

Review of Abels et al., “Carbon isotope excursions in paleosol carbonate marking five early Eocene hyperthermals in the Bighorn Basin, Wyoming,” *Climate of the Past Discussions* (cp-2015-48)

by Brian Schubert (schubert@louisiana.edu)

General Comments:

I would like to start by saying that this work should be published. It provides valuable new terrestrial carbon isotope records across several carbon isotope excursion (CIE) events (I1, I2, ETM2, and H2) that occurred following the well-studied Paleocene-Eocene Thermal Maximum (PETM). The authors compare these records to published marine records and try to explain the proportional offsets between these two settings using the relationship between $p\text{CO}_2$ and carbon isotope discrimination in C_3 land plants (Δ_p), described within Schubert and Jahren (2012, *GCA*, 96: 29–43). I am delighted that the authors find our recent work to be useful in interpreting their records, but I identify three errors in citing of our work:

- 1) The authors twice cite Schubert and Jahren (2012) (p1863, line 14; and p 1872, line 5), but this publication is not included in their reference list.
- 2) The context suggests that the authors may have meant to have cited Schubert and Jahren (2013, *Nature Communications*, “Reconciliation of marine and terrestrial carbon isotope excursions based on changing atmospheric CO_2 levels,” doi: 10.1038/ncomms2659) with the citation of Schubert and Jahren (2012) on page 1863: that paper first showed how the $p\text{CO}_2$ effect can reconcile differences in the magnitudes between marine and terrestrial CIEs, and the analysis was applied to the PETM specifically.
- 3) Δ_p **increases** with increasing $p\text{CO}_2$ (Schubert and Jahren 2012), but the text repeatedly presents this backwards (as a **decline** in Δ_p with increasing $p\text{CO}_2$) (see: p1872, lines 5-7, 11-13; p1873, lines 13-15; p1875 lines 1-3).

A major claim by the authors is that, “In conclusion, our model results indicate that the reduction [should be **increase**] of carbon isotope fractionation in plants cannot explain the observed difference in terrestrial-marine CIE scaling for the PETM relative to the subsequent hyperthermals.” However, this conclusion is based on an incorrect assumption of static background $p\text{CO}_2$. Here I show that the $p\text{CO}_2$ effect **can** reconcile the offsets between the paleosol carbonate and marine records for all five CIEs, including the PETM, and that the $p\text{CO}_2$ levels required to do so match, in both trend and absolute value, the other $p\text{CO}_2$ proxy estimates available for this time period.

Specific Comments:

The authors recognize that background $p\text{CO}_2$ levels were likely not static throughout the study interval (p1863, 19-22), and changing $p\text{CO}_2$ across this interval is supported by recent proxy complications (e.g., Beerling and Royer 2011, *Nature Geoscience*, vol 4, their figure copied below). The $\delta^{18}\text{O}$ record (e.g., Zachos et al. 2008, *Nature*,

doi:10.1038/nature06588) also supports a general warming trend across the first ~5 million years of the Eocene (which spans the interval with the CIEs studied here), and is also at odds with an assumption of static $p\text{CO}_2$. Yet, the authors assume that background $p\text{CO}_2$ ($p\text{CO}_{2,i}$) was in fact static (p1863, 22). Static background $p\text{CO}_2$ is a fundamental assumption within Eq. (2) of their manuscript and without static $p\text{CO}_{2,i}$, the calculated values for $\Delta p\text{CO}_2$ are difficult to reconcile. I illustrate how changing $p\text{CO}_{2,i}$ yields conflicting results on the calculated values for $\Delta p\text{CO}_{2,I2}$ and $\Delta p\text{CO}_{2,H2}$ using $p\text{CO}_{2,i} = 700$ and 500 ppm for I2 and H2, respectively, and maintaining $\Delta p\text{CO}_{2,PETM}$ constant at 1000 ppm (all values within the ranges explored in this manuscript).

Equation (2) is given as:

$$\Delta p\text{CO}_{2,h} = p\text{CO}_{2,i} + \Delta p\text{CO}_{2,PETM} \times \text{CIE}_{\text{benth},h} / \text{CIE}_{\text{benth},PETM} \quad (2)$$

Using the values above, for I2:

$$\Delta p\text{CO}_{2,I2} = 700 + 1000 \times 0.73 / 3.38$$

$$\Delta p\text{CO}_{2,I2} = 916 \text{ ppm}$$

and for H2:

$$\Delta p\text{CO}_{2,I2} = 500 + 1000 \times 0.97 / 3.38$$

$$\Delta p\text{CO}_{2,I2} = 787 \text{ ppm}$$

This shows that if $p\text{CO}_{2,i}$ is not held constant (in this case $p\text{CO}_{2,i}$ increased from 500 to 700 ppm from H2 to I2), then one can calculate a bigger $\Delta p\text{CO}_2$ value for I2 (916 ppm) than H2 (787 ppm), despite a smaller CIE recorded for I2 (0.73‰) than for H2 (0.97‰). This is a problem (provided one assumes a common forcing among the events) and requires strong justification for why $p\text{CO}_{2,i}$ should be kept constant. A reference or description of from where Eq. (2) is derived is also needed.

Constant $p\text{CO}_{2,i}$ also causes significant issues when using the $p\text{CO}_2$ effect to reconcile the marine and terrestrial CIEs. The authors state on page 1873 (lines 12-15), “In conclusion, our model results indicate that the reduction [**increase**] of carbon isotope fractionation in plants cannot explain the observed difference in terrestrial-marine CIE scaling for the PETM relative to the subsequent hyperthermals.” Yet, if $p\text{CO}_{2,i}$ is allowed to change, then the $p\text{CO}_2$ effect *can* reconcile the offsets between the paleosol carbonate and marine records for all five CIEs (including the PETM). Using the data provided in Table 1, I calculate that the $p\text{CO}_2$ effect not only reconciles the offsets reported here between $\text{CIE}_{\text{benth}}$ and $\text{CIE}_{\text{paleosol}}$, but the reconstructed $p\text{CO}_{2,i}$ values I calculate match previous proxy estimates and trends across this time period, which suggest a $p\text{CO}_2$ minimum between the PETM and ETM2, followed by an increase in $p\text{CO}_2$ across the 4 events following the PETM (see Figures 1-2, below).

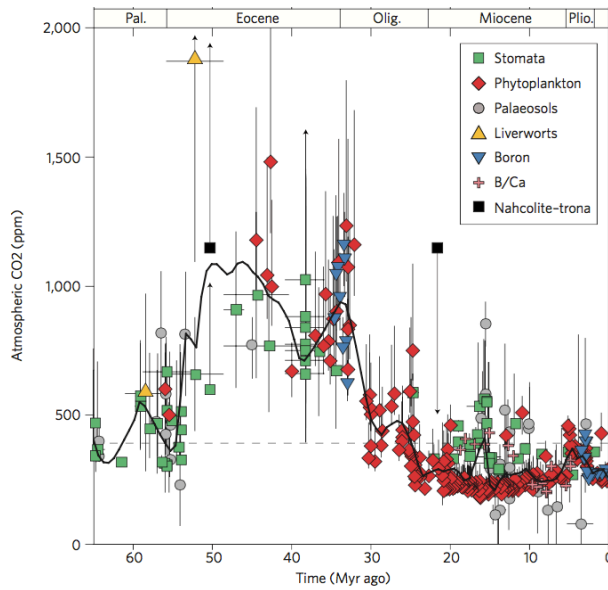


Figure 1: Cenozoic $p\text{CO}_2$ proxy data. This figure is copied from Beerling and Royer (2011). Note the $p\text{CO}_2$ minimum near 55 Ma, followed by an increase in $p\text{CO}_2$ across the early Eocene.

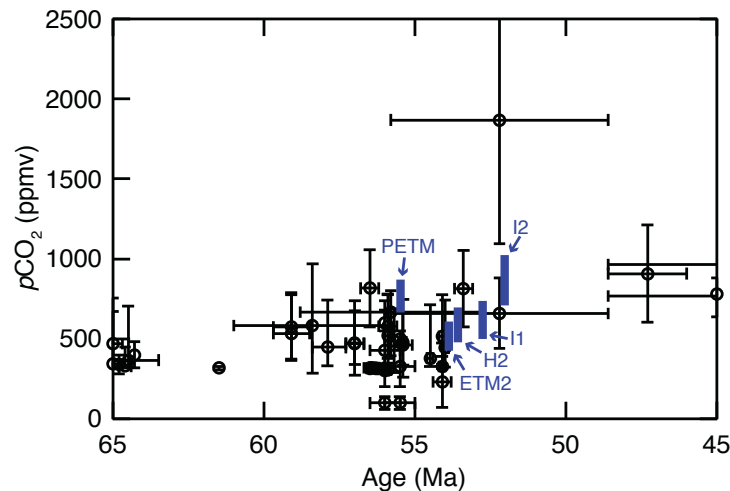


Figure 2: This is an inset of Figure 1 (above) showing background $p\text{CO}_2$ levels only from 65 to 45 Ma. Black symbols show proxy data compiled within Beerling and Royer (2011, same data in Figure 1, above). Blue bars show $p\text{CO}_{2,i}$ reconstructed following the methods described within Schubert and Jahren (2013) using $\text{CIE}_{\text{paleosol}}$ and $\text{CIE}_{\text{benthic}}$ data from Table 1 of Abels et al., (in review, *CPD*) and $\delta^{13}\text{C}_{\text{source}} = -30$ to -60‰ (i.e., $\Delta p\text{CO}_2 = 937$ to 2102 ppm). Values for $p\text{CO}_{2,h}$ are not shown. Note that the $p\text{CO}_{2,i}$ values reconstructed using the $p\text{CO}_2$ effect (blue bars) are similar to other $p\text{CO}_2$ values (black) in both trend and absolute value. I note that $p\text{CO}_{2,i}$ for the PETM decreases to 267 to 372 ppm if $\text{CIE}_{\text{paleosol}} = 9.5\text{‰}$ (the extrapolated value) is used. The ages for the CIEs are based on Chen et al., (2014, *GRL*).

Similar to the authors' work, my above calculations assume no changes in environmental conditions (e.g., climate, plant communities, productivity) and attribute the entire offset between CIE_{paleosol} and CIE_{benthic} as being caused by the pCO_2 effect. However, as the authors correctly identify, this assumption may not be valid, especially when looking at individual sites, as is the case here. For example, the authors cite evidence for drying in their study region during the PETM (and they find little precipitation change for the other CIEs). Drying could dampen the magnitude of the CIE at the PETM at this site through diminished carbon isotope fractionation and reduced productivity.

Evidence for drying and a dampening of the CIE at the PETM is also provided by the n-alkane $CIE = 4.2\text{‰}$ for this site. This value is smaller than most of the other reported n-alkane CIEs for the PETM (median = 5.0‰ , McInerney and Wing, 2011), which is also consistent with drying. In fact, using a larger CIE (e.g., 5.0‰ versus 4.2‰) gives a better match across lower $pCO_{2,i}$ between the model estimated terrestrial CIE and the measured value than is shown in Fig. 5A of the text. All else being equal, increasing the absolute magnitude of the terrestrial CIE results in a lower $pCO_{2,i}$.

I am somewhat confused, however, to how Figure 5 of the text is presented. Panel A shows how well the pCO_2 effect reconciles a 4.2‰ magnitude terrestrial CIE and panel B shows how well it reconciles a 9.5‰ magnitude terrestrial CIE. It is noted that for panel B, that the pCO_2 effect cannot reconcile this large of a CIE within the explored parameter space (bottom of p1872); however, the pCO_2 effect *can* reconcile this 9.5‰ CIE with the 3.38‰ benthic CIE outside of this parameter space (e.g., $pCO_{2,i} = 267$ to 372 ppm and $\Delta pCO_2 = 937$ to 3145 ppm). As shown in Figure 2 (above), $pCO_{2,i}$ values in this range are not inconsistent with previous proxy estimates for background pCO_2 in the late Paleocene. I do not understand why these plots are limited to $pCO_{2,i} > 500$ ppmv? The Y-axis should be extended to include lower $pCO_{2,i}$.

Further, it is not clear to me what the authors are trying to demonstrate with the comparison of Figure 5A and 5B. On page 1873, lines 1-5, the authors imply that $pCO_{2,i}$ and ΔpCO_2 should match across Fig. 5A and 5B. However, these cannot match nor should they match, as widely different CIE values are used in both (4.2‰ from n-alkanes *versus* 9.5‰ from extrapolated paleosol values). Schubert and Jahren (2013) pointed out that "The very large CIE measured in paleosol carbonate (average = -5.5‰ , median = -6.3‰) may reflect a combination of the enhanced fractionation by plants under high pCO_2 , diffusion of increased pCO_2 levels into the soil and increased productivity." Such a claim could be made here as well that the paleosol carbonate CIE reflects the pCO_2 effect plus additional affects from a change in productivity. Thus, the paleosol $CIE = 5.9\text{‰}$, while the n-alkane $CIE = 4.2\text{‰}$ for the same site.

Technical Corrections:

The constants in Eq. (1) have been updated within Schubert and Jahren (2015, *Geology*, doi: [10.1130/G36467.36461](https://doi.org/10.1130/G36467.36461)). The changes are very minor and do not affect the results of this manuscript. I only point this out to the authors if they apply this work further.

Please provide reference(s) for fractionation values of -24 to -28‰ and -7 to -11‰ for C₃ and paleosol carbonate, respectively (p1861, lines 5-8). Also, the values for Δ_p are reported here as being negative values. Are these describing $\delta^{13}\text{C}$ values or Δ_p values? Normally, Δ_p values are positive (e.g., see Farquhar 1989, *Annual Review of Plant Physiology and Plant Molecular Biology*). It may be useful to define or provide the equation used for Δ_p at its first mention in the text.

Page 1859, line 27: Change “other than” to “in addition to”.

Page 1861, lines 8-13: Please add reference to Schubert and Jahren (2013).

Page 1863, lines 4-8: “How were the standard errors for the marine and terrestrial CIEs calculated?”

Page 1865, 9-10: Please describe the methods (or provide a reference) for how the bandpass filtering was done.

P1871, 3-5: I see how the anomaly of 3.6‰ was calculated ($9.5 - 5.9 = 3.6\%$), but how was the anomaly of 2.1‰ calculated?

P1871, 5-8: McNerney and Wing (2011) show no difference in the size of the CIE between benthic and planktic forams (Benthic: range = -0.6 to -5.1‰, mean = $-2.5 \pm 1.0\%$, median = -2.6‰, n = 36; Planktic: range = -0.7 to -4.4‰, mean = $-2.7 \pm 1.0\%$, median = -2.6‰, n = 36). Can you please expand on the claim for a larger CIE in planktic than benthic forams?

P1871, line 16: Add Schubert and Jahren (2013).

What is the explanation for why the data for the PETM, ETM2, and H2 scaled linearly in Abels et al. (2012), but do not scale linearly here (granted it is only three points, but the relationship between $\text{CIE}_{\text{benthic}}$ and $\text{CIE}_{\text{paleosol}}$ for these three events looks fundamentally different)?