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A SIMPLE CONCEPTUAL MODEL TO INTERPRET THE 100,000 YEARS DYNAMICS OF PALEO-CLIMATE RECORDS

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Spectral analysis performed on records of cosmogenic nuclides [1–4] reveals a group of dominant periodicities during the Holocene period. Only a few of these periodicities are related to known solar cycles, i.e., the De Vries/Suess, Gleissberg and Hallstat cycles, while the origin of the others remains uncertain.

On the other hand, climate records from the North Atlantic region show significant temperature variations during the last ice age associated with transitions between cold stadials and warm interstadials, the so-called Dansgaard-Oeschger (DO) events. The recurrence time between these events varied considerably, ranging from 1 to 12 kyr during the last 90 kyr before present (BP) [5]. This variability is greatly reduced between 25 and 60 kyr BP, when the spacing between warming events was $\sim 1-5$ kyr. Finally, in the interval $12-50$ kyr BP a prominent periodicity of 1470 years is observed [6].

The link between DO events and solar cycles was recently tested on a coupled climate system model CLIMBER-2 (version 3) forced with oscillations of 210 and 87 years cycles in the influx of fresh water into the Northern-Atlantic [7]. The same idea was re-analyzed in a nonlinear simple conceptual model [8, 9] driven by similar frequencies. In both cases a sola origin was demonstrated, however the results were restricted to DO events during the interval $12-50$ kyr BP where they show to be often spaced by periods multiple of ~ 1470 years.

A global perspective of the climate records from the North Atlantic region for the last ice age suggests that temperature variations are the result of the switching between two stable states (a warm and a cold one) with different dynamical regimes, being the quasi-periodicity of about 1470 years during the interval $12-50$ kyr BP one of those dynamical regimes. The hypothesis underlying the present work is that the existence of a driving force composed by the near De Vries/Suess and Gleissberg cycles (with phases and relative amplitudes obtained from a ^{14}C spectral analysis) plus a Gaussian noise (representing the multiples degrees of freedom that we do not take explicitly account for) control the transitions between both states. If so, this simple scheme should explain the main features of temperature variations for the whole ice age and the effects of the solar forcing should be noticeable also during the Holocene when DO events were absent.

To test this hypothesis we propose a new conceptual model based on the key assumptions of the CLIMBER-2 and the information obtained after having analyzed two climate records, the GISP2 δ^{18}O and ^{14}C measurements from tree rings. These records are commonly used as proxies for temperature and solar activity, despite the fact that it is known that ^{14}C can be affected by a number of processes, including exchange between the atmosphere and the ocean, variations in geomagnetic fields, and changes in vegetation, among others.

The model is able to reproduce the main characteristics of the frequency spectra of the various stages of Greenland temperature variations, as it is shown in Fig.1 leading to a plausible explanation of the dominant periodicities seen in the Holocene period. The main features of the model are:

1. The existence of two states, the cold and the warm one.

2. The states represent two different modes of operation of the thermohaline circulation (THC) in the North Atlantic region; the modern and the glacial one.

3. The model is forced by a solar process with the frequencies of the De Vries/Suess and Gleissberg cycles (~ 207 and ~ 87 years respectively) and a stochastic component.

4. A transition between states takes place each time a certain threshold is crossed.

5. With every transition the threshold overshoots and afterwards approaches equilibrium following a millennial time scale relaxation process.

6. During the Holocene the periodic forcing is not able to produce transitions and the climate temperature remains in the warm state.

These features are simulated by the dynamic of a double well potential system subjected to periodic forcing (with the frequencies mentioned before) and a stochastic component. This is represented by the following set of differential equations:

$$\dot{x} = \frac{1}{a}\left[y.(x-x^3)+f(t)+D\sqrt(a)\xi(t)\right] \quad (1)$$
$$\dot{y} = -\frac{y}{\tau_s}+\delta_s, \quad (2)$$

where $y(x-x^3) = -\frac{dV}{dx}$ and $V(x)$ is a double well potential with a potential barrier controlled by the dynamics of the y variable. $f(t) = F\left(cos(2\pi f_1 t+\phi_1)+\alpha sin(2\pi f_2 t+\phi_2)\right))$ represents the solar forcing whose main parameters, amplitude F, frequencies f_1 and f_2, phases ϕ_1 and ϕ_2 and α the relative amplitude of both solar periodic components. The term $D\xi(t)$ stands for a white noise process (with zero mean and amplitude D) and a is a scaling constant. In the equation for threshold dynamics, τ_s and δ_s are the characteristic time decay and asymptotic threshold respectively ($s = 1(0)$ for warm (cold) state).

For the simulations shown in this paper we take $f_1 = 1/209.4$ years^{-1}, $f_2 = 1/87.7$ years^{-1}, $\phi_1 = -0.1483$, $\phi_2 = -0.5255$, $\alpha = 1.1303$, all from Fourier analysis of ^{14}C time series . The value of the constant $a = 7.7986$ was taken in order to adjust the characteristic times of the model to the scale of experimental data and the values $\tau_0 = 1200$ and $\tau_1 = 800$ was taken like in [8]. We also set $\delta_s = 0.8/\tau_s$ and the initial condition for the y variable $y(0) = 1.5$. In order to match the experimental data, the model was simulated for a wide range of noise amplitudes. As shown in Fig. 1 there is an optimum amplitude that minimizes the distance between model and GISP2 records' spectra. This is a noise-induced frequency matching effect already seen in many cases of stochastic resonance. In summary we found that a simple bistable model forced with the De Vries/Suess and Gleissberg cycles and noise displays a group of dominant frequencies similar to those obtained from Fourier spectra from the GISP2 δ^{18}O during the last ice age. In line with previous results [7–9], the present work provides a general dynamical framework to interpret the main characteristic of the paleoclimate records from the last 100,000 years.

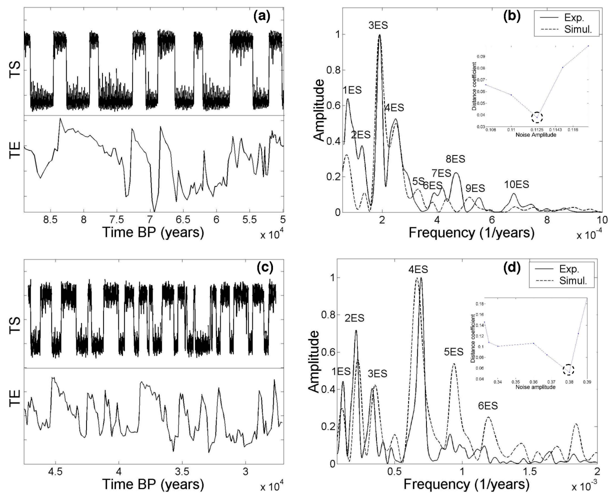

Figure 1 – Traces on the left panels (a and c) show the GISP2 δ^{18}O records (i.e., temperature) and the model output for noise amplitude optimized to match the frequency spectra (panels b and d). Insets shows the distance between data and model output spectra as a function of noise amplitude.

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