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## ***Interactive comment on “The Plio-Pleistocene climatic evolution as a consequence of orbital forcing on the carbon cycle” by Didier Paillard***

**P. Köhler**

[peter.koehler@awi.de](mailto:peter.koehler@awi.de)

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Please also note the supplement to this comment:

<http://www.clim-past-discuss.net/cp-2017-3/cp-2017-3-SC1-supplement.pdf>

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Discussion paper



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

4 Peter Köhler

Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung (AWI)

P.O. Box 12 01 61, 27515 Bremerhaven, Germany

email: Peter.Koehler@awi.de, Tel: +49 471 4831 1687

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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  $-5\text{‰}$  source as intended, but as some isotopic  
 26 fractionation by  $-5\text{‰}$  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  $\delta$ -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  $\text{CO}_2$  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  $\text{CO}_2$   
 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  $\text{CO}_2$  outgassing into the atmosphere, one  
 64 might also evaluate the corresponding changes in atmospheric  $\text{CO}_2$  concentration by the  
 65 so-called airborne fraction, the fraction of injected carbon that stays in the atmosphere.  
 66 With the given equation for  $\text{CO}_2$  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  $\text{CO}_2$   
 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  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  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  $\gamma$  leads only to a decrease  
87 in carbon content and  $\text{CO}_2$ . Thus, to really mimic the multi-million decrease in  $\text{CO}_2$   
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  $\text{CO}_2$  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.

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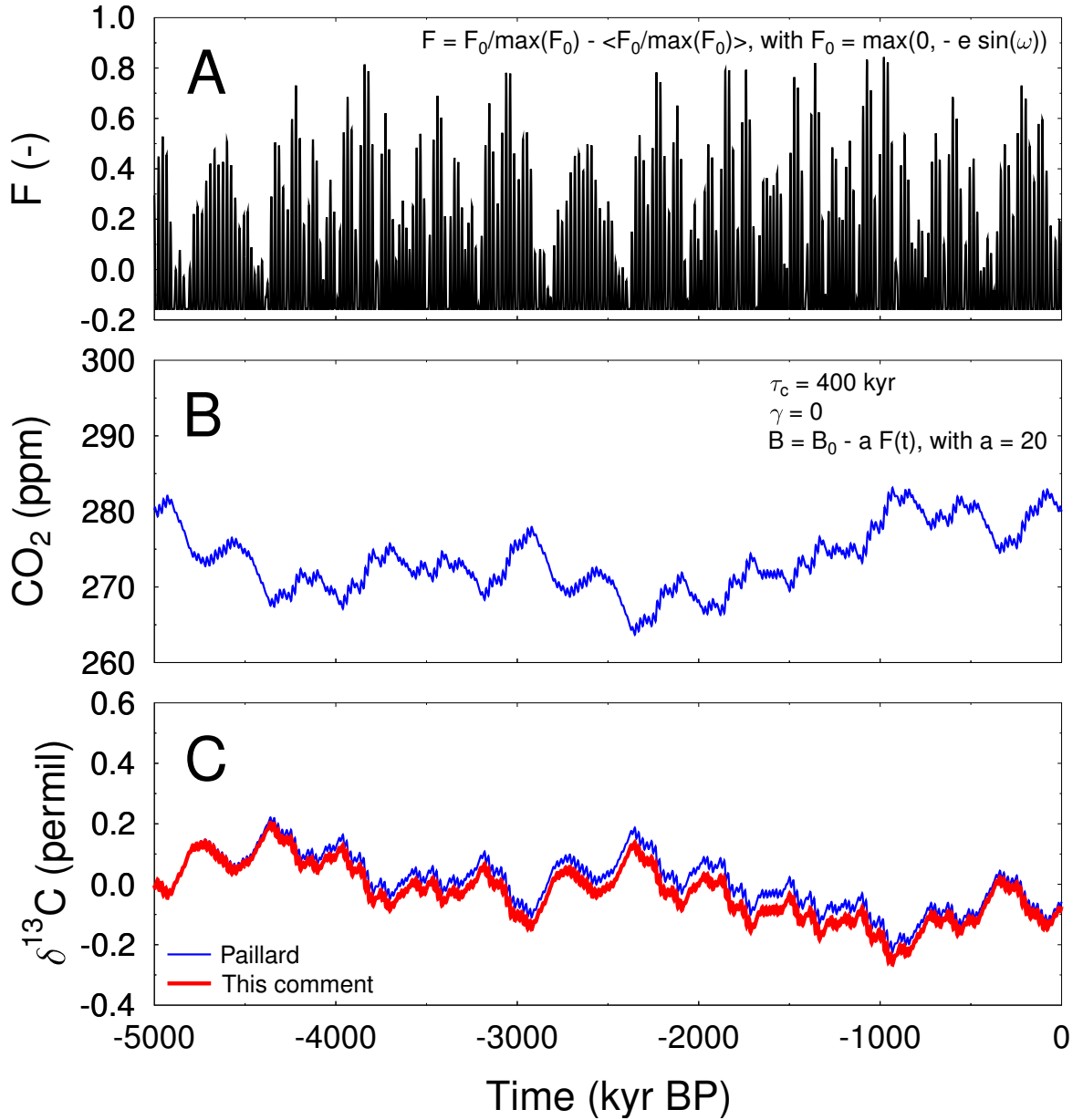


Figure 1: Rebuilding the model of Paillard. A: Dimensionless orbital forcing function  $F$  with an amplitude of 1 and a mean value of 0 based on Laskar et al. (2004). B: Change in atmospheric  $\text{CO}_2$  concentration (following Eq. 9 of this comment) for the Amazon-like burial of organic carbon ( $B = B_0 - aF(t)$ ,  $a = 20$ ). No long-term trend in  $\text{CO}_2$  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).