

1 Comment on *The Plio-Pleistocene climatic evolution as a*
2 *consequence of orbital forcing on the carbon cycle* from D.
3 Paillard, Clim. Past Discuss., doi:10.5194/cp-2017-3, 2017

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5 March 8, 2017

6 The paper of Paillard investigates the Plio-Pleistocene carbon cycle by setting up a concep-
7 tual model, consisting of differential equation for the carbon content of the atmosphere-ocean-
8 biosphere C , the alkalinity of the ocean, A , and the stable carbon isotope values of C , $\delta^{13}C$.

9 The analysis starts with the following equation for temporal changes in the carbon content of
10 the system

$$\frac{\delta}{\delta t}C = V - B - D \quad (1)$$

11 with V being the volcanic carbon input, B the organic carbon burial, D the oceanic carbonate
12 deposition flux. Furthermore, the assumption that carbonate compensation will restore on
13 multi-millennial years time scale the carbonate ion concentration is used. Here, the implicit
14 used knowledge that alkalinity A changes might be approximated after $\frac{\delta}{\delta t}A = W - 2D$ was used
15 (but not mentioned explicitly) to final end with

$$\frac{\delta}{\delta t}C = 2(V - B) - W \quad (2)$$

$$\frac{\delta}{\delta t}(\delta^{13}C) = (V(-5 - \delta^{13}C) - B(-25 - \delta^{13}C))/C \quad (3)$$

16 with W being the silicate weathering rate. According to the manuscript, the terms in brackets
17 in Equation 3 are meant to be the following:

- 18 • $(-5 - \delta^{13}C)$: a volcanic source with constant isotopic signature of -5% ,
- 19 • $(-25 - \delta^{13}C)$: a constant -25% fractionation of organic matter with respect to the mean
20 $\delta^{13}C$ of the considered system.

21 I find the conceptual idea how to understand the observed long-term changes in the carbon
 22 cycle very interesting. However, I have some fundamental comments to Equation 3 describing
 23 the evolution of the the carbon isotope of the system:

- 24 1. The term $(-5 - \delta^{13}C)$ in Equation (2) does not serve to describe the volcanic source
 25 with the constant isotopic signature of -5‰ source as intended, but as some isotopic
 26 fractionation by -5‰ with respect to the negative of the mean isotopic values $\delta^{13}C$ of the
 27 atmosphere-ocean-biosphere system.
- 28 2. The author decides to follow the initial Equation 1 when setting up the changes in the
 29 carbon isotopes. This approach is not wrong, but neglecting any impacts of the carbonate
 30 deposition flux D on $\delta^{13}C$ might be too simple.
- 31 3. It is not clear to me, why in Equation 3 the isotopic signature of both fluxes B and V are
 32 described as a function of negative $\delta^{13}C$.
- 33 4. Changes in the isotopic value are always also depending on the content of the system. This
 34 implies that the differential equation has to be treated with care. In detail, one has to
 35 take into account, that when solving $\frac{\delta}{\delta t}(\delta^{13}C)$, one has to find a solution for $\frac{\delta}{\delta t}(C \cdot \delta^{13}C)$.
 36 Following the product rule, it follows:

$$\frac{\delta}{\delta t}(C \cdot \delta^{13}C) = C \cdot \frac{\delta}{\delta t}(\delta^{13}C) + \delta^{13}C \cdot \frac{\delta}{\delta t}(C) \quad (4)$$

37 Solving for $\frac{\delta}{\delta t}(\delta^{13}C)$ gives:

$$\frac{\delta}{\delta t}(\delta^{13}C) = \left(\frac{\delta}{\delta t}(C \cdot \delta^{13}C) - \delta^{13}C \cdot \frac{\delta}{\delta t}(C) \right) \cdot \frac{1}{C} \quad (5)$$

$$\frac{\delta}{\delta t}(\delta^{13}C) = \left(\text{RHS of DE} - \delta^{13}C \cdot \frac{\delta}{\delta t}(C) \right) \cdot \frac{1}{C} \quad (6)$$

38 The first term in equation (5), $\frac{\delta}{\delta t}(C \cdot \delta^{13}C)$, is what is typically found on right-hand sides
 39 of differential equations (RHS of DE). The 2nd term in equations (5,6), $-\delta^{13}C \cdot \frac{\delta}{\delta t}(C)$, is
 40 probably small and might be negligible. However, its existence and any assumptions on
 41 neglecting it should in my view be mentioned for the sake of completeness.

- 42 5. When setting up differential equations for isotopes in the so-called δ -notation one typically
 43 starts with the equation for the matter fluxes and multiplies each matter flux with the
 44 assumed isotopic signature of the flux, including any potential isotopic fractionation. With
 45 respect to the problem at hand (starting with equation 1) I end up with the following
 46 differential equation for $\delta^{13}C$:

$$\frac{\delta}{\delta t}(\delta^{13}C) = \left(V \cdot \delta^{13}C_V - B \cdot \delta^{13}C_B - D \cdot \delta^{13}C_D - \delta^{13}C \cdot \frac{\delta}{\delta t}(C) \right) \cdot \frac{1}{C} \quad (7)$$

47 According to the manuscript I get $\delta^{13}C_V = -5\text{‰}$ and $\delta^{13}C_B = \delta^{13}C - 25$. The argument
 48 that isotopic signature of the carbonate burial flux D is identical to $\delta^{13}C$ of the system can
 49 be used to define $\delta^{13}C_D = \delta^{13}C$. Using the knowledge from the carbonate compensation
 50 that $D = W + B - V$ finally gives me a new equation for changes in the isotopic signature:

$$\frac{\delta}{\delta t}(\delta^{13}C) = \left(V \cdot (-5) - B \cdot (\delta^{13}C - 25) - (W + B - V) \cdot \delta^{13}C - \delta^{13}C \cdot \frac{\delta}{\delta t}(C) \right) \cdot \frac{1}{C} \quad (8)$$

51 I show in Figure 1 for the simplest scenario without long-term trend in CO_2 and the
 52 Amazon-like organic burial that both approaches (Paillard: Eq. 3; this comment: Eq. 8)
 53 lead to slightly different results, but they agree on large scale features. This comparison
 54 would therefore suggest, that the simplifications done in the setting up of the differential
 55 equation for the changes in the carbon isotopes by Paillard might be justified (even if I do
 56 not yet understand them in detail). However, I still believe that setting up the differential
 57 equation for the carbon isotope the way I describe above might be a way which is at least
 58 better to understand and easier to reproduce.

59 I like to finish with some more general comments:

- 60 1. Another simplification of the setup is the estimation of the change in atmospheric CO_2
 61 mixing ratio by

$$\text{CO}_2 = 280 \cdot \left(\frac{C}{40,000 \text{ PgC}} \right)^2 \quad (\text{in ppm}). \quad (9)$$

62 This equation was given without any further motivation. However, since all inputs of
 63 carbon to the system are given by volcanic CO_2 outgassing into the atmosphere, one
 64 might also evaluate the corresponding changes in atmospheric CO_2 concentration by the
 65 so-called airborne fraction, the fraction of injected carbon that stays in the atmosphere.
 66 With the given equation for CO_2 above (Eq. 9), this airborne fraction turns out to be
 67 around 3%. For example, a rise in C by 100 PgC, for example, would lead to a new CO_2
 68 mixing ratio of 281.4 ppm. Following the well known relation of 1 ppm of $\text{CO}_2 = 2.12 \text{ PgC}$,
 69 this rise in CO_2 by 1.4 ppm is similar to a rise in atmospheric carbon by nearly 3 PgC, thus
 70 3% of the initial perturbation. The long-tail of the airborne fraction for potential future
 71 CO_2 emissions was recently investigated systematically with the GENIE Earth System
 72 Model. It was found (Equation S1 and Table S2 in Lord et al. (2016)) that the airborne
 73 fraction is around 5% and 1.6% on a timescale of 10^5 and 10^6 years, respectively. Thus, the
 74 so-far unmotivated assumption for CO_2 as given in Equation (7) above might be supported
 75 with such results but also illustrates, that variabilities faster than several 10^5 years are
 76 not contained in this approximation of CO_2 given in Eq. 9.

- 77 2. Some of the assumptions are rather implicit and not supported with any further details or
78 citations. The assumption that ocean alkalinity changes are approximated as changes in
79 carbonate alkalinity by only considering variations in the carbonate ion concentration as
80 $W - 2D$ was already mentioned above, and might find support in Zeebe and Wolf-Gladrow
81 (2001). Furthermore, the assumption that the monsoon response to astronomical forcing
82 as a simple function of the precessional forcing after $F_0 = \max(0, -e \cdot \sin(\omega))$ needs some
83 backup from proxy reconstructions. References for the assumed isotopic signature of -5%
84 for volcanic outgassing V and for the fractionation of -25% in the organic burial flux B
85 would also be highly welcome.
- 86 3. The assumed long-term trend in weathering via the parameter γ leads only to a decrease
87 in carbon content and CO_2 . Thus, to really mimic the multi-million decrease in CO_2
88 from 350 ppm 4 Myr ago to 280 ppm in the preindustrial time one needs also to increase
89 the overall carbon content of the system at the beginning of the simulations. This is not
90 mentioned. Otherwise CO_2 would start during scenarios which include this trend ($\gamma > 0$)
91 at 280 ppm at the start of the simulations 4 Myr ago and decrease thereafter.
- 92 4. To reconstruct the carbon cycle in detail it would be helpful for the reader to be provided
93 with the finally chosen parameter values.

94 References

- 95 Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., and Levrard, B.: A long
96 term numerical solution for the insolation quantities of the Earth, *Astronomy and Astro-*
97 *physics*, 428, 261–285, doi:10.1051/0004-6361:20041335, 2004.
- 98 Lord, N. S., Ridgwell, A., Thorne, M. C., and Lunt, D. J.: An impulse response function for
99 the long tail of excess atmospheric CO_2 in an Earth system model, *Global Biogeochemical*
100 *Cycles*, 30, 2–17, doi:10.1002/2014GB005074, 2016.
- 101 Zeebe, R. E. and Wolf-Gladrow, D. A.: CO_2 in Seawater: Equilibrium, Kinetics, Isotopes,
102 vol. 65 of *Elsevier Oceanography Book Series*, Elsevier Science Publishing, Amsterdam, The
103 Netherlands, 2001.

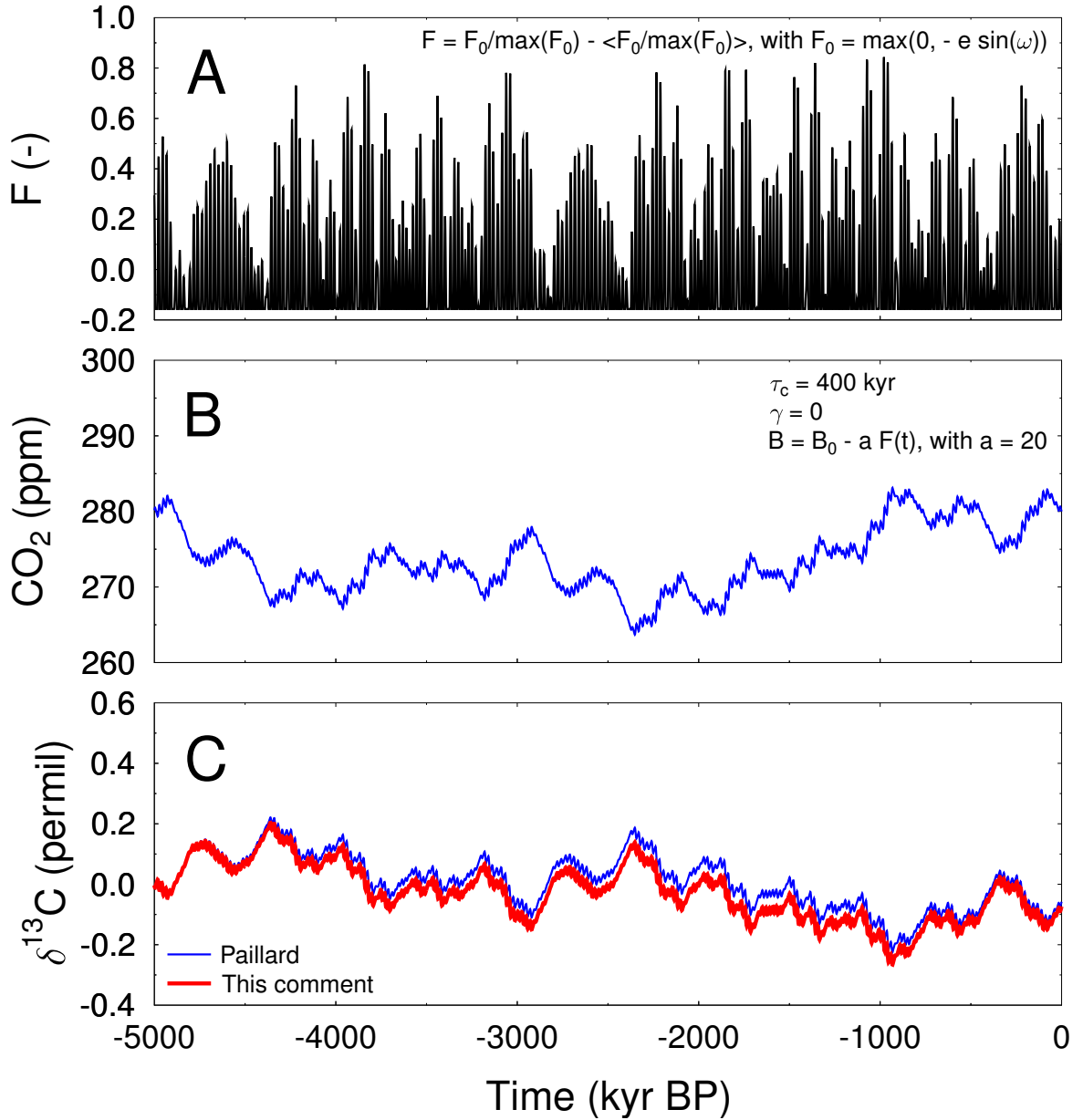


Figure 1: Rebuilding the model of Paillard. A: Dimensionless orbital forcing function F with an amplitude of 1 and a mean value of 0 based on Laskar et al. (2004). B: Change in atmospheric CO_2 concentration (following Eq. 9 of this comment) for the Amazon-like burial of organic carbon ($B = B_0 - aF(t)$, $a = 20$). No long-term trend in CO_2 is considered ($\gamma = 0$) and the carbon fluxes W , V , B are determined from the carbon turnover time of $\tau_C = 400$ kyr. C) Changes in $\delta^{13}\text{C}$ of the same Amazon-like burial scenario following either Paillard (Eq. 3) or this comment (Eq. 8).