they obtained a palaeo-temperature curve which is significantly warmer in the early Phanerozoic. This reinterpretation is more consistent with observations of very limited glaciation during the Ordovician-Silurian ice-age (480–400 Ma), but recent work by Finnegan *et al.* (2011) indicates that SSTs at this time were similar to those of today. In this paper, I assume that the SST curves of Veizer *et al.* (2000) and Royer *et al.* (2004) are end-members, with an intermediate best estimate giving the lowest Ordovician-Silurian the same SST as today (Fig. 1).

The next step is to use SST deviations to estimate global-mean surface temperature. Global fluctuations are greater than equatorial fluctuations because fluctuation strength increases with latitude. Lea *et al.* (2000), for example, show polar-temperature oscillations which have consistently been twice the size of equatorial fluctuations over the last 350 ka. This phenomenon is confirmed by global circulation models, which also show greater climate sensitivity at the poles than the equator (Solomon *et al.*, 2007). A rough estimate for the global-mean temperature can be obtained by assuming that the fluctuation-amplitude increases linearly with latitude to give

$$\begin{aligned} T &= T_0 + \int_0^{\pi/2} \Delta\mathrm{SST} \\ &\quad \left[1 + (2a_\mathrm{p}L/\pi) - (2L/\pi)\right]\cos(L)\mathrm{d}L \\ &= T_0 + \left[a_\mathrm{p}(1-2/\pi) + 2/\pi\right]\Delta\mathrm{SST} \\ &= T_0 + \alpha\Delta\mathrm{SST} \end{aligned} \qquad (1)$$

where T_0 is the present-day global-mean temperature, ΔSST is the equatorial SST deviation, L is latitude, a_p is the polar amplification and α is the ratio of global temperature fluctuations to equatorial fluctuations. Polar amplification of $a_\mathrm{p} = 2.0$ gives $\alpha = 1.36$, while other reasonable values for a_p and different assumptions for the latitude-dependency all give $\alpha = 1.4 \pm 0.3$. For comparison, modern GCMs yield $\alpha = 1.2 \pm 0.2$ (see Bony *et al.*, 2006, fig. 17). The maximum α is critical to the conclusions of this paper and so, to be conservative, the larger estimate ($\alpha = 1.4 \pm 0.3$) is used below. Note that the amplification factor could vary with time and account will be taken of this later.

Removal of the solar contribution

Direct solar warming, and the effects of feedback mechanisms, can be simultaneously removed by introducing climate sensitivity

$$S = \partial T/\partial F \qquad (2)$$

which governs how strongly the Earth's mean surface temperature is altered by changes in incoming solar flux, F. Integration of Eq. (2) gives

$$\Delta T = \bar{S}\Delta F \qquad (3)$$

where ΔT is the temperature change produced by flux change ΔF, while $\bar{S}$ is the climate sensitivity averaged over this flux range. However, most climate literature defines climate sensitivity as the temperature rise, T_{2x}, produced by a doubling of atmospheric CO_2. These different definitions are related as doubling of carbon dioxide produces a forcing of 3.7 Wm^{-2} at the tropopause (Solomon *et al.*, 2007), which, because of the Earth's reflectivity, requires an increased flux of 5.3 Wm^{-2} at the atmosphere top. Eq. (3) therefore gives

$$\bar{S} = T_{2x}/5.3 \qquad (4)$$

Estimation of T_{2x} depends on the time-scale of observation (Rohling *et al.*, 2012), but Park and Royer (2011) concluded that modelled CO_2 levels match proxy data only if long-term climate sensitivity is >1.5 K with a best estimate of 3–4 K. They also concluded that T_{2x} probably varies with time. These estimates for long-term climate sensitivity are similar to those obtained by other workers (Rohling *et al.*, 2012) and include any feedback mechanisms that operate over the multi-million-year time-scale considered in this paper [e.g. silicate-weathering (Walker *et al.*, 1981) or biologically mediated feedbacks (Lovelock and Watson, 1982)].

Note that a climate sensitivity of $T_{2x} = 3$ K, along with a 4.4% increase in solar heating, should have warmed the Earth by about 8 K over the Phanerozoic, but no such warming is seen. The implication is that it was cancelled out by intrinsic cooling of the Earth due to geological and biological changes. To investigate the

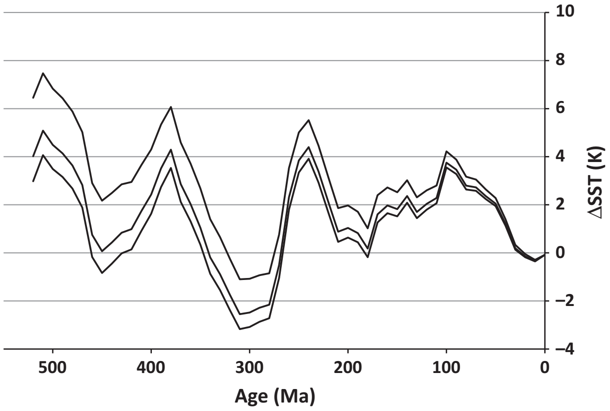

Fig. 1 Estimated deviations in equatorial sea-surface temperatures (ΔSST) from the modern mean value. Upper curve after Royer *et al.* (2004); lower curve after Veizer *et al.* (2000). Intermediate best-estimate curve chosen to make SST at 450 Ma similar to today's (following Finnegan *et al.*, 2011).

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scale of this intrinsic cooling, Eqs (1), (3) and (4) can be combined to give

$$\Delta\mathrm{SST}' = \Delta\mathrm{SST} + (T_{2x}/5.3\alpha)\Delta F \quad (5)$$

where $\Delta\mathrm{SST}'$ is the change in SST that would have occurred had there been no increase in solar luminosity. Eq. (5) requires the change in solar flux through time. This can be estimated using Bahcall *et al.'s* (2001) solar model, which is well reproduced by

$$F(t) = 0.25\left(a_0 + a_1 t + a_2 t^2 + a_3 t^3\right) \quad (6)$$

where t is Ma before present, $a_0 = 1369.8\ \mathrm{Wm^{-2}}$, $a_1 = -0.11598\ \mathrm{Wm^{-2}Ma^{-1}}$, $a_2 = 9.4538 \times 10^{-6}\ \mathrm{Wm^{-2}Ma^{-2}}$ and $a_3 = -6.4927 \times 10^{-10}\ \mathrm{Wm^{-2}Ma^{-3}}$.

Figure 2 shows the resultant largest estimate, best estimate and lowest estimate for $\Delta\mathrm{SST}'$. These curves correspond to those from Fig. 1, but the top one has maximum climate sensitivity ($T_{2x} = 6$ K) and minimum temperature amplification ($\alpha = 1.1$), while the central one has $T_{2x} = 4$ K and $\alpha = 1.4$, and the lower one assumes $T_{2x} = 2$ K and $\alpha = 1.7$. The upper and lower curves can be thought of as delineating an uncertainty range for the best-estimate curve.

Statistical analysis

The gradients in Fig. 2 show that intrinsic changes in the Earth's climate system have tended to cool our planet through time. However, it is not obvious whether these gradients are statistically significant or could, instead, be explained by stochastic variation in a fundamentally random process. Simple linear regression cannot resolve this, as the residuals are correlated making a t-test of regression invalid (Swan and Sandilands, 1995). Instead, the data from Fig. 2 should be sequentially decimated from its original sampling interval of $\Delta t = 10$ Ma until residuals are no longer correlated. Figure 3 shows the Durbin-Watson statistic [which measures the correlation between successive variables in a time-series (Swan and Sandilands, 1995)] for the central-curve residuals in Fig. 2 as a function of sampling interval. Note that the test-statistic does not exceed the upper critical value until sampling reaches 40 Ma. This is therefore the correct sampling interval at which to estimate the significance of the gradient. Note that, as the data are sequentially decimated, the probability that the gradient is a chance fluctuation increases (Fig. 4). Thus, without this decimation procedure, the hypothesis that the gradient is statistically significant would be too readily accepted.

Similar trends are found when the other two curves from Fig. 2 are analysed. The resulting gradients, P values and trend-lines are plotted in Fig. 5. For the best-estimate case, the intrinsic cooling was $18 \pm 3\ \mathrm{K\ Ga^{-1}}$ with a probability for the null-hypothesis (that there is no gradient) of 9×10^{-5}, i.e. well below a significance-level threshold of 5%. The gradient of the upper $\Delta\mathrm{SST}'$ estimate ($35 \pm 3\ \mathrm{K\ Ga^{-1}}$) is even more significant ($P = 7 \times 10^{-8}$). The gradient of the lower curve ($6 \pm 3\ \mathrm{K\ Ga^{-1}}$) also falls below the significance threshold ($P = 3\%$).

However, as both T_{2x} and α in Eq. (5) may be functions of time, it is possible that the true variations were greater than in any single curve shown in Fig. 2 and involved fluctuations between the upper and lower curves. These larger fluctuations might, in turn, allow a stochastic explanation of the cooling trend to be more probable. A Monte-Carlo analysis was therefore undertaken using randomly chosen curves oscillating between the upper and lower bounds of Fig. 2. This was done at a 40-Ma sampling rate, so that correlations between adjacent points were unimportant, allowing curves to be generated by independently choosing random values between the limits at each successive point. The resulting curves were then analysed using the same technique as before. Gradients typically came out with values similar to that of the best-estimate case ($25 \pm 5\ \mathrm{K\ Ga^{-1}}$), but, as the fluctuations were now stronger, the gradient was less significant ($P = 0.5 \pm 0.5\%$) but still low enough to warrant rejection of the null hypothesis.

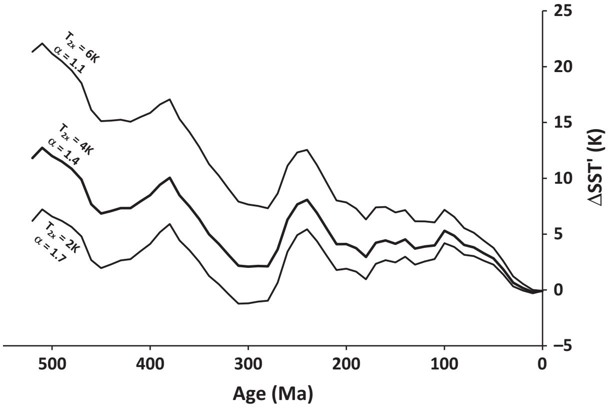

Fig. 2 Estimated deviations in equatorial sea-surface temperatures, from the modern mean value, after removing the warming influence of solar evolution. The upper curve assumes the maximum SST, maximum climate sensitivity and minimum polar amplification. The lower curve assumes the smallest SST, smallest climate sensitivity and largest polar amplification.

Discussion

This paper's conclusion is that the observed fluctuations in Phanerozoic SST data are not sufficiently large to hide the expected solar warming. Explanations for this 'Faint Cambrian-Sun Paradox' [with apologies to Sagan and Mullen (1972)] must therefore be sought. One obvious possibility is that the analysis presented in this paper indicates problems with the SST estimates themselves. This certainly warrants further investigation but is beyond the scope of this study. Another possibility is that long-term, negative-feedback processes are stronger than currently believed, so that the climate sensitivity of the Earth is lower than the $T_{2x} = 2$ K I have used as my

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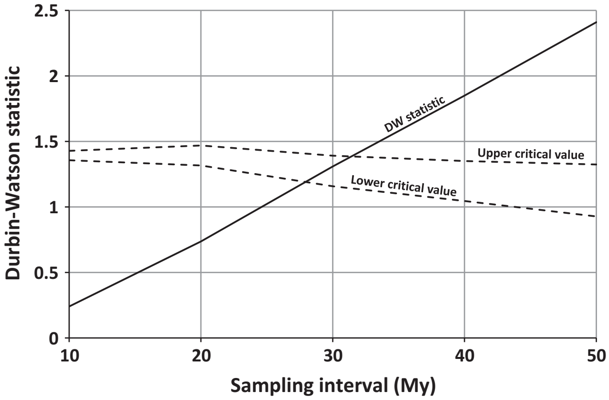

Fig. 3 The Durbin-Watson statistic as a function of sampling interval for the residuals of the central curve in Fig. 2. The dashed lines give the upper and lower estimates of the critical value beyond which consecutive values in a time-series are uncorrelated. The adjusted ΔSST′ curve must therefore be sub-sampled at 40 Ma to ensure that the residuals are uncorrelated.

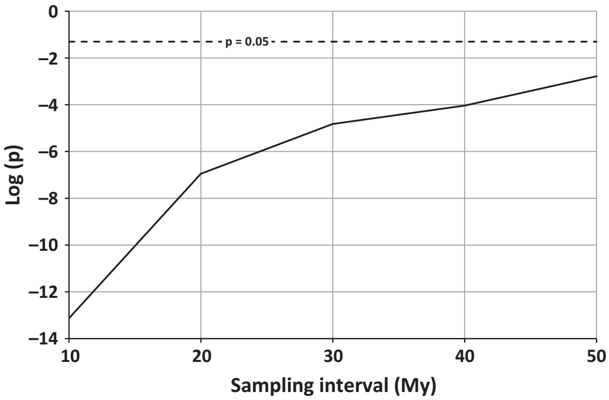

Fig. 4 The probability that the true gradient of the central curve in Fig. 2 is less than zero as a function of the sampling interval. Even at the 40-Ma interval required to have uncorrelated residuals, the probability falls far below 5%.

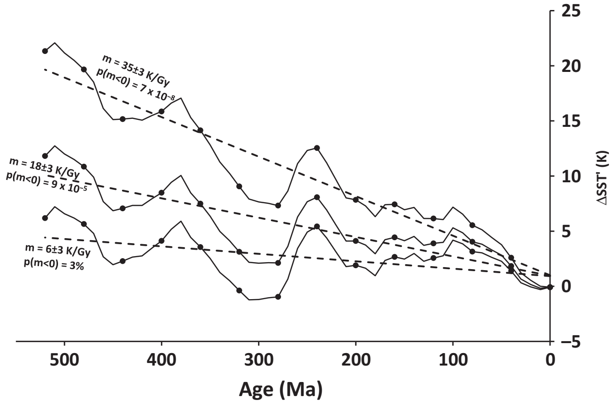

Fig. 5 Linear regressions through the data shown in Fig. 2, after decimation to an interval of 40 Ma to make the residuals uncorrelated (as shown in Fig. 3). Gradients are assumed to be statistically significant if $P < 5\%$.

minimum estimate. The implications of revising long-term climate sensitivity downwards would be profound for our understanding of palaeoclimates and would, for example, make it hard to explain how recent glaciations have been driven by the relatively small influences of Milankovitch cycles. Another possibility is that the analysis has been skewed by unusually warm conditions at the start of the Phanerozoic together with unusually cold conditions more recently. However, statistical analysis of the residuals in Fig. 5 does not suggest that the deviations from the trend line are unusually large at these time periods. When age>440 Ma and age<80 Ma are excluded, the mean residual shifts by much less than its standard error and the standard deviation of the residuals actually rises, which suggests that climate fluctuations at these times are, if anything, slightly smaller than average. Furthermore, even if the analysis is artificially restricted to 440–80 Ma to minimize the gradient in Fig. 5, the probability of the best-estimate gradient falling below zero is still only 5%.

If the problems do not lie with the data or with our estimates of climate sensitivity, then the absence of a warming trend can only result from coincidental cancellation of solar warming by concurrent, biogeochemical cooling. This coincidence is surprising given the very different natures of solar, geological and biological processes and so I will finish with two possible explanations:

1. The Gaia hypothesis (Lovelock, 1972; Lovelock and Watson, 1982; Lovelock and Whitfield, 1982) in which the emergent properties of an evolving and complex biogeochemical system act to stabilize the climate.
2. Anthropic selection. If a broadly stable climate is a prerequisite for a complex biosphere, our planet could be a rare example of a world where the effects of solar evolution have, purely by chance, been approximately cancelled by geological and biological processes (Waltham, 2011). Selection occurs because "what we observe must be compatible with our existence as observers" (Carter, 1983).

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