

# Detailed Response to Royer et al.'s letter "CO<sub>2</sub> as a primary driver of Phanerozoic Climate"

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Royer et al. (2004) introduce a seawater pH correction to the Phanerozoic temperature reconstruction based on  $\delta^{18}\text{O}$  variations in marine fossils. Although this correction is a novel idea and it is likely to have played some role in offsetting the  $\delta^{18}\text{O}$  record, we show that (a) The correction cannot be as large as claimed by Royer et al. (b) Irrespective of the size of the correction, a CO<sub>2</sub> signature cannot possibly be seen in the data. (c) Even though the CO<sub>2</sub> signature cannot be seen, the pH correction implies only a somewhat higher global temperature sensitivity than that in Shaviv and Veizer (2003), a sensitivity that is consistent with a "black body Earth", but only marginally with the lower limit of the IPCC range.

## I. INTRODUCTION

Royer et al. (2004) citing the standard references from the IPCC (2001) volume assert that CO<sub>2</sub> is the principal climate driver on modern as well as geological time scales. Although some of these cited publications (e.g. Mann et al., 1998) were questioned recently (Soon and Baliunas, 2003; McIntire and McKittrick, 2003), it is not our intention to scrutinize their methodology. We would only like to point out that these publications implicitly assume that the various radiative forcings at play do not include an amplifier to solar activity. However, a large body of empirical evidence, published mostly subsequent to the IPCC summary (e.g., Bond et al., 2001; Neff et al., 2001; Solanki, 2002; Rind, 2002; Foukal, 2002; Usoskin et al., 2003) suggests that such an amplifier exists, and it is most likely in the form of solar modulation of the cosmic ray flux (CRF) (e.g., Tinsley and Deen, 1991; Svensmark, 1998, 2000; Marsh and Svensmark, 2000, 2003; Palle Bago and Butler, 2000; Egorova et al., 2000). Note that Royer et al. do not dispute the existence of the CRF/temperature correlation of Shaviv and Veizer (2003), only its role relative to that of CO<sub>2</sub>. The CRF effect should therefore be incorporated as a complementary factor into the existing climate models.

Once this solar amplification is included, the paleoclimatic data is consistent with a solar (direct and indirect) contribution of  $0.32 \pm 0.11^\circ\text{C}$  towards global warming over the past century (Shaviv, 2004). While these results imply different conclusions than the IPCC scenarios, they are not necessarily contradictory given the differences in basic assumptions. Note also that when the temperature trend over the past century is compared to the monotonic increase in greenhouse gases vs. the non-monotonic increase in solar activity, the best fit suggests that more than half of the warming should be attributed to solar activity, and somewhat less to greenhouse gases (GHG) (Soon et al. 1996). A similar comparison with the Total Solar Irradiance (TSI) flux led Foukal (2002) to state that the TSI can explain 80% of the 11-year

smoothed variance in the centennial global temperature trend. Such empirical observations strongly suggest that celestial forcing played an important role in the climate history of our planet.

Royer et al. (2004) cite the unquestionably impressive correlation of CO<sub>2</sub> and polar temperatures in Antarctic ice cores (Barnola et al., 1987; Petit et al., 1999) as a proof that CO<sub>2</sub> is the climate driver on  $\sim 10^5$  year time scales. This correlation, however, cannot distinguish by itself between cause and effect. More importantly, recent high-resolution data (Mudelsee, 2001; Clarke, 2003) demonstrates that the rises in CO<sub>2</sub> lag by centuries (i.e., much smaller than the  $10^5$ yr time scale) behind the increases in temperature. Clearly, the CO<sub>2</sub> may act as a temperature amplifier, but not as the driver for climate changes that happened centuries earlier.

On still longer, Phanerozoic, time scales, Royer et al. (2004) cite the "close correspondence between CO<sub>2</sub> and temperature" as advocated in Crowley and Berner (2001). A simple visual inspection of the alternatives (Fig. 1) shows that it is the "four-hump" reconstruction of  $\delta^{18}\text{O}$  based paleotemperatures (Veizer et al., 2000) and the CRF (Shaviv and Veizer, 2003) that correlate closely with the paleoclimate history based on sedimentary indicators (<http://www.scotese.com/climate.htm>; Boucot and Gray, 2001), and not the "two-hump" GEOCARB III reconstruction (Royer et al., 2004) of atmospheric CO<sub>2</sub>. Note also that the GEOCARB III results in high atmospheric CO<sub>2</sub> levels for most of the Paleozoic and mid-Mesozoic. In order to explain the recurring cold intervals during these times, one has to resort to a multitude of special pleadings. The late Ordovician glaciation at an apparent  $\sim 5000$  ppm CO<sub>2</sub> is a classic example.

Royer et al. (2004) discount the validity of all other Phanerozoic CO<sub>2</sub> reconstructions, citing the general agreement of the GEOCARB III trend with estimates based on CO<sub>2</sub> proxies. Considering the many assumptions and large uncertainties in the proxy data (Royer et al., 2001) this statement may need future confirmation, but we are

prepared to accept it at this stage. Nevertheless, we (Shaviv and Veizer, 2003) believe that in view of the above, it is necessary to test all presently available Phanerozoic  $\text{CO}_2$  scenarios. The outcome, however, is more or less the same for all alternatives—a lack of correlation with the  $\delta^{18}\text{O}$  based paleotemperatures as well as with the paleoclimate trend based on sediments.

## II. SPECIFIC MODELING COMMENTS CONCERNING THE pH CORRECTION OF ROYER ET AL.

The pH effect introduced by Royer et al. (2004) may well have played a role in distorting the  $\delta^{18}\text{O}$  data, such that a reconstructed temperature should take it into consideration. We show here, however, that while the inferred influence of  $\text{CO}_2$  (and global temperature sensitivity in general) is somewhat higher once the pH effect is considered, the qualitative conclusions reached in Shaviv and Veizer (2003) are generally the same. This is because of several critical points elaborated here.

### A. Theoretical Background:

Zeebe (1999) considered the possible bias of  $\delta^{18}\text{O}$ -derived temperature due to the carbonate ion effect on oxygen isotope incorporation in carbonates controlled by temporal changes in the pH. Zeebe (2001) derived the expression  $\Delta T_{pH} = bs\Delta(pH)$  for the correction of the reconstructed temperature using  $\delta^{18}\text{O}$  of carbonates.  $s$  is linear coefficient between  $\delta^{18}\text{O}$  and pH from theory and experiments ( $s = -1.42\text{‰}$  per unit pH).  $b$  is the linear coefficient between  $\delta^{18}\text{O}$  and temperature. The value of  $b$  taken by Royer et al. (2004) is  $-4.90^\circ\text{C}$  per  $1\text{‰}$  of  $\delta^{18}\text{O}$ . However, this does not allow for an ice-volume effect. If one assumes no ice-caps at the peak of the greenhouse epochs, and ice-sheets twice as large as today at the height of the icehouses, then as much as  $2\text{‰}$  of the  $3\text{--}5\text{‰}$  range in the  $\delta^{18}\text{O}$  data should be attributed to an ice-volume effect and not to temperature (Guilderson et al. 1994; Savin, 1977; Veizer et al., 2000). Thus, on average over the Phanerozoic, a more appropriate value is  $b$  of  $-2.0^\circ\text{C}$  per  $1\text{‰}$  of  $\delta^{18}\text{O}$ .

Once this is considered, the pH correction to the  $\delta^{18}\text{O}$ -reconstructed temperature is

$$\Delta T_{pH} = a\{\log R_{\text{CO}_2} + \log \Lambda(t) - \log \Omega(t)\}, \quad (1)$$

where  $R_{\text{CO}_2}$  is the atmospheric partial pressure of relative to today,  $\Lambda(t)$  is  $(Ca)(t)/(Ca)(0)$  - the mean concentration of dissolved calcium in the water relative to today, while  $\Omega(t)$  is  $[Ca^{++}][\text{CO}_3^{--}]/K_{sp}$  at time  $t$  relative to today. The value of  $a$  obtained in Royer et al. (2004) assumes no ice-volume correction, yielding  $a = 3.4^\circ\text{C}$ . If we take the smaller  $b$ , given the likely ice-volume effect, we obtain  $a = 1.4^\circ\text{C}$ . This correction is important, as documented below.

### B. Methodology

Royer et al. (2004) apply the pH correction to obtain a corrected reconstructed temperature of:

$$\begin{aligned} \Delta T_{O18} &= b\delta^{18}\text{O} + \Delta T_{pH} \\ &= b\delta^{18}\text{O} + a\{\log R_{\text{CO}_2} + \log \Lambda(t) - \log \Omega(t)\}. \end{aligned} \quad (2)$$

When comparing to the variable  $\text{CO}_2$  and cosmic ray flux (CRF), one essentially compares the temperature to a modeled temperature of the form:

$$\Delta T_{\text{model}} = A + Bt + C \log_2 R_{\text{CO}_2} + Dg(\Phi_{\text{CRF}}(t)), \quad (3)$$

where the last term is the contribution from the CRF as described in Shaviv and Veizer (2003). The first two terms allow for systematic variations in temperature, some of which are poorly known (e.g., secular solar luminosity increase, systematic error in the  $\delta^{18}\text{O}$  detrending, etc.).

The comparison of Royer et al. (2004) is basically between  $\Delta T_{O18}$  and  $\Delta T_{\text{model}}$ . The  $\Lambda(t)$  and  $\Omega(t)$  terms are relatively minor. Thus, the predominant pH correction is from the  $R_{\text{CO}_2}$  term. Without this term, Shaviv and Veizer (2003) find that there is no apparent correlation between  $\Delta T_{O18}$  and  $\Delta T_{\text{model}}$ . In other words, the correlation (i.e., agreement) between the GEOCARB III reconstruction and pH corrected temperature was obtained through bootstrapping. Any  $R_{\text{CO}_2}$  reconstruction would have contributed to a  $\Delta T_{pH}$  correction, making the  $\Delta T_{O18}$  correlate with the  $R_{\text{CO}_2}$ . That is to say, the temperature reconstruction cannot be used to claim that a  $R_{\text{CO}_2}$  fingerprint is seen. In fact, any  $R_{\text{CO}_2}$  used will imply a correlation between  $\text{CO}_2$  and  $\Delta T$  of about  $C \sim a \log_{10} 2 = 0.4^\circ\text{C}$  (or  $1.0^\circ\text{C}$  if no ice-volume effect is present), even for the extreme case where absolutely no correlation exists between  $\delta^{18}\text{O}$  and  $R_{\text{CO}_2}$  (In reality, of course, the statement that there is “no apparent correlation” between  $\delta^{18}\text{O}$  and  $R_{\text{CO}_2}$  is statistically limited, such that  $C$  has errors around the above value).

Because the correction to  $\Delta T_{O18}$  includes  $R_{\text{CO}_2}$ , a more appropriate approach should be as follows.

Let us define an “uncorrected” temperature as

$$\Delta T' = \Delta T - a \log R_{\text{CO}_2}. \quad (4)$$

This uncorrected temperature does not depend on  $R_{\text{CO}_2}$  for its reconstruction

$$\begin{aligned} \Delta T'_{O18} &= b\delta^{18}\text{O} + \Delta T_{pH} - a \log R_{\text{CO}_2} \\ &= b\delta^{18}\text{O} + a\{\log \Lambda(t) - \log \Omega(t)\}. \end{aligned} \quad (5)$$

On the other hand, when we model this uncorrected temperature, we should do so with

$$\begin{aligned} \Delta T'_{\text{model}} &= A + Bt + (C - a \log_{10} 2) \log_2 R_{\text{CO}_2} \\ &\quad + Dg(\Phi_{\text{CRF}}(t)). \end{aligned} \quad (6)$$

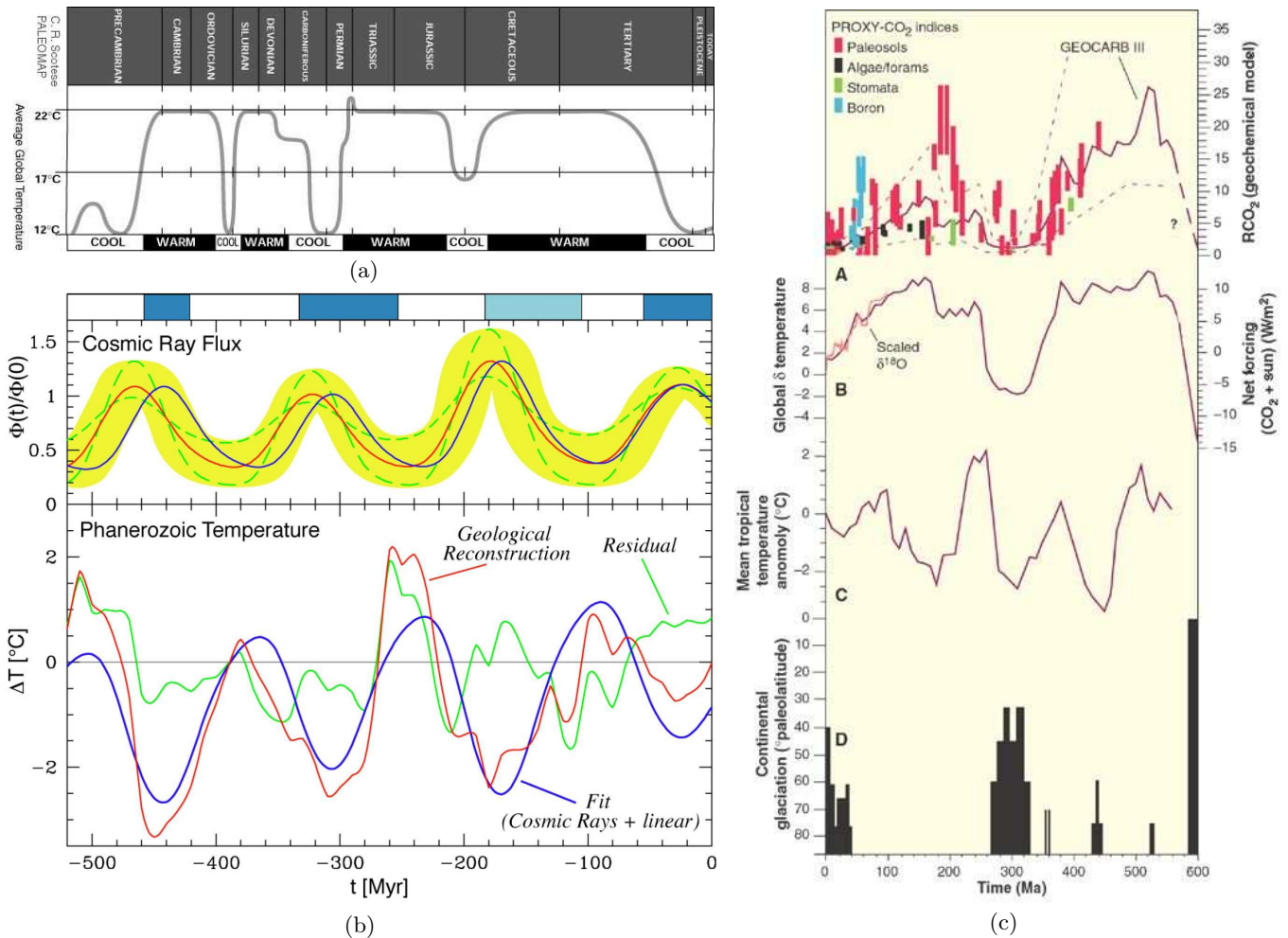


FIG. 1 The temporal reconstruction of (a) Phanerozoic climate based on the paleogeographic distribution of climate sensitive sediments and fossils (<http://www.scotese.com/climate.htm>; Boucot and Gray, 2001), (b) the trend in CRF and  $\delta^{18}O$  based on paleotemperatures (Shaviv and Veizer, 2003), and (c) the reconstructions of global temperatures and atmospheric  $CO_2$  from GEOCARB models and proxies (Crowley and Berner, 2001). Note that the “5-hump” pattern in (a) is due to the 600 Ma time span, as opposed to only the 500 Ma in (b). This is because Scotese incorporates sedimentation records from before the Cambrian, while the  $\delta^{18}O$  reconstruction requires shelly fossils which did not exist prior to the Cambrian.

We added the  $(a \log_{10} R_{CO_2}) = (a \log_{10} 2) \log_2 R_{CO_2}$  term such that we will keep the meaning of  $C$ , which is the tropical temperature increase associated with a doubled  $R_{CO_2}$ . In other words, the appropriate method to perform this analysis is to repeat the analysis of Shaviv and Veizer (2003), while correcting for the relatively small  $\log \Lambda(t)$  and  $\log \Omega(t)$  terms. To first approximation, if the latter small terms are neglected, the values of “ $C$ ” in Shaviv and Veizer (2003) should simply be replaced with  $(C - a \log_{10} 2)$ . Thus, we should add the value  $a \log_{10} 2 = 0.4^\circ C$  to the results of Shaviv and Veizer (2003), or  $0.6^\circ C$  if we wish to correct the estimates for  $\Delta T_{\times 2}$ , the globally averaged temperature increase associated with a doubled  $R_{CO_2}$ .

The lack of a correlation between  $\delta^{18}O$  and  $R_{CO_2}$  originates from the fact that  $(C - a \log_{10} 2)$  happens to be coincidentally close to 0. In other words, the pH correction to  $\delta^{18}O$  and  $\Delta T$ , happens to be similar to the trop-

ical temperature sensitivity to changes in  $R_{CO_2}$  (Without the pH correction, the preferred value for  $C$  in the absence of correlation is not  $a \log_{10} 2$ , but 0). Scientifically, this is somewhat unfortunate, because without this coincidence the  $\delta^{18}O$  signal would have had a clear correlation with the  $R_{CO_2}$  signal, and the  $R_{CO_2}$  fingerprint would have been discernible. Note nevertheless that for a global temperature sensitivity much higher than discussed above, the  $CO_2$  signal in the  $\delta^{18}O$  data should have been present, but this is not the case.

If we repeat the analysis of Shaviv and Veizer (2003), and consider also the effects of  $a \log \Lambda(t) - \log \Omega(t)$ , such correction introduces a small positive correlation between  $\Delta T'_{O_{18}}$  and  $\Delta T'_{model}$ .

We obtain:

$C = 0.69^\circ C$  (or an upper limit of 1.12, 1.42 and  $1.73^\circ C$  at 68%, 90% and 99% confidence levels, and a lower limit of 0.39, 0.10,  $-0.21^\circ C$ , respectively).

Here, the CRF can explain 70% of the variance in  $\Delta T$  (additional 11% is due to measurement error in  $\delta^{18}\text{O}$ ). That is, the CRF is still the main climate driver, while  $\text{CO}_2$  plays only a secondary role.

If we ignore the ice-volume effect and take a large  $a$ , we obtain:  $C = 1.29^\circ\text{C}$  (or an upper limit of 1.64, 1.95,  $2.26^\circ\text{C}$  at 68%, 90% and 99% confidence levels, and a lower limit of 1.07, 0.77,  $0.45^\circ\text{C}$ , respectively). In this case, the variance in  $\Delta T$  is larger, but so is the contribution of  $\text{CO}_2$ . One obtains that either the CRF or the  $\text{CO}_2$  alone can explain 49% of the total variance, while together, they can explain 83% of the variance. In this case, the relative role of  $\text{CO}_2$  is as high as that of the CRF, but the pH correction is unrealistically high, due to the neglected ice-volume correction.

The above values for  $C$  are somewhat larger than those in Shaviv and Veizer (2003), nevertheless, even with the neglected ice-volume effect, the value of  $C$  obtained is still relatively small. The best estimate for the global temperature sensitivity with ice-volume effect is  $\Delta T \sim 1.1^\circ\text{C}$  for  $C = 0.69^\circ\text{C}$ , and without it  $\sim 1.9^\circ\text{C}$ . For comparison, the “widely cited” range in the IPCC/TAR is 1.5 to  $4.5^\circ\text{C}$  (IPCC, 2001), while the global circulation models used in the IPCC/TAR, yield a range of 2.0 to  $5.1^\circ\text{C}$ . This lower estimate for climate sensitivity is supported also by 6 additional paleoclimatic sensitivity analyses by Shaviv (2004) that yield  $\Delta T_{\times 2} = 1.15 \pm 0.25^\circ\text{C}$ .

### III. CONCLUSIONS

The analysis of Royer et al. (2004) assumes an unrealistically high pH correction. First, it neglects the ice-volume effect, which changes the relation between  $\delta^{18}\text{O}$  and  $\Delta T$ . Second, this large pH correction implies high temperatures for seawater even during times of extensive glaciations.

Moreover, the analysis of Royer et al. (2004) consists of bootstrapping, by introducing a correction to  $\Delta T$  that is an implicit function of  $R_{\text{CO}_2}$ . It is then not surprising that a correlation between  $\Delta T$  and  $R_{\text{CO}_2}$  is obtained. This would be the case irrespective of the  $R_{\text{CO}_2}$  model utilized.

A proper analysis, which avoids this bootstrapping and considers a more realistic pH correction, shows that the global temperature sensitivity to  $\text{CO}_2$  is still relatively small. Such a conclusion is supported by six additional paleoclimate sensitivity analyses (Shaviv, 2004). In summary, while we acknowledge that the proposition of Royer et al. (2004) has some merit and likely will result in some modification of the  $\delta^{18}\text{O}$  signal, the CRF still remains the primary climate driver for any realistic pH correction (see also Wallmann, 2004). Even for the scenario that entirely disregards the ice-volume effect, the impact of CRF would still be at par with that of  $\text{CO}_2$ .

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