The Carbon Cycle as the Main Determinant of Glacial-Interglacial Periods

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Abstract

An intriguing problem in climate science is the existence of Earth’s glacial cycle. We show that it is possible to generate these periodic changes in climate by means of the Earth’s carbon cycle as the main source factor. The carbon exchange between the Ocean, the Continent and the Atmosphere is modeled by means of a Lotka-Volterra three species system and the resulting atmospheric carbon cycle is used as the unique radiative forcing mechanism. It is shown that the carbon dioxide (CO2) and temperature paths that are thus obtained have the same qualitative structure as the 100 kyr glacial-interglacial cycles depicted by the Vostok ice core data, reproducing the asymmetries of rapid heating–slow cooling, and short interglacial–long glacial ages.

Keywords: glacial cycles, carbon cycle, Lotka-Volterra

1. Introduction.

For the last 3 million years the Earth - and thus its climate- has cycled from having a large volume of ice covered surface, or glacial periods, to intervals with smaller ice volumes and milder temperatures, or interglacial ages. Adhémar and Croll, both in the XIX century, suggested that Earth’s orbital changes could be responsible for the glacial cycle[1] as quoted by Paillard (2001). However, it was not until the following century that M. Milanković took up the study of the orbital theory of climate in a series of seminal papers (Milanković (1920, 1930b,a), and later translation Milanković (1998)).

Milanković recognized the importance of periodic changes in orbital parameters - mainly eccentricity, obliquity and precession- in Summer insolation in the Northern Hemisphere. This insolation forcing triggers an ice-albedo feedback mechanism which has been a popular explanation for driving the glacial cycles (Hays et al., 1976; McGehee and Lehman, 2012).

The glacial cycles started off as having a 41 kyr period and being essentially symmetric during the Pliocene, but about one million years ago the period changed to 100 kyr, the amplitude became greater and the cycles became asymmetric: glaciations develop slowly and warm periods arise in a very short time, geologically speaking. This structural change is referred to as the mid-Pleistocene transition (McGehee and Lehman, 2012; Huybers, 2007; Ashkenazy and Tziperman, 2004; Tziperman and Gildor, 2003).

Given that orbital parameters have remained essentially unchanged, the mid-Pleistocene transition needs to be explained by phenomena other than insolation. In particular, ice sheet dynamics, Ocean circulation, nonlinear responses and carbon dioxide (CO2) may also play a strong role in driving glacial cycles (Paillard, 2001; Huybers, 2007; Ikeda and Tajika, 1999; Tajika, 1998).

The role of CO2 as a determinant of climate has been acknowledged since John Tyndall in 1861, who studied the absorption properties of several gases, in particular CO2 and water vapor (Heringshaw, 1888), up to the most recent IPCC (2012) assessment reports. However, its impact over the glacial cycles of the past million years remains somewhat obscure. Recently, Hogg (2008) proposed a feedback mechanism in which the carbon cycle is a function of temperature. His model manages to reproduce some main features of the glacial cycles; nonetheless, the cycles themselves are still triggered by changes in orbital parameters and carbon only has an effect on their amplitude.

In this work we propose a simple model for the carbon cycle that could account for the 100 kyr asymmetric glacial cycles depicted in the data from the Vostok ice core (Petit et all, 1999). The aim is to show that the Earth’s “metabolism” (Steffen, 2000) could be the main determinant of climate; consequently, CO2 variations would be much more than just an amplifying mechanism in the cli-
mate system, but rather the main driving factor. In this way, this work contributes in underlining the importance of CO$_2$ in producing climate changes (Shakun et al. 2012).

Following the work of the International Geosphere and Biosphere Programme, we may think of the Earth’s Biogeophysicochemical processes in a holistic way (Falkowski et al. 2000; Steffen 2000). The ice core records, such as Vostok’s (Petit et al. 1999), depict temperature, CO$_2$ and methane data that resemble a rhythmic metabolic pattern. Just as the Earth’s short term orbital/insolation features are embedded into our human metabolism, the long term orbital/insolation changes must be an integral part of the Earth’s metabolism. It is the planet’s metabolic process that is proposed as the primary driving factor for the climate system. Steffen (2000) presents a simple qualitative description about how this complex system works. We shall bypass the complexities to construct a simple model describing the CO$_2$ and temperature oscillations from the time series extracted from the Vostok Ice Cores.

2. The Vostok Ice core time series

Here we give a brief description of the Vostok Ice Core Time Series, we shall concentrate exclusively on the CO$_2$ and temperature series.

There are two time series belonging to the variables of interest: CO$_2$ in ppmV and temperature (deviation from the mean at Antarctic Vostok station), $\Delta T$, in Celsius, extracted using $\delta$O$^{18}$ as a proxy as described in Petit et al. (1999). In figure 1 we present both time series with time labeled from 0 (the deepest data and therefore the oldest one) to the most recent data. Data and the depth-age correlation were downloaded from NOAA-NGDC (Petit et al., 2000).

The time series display the following well known striking features (McGehee and Lehman 2012; Petit et al. 1999; Steffen 2000; Falkowski et al. 2000):

1. Both are periodic: There are four cycles with five maxima and four minima regularly distributed along temporal record.
2. Both are (almost) in phase (Garduño et al. 2005), that is, main and secondary extrema are matched over time. This implies a correlation between $\Delta T$ (and therefore $T$) with the concentration of CO$_2$ along the milenia time scale.
3. Both are bounded. This feature, together with periodicity, shows that the climatic system oscillates between two extremal states along the time record analyzed (Petit et al. 1999; Steffen 2000).
4. There is an asymmetry in the cycles: Heating seems to occur very fast while cooling is slow.
5. Closely related with the previous asymmetry, we observe that interglacials are short but glacial periods are long.

3. The model

A qualitative explanation of the glacial-interglacial cycles (Falkowski et al. 2000; Steffen 2000) may be described in a short stylized version as follows: starting near a peak in the time series, surface temperature and atmospheric CO$_2$ are at their highest. Increased precipitation causes a surge in continental biomass and carbon is transferred to the continent until a saturation level is reached. At that point, triggered by runoff, the Ocean takes control absorbing CO$_2$ and creating Oceanic biomass. Atmospheric temperature and CO$_2$ drop until the Ocean reaches its saturation level and the process is now reversed. In this scenario, the “control switching” between the Ocean and the continent -mediated by the Atmosphere- is the main driver of the glacial cycles.

On the same token, radiative forcing and CO$_2$ involve the following basic subsystems driving the Earth’s climate system: water cycle, trophic chain, carbon cycle and energy chain. However, the Vostok time series only provide us with carbon and temperature data (carbon cycle and energy chain). Thus, the water cycle and trophic chain will not be considered explicitly, though their impact is embedded into the model parameters. The modeling of the carbon cycle and energy chain will be simplified by the following assumptions:

- A generic carbon, representing the set of carbon compounds, is the one that participates in the carbon cycle. The transformations between different compounds are of no interest since they are internal to three carbon reservoirs: Continent ($C_1$), Atmosphere ($C_2$) and Ocean ($C_3$). All the carbon that is being considered participates in the cycle, that is, for our purposes carbon that is not transferred between the different reservoirs is not relevant.
- The energy chain assumes a constant radiative input from the Sun, the Earth a spherical blackbody with the Atmosphere being “gray” to long-wave radiation. Energy reservoirs consist of surface ($S$) and Atmosphere ($A$). The temperature obtained will be a mean global temperature.
- We consider that phenomena driving all the relevant processes are bounded and continuous with continuous derivatives.
- The surface temperature is determined, as usual, by means of the energy chain and radiative equilibrium.
- The planetary albedo and atmospheric absorption and emission are dependent on the carbon content, thus linking the carbon cycle and the energy chain. These parameters respond to the carbon content, not in an exponential way, but in a logistic fashion. More details will be provided below when we model the energy chain.
3.1. Modelling the carbon cycle.

We assume that the Ocean and Continental reservoirs cycle carbon between them with the Atmosphere acting as a conduit. Additionally, only a fraction of the carbon stock in each reservoir participates in this process. In the time span covered by the Vostok data, the carbon content in each of the reservoirs cycles with the same periodicity (100 kyr) and these flows are not entirely linear.

In our model, the stocks refer to the relative (dimensional) carbon content in each of the reservoirs, that is, $C_1$, $C_2$ and $C_3$, where $0 \leq C_i \leq 1$ represents the fraction of total carbon in each reservoir. The Continent loses carbon by a runoff process at a rate $\alpha$ and gains or loses carbon due to interaction with the Atmosphere at a rate $\beta$. The Ocean loses and acquires carbon by dissolution and outgassing to and from the Atmosphere, at a rate $\varepsilon$. Additionally, Oceanic carbon increases at a rate $\eta$ due to various internal processes.

The parameters $\alpha$, $\beta$, $\varepsilon$ and $\eta$ are dependent on temperature in a logistic fashion: the values of $\beta$ and $\varepsilon$ oscillate between positive and negative values depending on whether we are in a glacial or interglacial period and $\alpha$, $\eta > 0$.

The equations that represent the above interactions are given by:

\[
\begin{align*}
\dot{C}_1 &= -\alpha C_1 + \beta C_1 C_2, \\
\dot{C}_2 &= -\beta C_1 C_2 + \varepsilon C_2 C_3, \\
\dot{C}_3 &= \eta C_3 - \varepsilon C_2 C_3.
\end{align*}
\]

We notice that the above equations resemble a predator-prey Lotka-Volterra system for three species. It is worth mentioning that a well-known fact about these systems is that they generate phase-shifted asymmetric cycles, which is exactly what we are looking for. In this context, Oceanic carbon is the lowest trophic level prey and Continental carbon the predator, with atmospheric carbon serving as a go-between.

In order to simplify the model we may consider an average constant value of the parameters, in which case $\beta$ and $\varepsilon$ will be positive constants; that is, the net effect of carbon fluxes between the reservoirs is that the Continent absorbs carbon from the Atmosphere which in turn absorbs carbon from the Ocean. For compensating the lack of oscillation of $\beta$ and $\varepsilon$, a new constant parameter, $\gamma$, dependent on $\alpha$, $\beta$, $\varepsilon$ and the initial conditions, must be introduced. To generate cycles we must have that the survival ratio for $C_1$, $-\alpha/\beta$, should be the same as the survival ratio for $C_3$, $\eta/\varepsilon$, which implies that $\eta = \alpha \varepsilon/\beta$. In this case $C_1$, $C_2$ and $C_3$ all “coexist” and vary periodically over time (Chauvet et al., 2002).

The final system describing this carbon cycle is given by:

\[
\begin{align*}
\dot{C}_1 &= -\alpha C_1 + \beta C_1 C_2, \\
\dot{C}_2 &= \gamma C_2 - \beta C_1 C_2 + \varepsilon C_2 C_3, \\
\dot{C}_3 &= \frac{\alpha \varepsilon}{\beta} C_3 - \varepsilon C_2 C_3.
\end{align*}
\]

3.2. Modeling the energy chain.

An energy balance model is built assuming incoming shortwave (UV and visible) radiation reaching the Earth’s surface and longwave (IR) radiation being reemitted. We consider two reservoir variables, $S$ and $A$, corresponding to energy densities ($\text{Jm}^{-2}$) for the surface and for the Atmosphere (Deaton and Winebrake, 2000). Let $\Omega_{\odot}$ be the solar flux ($\text{Wm}^{-2}$), $a_1$ the planetary albedo, $a_2$ the fraction of...
nonradiative energy from the surface (thermal processes), $a_3$ the fraction of surface radiative flux absorbed by the Atmosphere (the rest goes out into space), $a_4$ the fraction of atmospheric flux radiated and absorbed by the Continent (the rest also goes into space). Adding all inflows and outflows for both reservoirs, assigning units of inverse time ($s^{-1}$) for $a_2$, $a_3$ and $a_4$, normalizing the constant $\Omega \odot$ to one and simplifying, we obtain the following flow equation for the reservoirs:

\[
\begin{align*}
\dot{S} &= (1 - a_1) + a_4 A - S, \\
\dot{A} &= (a_2 + a_3 (1 - a_2)) S - A.
\end{align*}
\]  

(3)

We note that $S$ and $A$ are adimensional quantities depending only on time, $t$. Not all the parameters in the above equations are constant, in particular, we shall assume that $a_1, a_3$ and $a_4$ are dependent on the atmospheric carbon content ($C_2$), thus linking the energy chain and the carbon cycle. This dependence is via the logistic solution function

\[
a_i(C_2) = \frac{1}{1 + \left(\frac{1}{a_0} - 1\right) e^{-r_i (C_2 - C_{2\text{ref}})}},
\]  

(4)

where $r_1 < 0$ and $r_{2,3,4} > 0$. This functional form allows for carbon to affect the way the Atmosphere radiates and absorbs energy to and from the surface, with more carbon causing an increase in $a_3$ and $a_4$ up to a saturation level. The quantity $C_{2\text{ref}}$ is a known magnitude for CO$_2$, and we use today’s value in order to determine a particular solution for the coefficients $a_i$.

Though it is fairly standard to have the absorption and emission properties of the Atmosphere dependent on carbon content, the effect on the planetary albedo is typically not considered. We use results showing that global mean albedo decreases in response to CO$_2$ reverse forcing [Bender, 2004].

Surface mean temperature (in Celsius) is calculated using Stefan-Boltzmann law as:

\[
T(t) = \left(\frac{1 - a_2 S \Omega \odot}{\sigma}\right)^{\frac{1}{4}} - 273.15
\]  

(5)

where $\sigma$ is Stefan-Boltzmann constant.

### 4. Simulation and results

The above system given by equations (1) and (3), together with (4), was solved numerically. The initial conditions for the energy chain ($S_0$ and $A_0$) were extracted and modified from similar problems in the literature [Deaton and Winebrake, 2000]. Additionally, considering the current value of $C_{2\text{ref}} = 387$ ppmv, we obtain: $a_{1,0} = 0.313$, $a_{2,0} = 0.207$, $a_{3,0} = 0.897$, $a_{4,0} = 0.624$. Unfortunately, initial conditions for the carbon cycle were difficult to establish since they are not known and the Vostok records only provide the atmospheric carbon content.

| Initial conditions | Parameters | Value | Value |
|--------------------|------------|-------|-------|
| $C_{1,0}$          | $\alpha$   | 0.2305| 0.02928|
| $C_{2,0}$          | $\beta$    | 0.6295| 0.1050 |
| $A_0$              | $\varepsilon$ | 1.260 | 0.3630 |
| $S_0$              | $r_1$      | 1.388 | $-4.122 \times 10^{-3}$ |
|                   | $r_2$      | -     | $4.135 \times 10^{-3}$ |
|                   | $r_3$      | -     | $4.76 \times 10^{-4}$ |
|                   | $r_4$      | -     | 7.4 $\times 10^{-5}$ |

Table 1: Initial conditions and best fitting parameters for carbon cycle and energy chain.

Given our hypothesis that the Atmosphere acts as a conduit between Continental and Oceanic carbon, and the fact that we start at an interglacial period with an active Continent and a dormant Ocean, we may infer the following ordering for the initial values of the carbon reservoirs: $C_3,0 \leq C_1,0 \leq C_2,0$. With this in mind, we searched for reasonable initial conditions, adjusting the parameters to understand their effect on the evolution of the system, and finally obtaining the best fitting parameters in several iterations. Results are presented in Table 1.

The time series for the three carbon reservoirs are depicted in figure 2. We observe that the phase shift between $C_1$ and $C_3$ mimics the transition between Continental and Oceanic controls: One of these carbon reservoirs becomes almost depleted (of carbon participating in the cycle) when the other one is dominant. This does not happen with atmospheric carbon $C_2$ which is always, figuratively speaking, alive.

We must emphasize that the purpose of this model is not to be an accurate fit for the Vostok time series, but rather to reproduce the main features: asymmetries and periodicity. The resulting time series for atmospheric CO$_2$ and temperature depicted in figure 2 show that this is indeed the case, with faster heating and slow cooling, and interglacials periods of shorter duration than glacial ones.

Analyzing the (frequency) power spectrum of the simulated series, there are several points worth underlying. The CO$_2$ series presents a dominant frequency around 105 kyr, followed by the 46 kyr and then 21 kyr frequencies. This closely agrees with the real data [McGehee and Lehman, 2012], which is not surprising as the model parameters were calibrated with the Vostok data. Nonetheless, it is reassuring to verify that this simple model does capture the main frequencies from orbital forcing of the climate system in the time period covered by the data. The power spectrum of the simulated temperature presents the same dominant frequencies, a striking fact, considering that the carbon cycle is the only driving mechanism for the temperature changes. Thus, the principal frequencies are obtained without any reference to the Earth’s orbital parameters; this is not to say that they are irrelevant, but rather that they are already incorporated into the Earth’s carbon metabolism which is the driver of our model. Figure 4 depicts these considerations.
Figure 2: Carbon cycle reservoirs simulation evolution in time. In dashed $C_2$, continued $C_1$ and dash-dotted $C_3$.

Figure 3: Simulations. Simulated atmospheric carbon–dashed line, and temperature–continued. Ordinate axis is not significant since simulated time series are scaled for comparison.

Figure 4: Frequency analysis. Comparison between the periodicities for atmospheric carbon and temperature change obtained form the Vostok data, dashed line, with those obtained from our model, continuous line. Ordinate axis is not significant since simulated time series are scaled for comparison. The insets are zooms of the main graph.
5. Conclusions

The model depicted here differs from existing glacial cycle models in one crucial aspect: it does not consider orbital parameters at all; thus, changes in insolation, either global or local, are not explicitely taken into account, as we hypothesise that their main impact on climate is through their effect within the carbon cycle. Our model shows that it is possible for the carbon cycle to drive glaciations and deglaciations. In this scenario, the behavioural change of the mid-Pleistocene transition may be explained by a change in carbon cycle fluxes which would bring about a change in one or more of the model parameters. In fact, this is probably the case in the lapse covered by the Vostok data, as one can observe anomalies like the last two interglacials: one of them is reached before than expected and the last one comes later than expected.

We show that it is possible for the glacial cycles to be driven by long term exchanges of carbon between Oceanic and Continental reservoirs, with the Atmosphere mediating the process. By introducing atmospheric carbon content as a forcing factor in the energy chain, we obtain the desired cyclic temperature pattern typical of the Vostok time series. Thus, the main conclusion is that glacial cycles could be essentially carbon driven and not insolation driven.

The use of a standard Lotka-Volterra system in order to model the interactions between the carbon species in each reservoir was found to be adequate, mainly because it generates the important qualitative results in a simple way. Clearly, modelling the interactions by simple order 2 terms (the products \( C_j C_k \)) assumes a one to one exchange between the different carbon species (one lynx eats one hare, not two!). There are extensions of the classical Lotka-Volterra system that allow for different interactions (Gavin et al., 2006); nonetheless, we have no grounds for assuming that this should be the case and opted for the simplest possible model.

The carbon cycle is implicit in the Oceanic-Continental control-switching and our model attempts to make a simple stylized description of long term cycles (100 kyr in the Vostok time series case) within the carbon cycle and energy chain. A consequence of our model is that these long term CO2 cycles should have the same periodicity for all three carbon reservoirs: Atmosphere, Continent and Ocean. Unfortunately, the only data currently available are for atmospheric CO2, so at this moment we do not know if this is indeed the case.

Here we pictured Earth’s metabolism as the long term carbon exchange between Oceanic and Continental reservoirs. The Atmosphere served only as an intermediary in this process; nonetheless, one can not help but worry about the possible effect of the present value concentration of greenhouse gases in the Atmosphere. Altering the Earth’s complex metabolic process is not something we should want to experiment with.

Appendix A. Methods Summary.

The observed carbon and temperature data need to be transformed to fit our model space. In the case of carbon, we take into account that the three parameters involved are coupled; hence, it is not possible to obtain a specific amplitude with no oscillation given a certain periodicity. With this in mind, we performed a series of iterations in order to obtain a periodicity similar to the observed one. We then used a translation and a homothetic transformation on the observed data to obtain an initial approximation for the amplitude and null oscillation in the model space. The results from this iterative process yield the following expression:

\[
C_{2,\text{model}} = 5.202 \times 10^{-3} (C_{2,\text{obs}} - 0.9) \quad (A.1)
\]

Similarly, for temperature, or rather temperature deviation from the mean, we established a (global) mean of 15 Celsius, that is,

\[
T_{\text{model, celsius}} = \delta T_{\text{obs}} + 15 \quad (A.2)
\]

All iterations and simulations were carried with SciPy libraries and Mathematica was used for the numerical integration.

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