Clim. Past Discuss., 8, 3143–3157, 2012
www.clim-past-discuss.net/8/3143/2012/
doi:10.5194/cpd-8-3143-2012

Climate
of the Past
Discussions

Terminations VI and VIII (~ 530 and ~ 720 kyr BP) tell us the importance of obliquity and precession in the triggering of deglaciations

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Received: 6 July 2012 – Accepted: 9 July 2012 – Published: 2 August 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The main variations of ice volume of the last million years can be explained from orbital parameters (Laskar et al., 2004) by assuming climate oscillates between two states: glaciations and deglaciations (Parrenin and Paillard, 2003; Imbrie et al., 2011) (or terminations). An additional combination of ice volume and orbital parameters seems to form the trigger of a deglaciation (Parrenin and Paillard, 2003), while only orbital parameters seem to play a role in the triggering of glaciations (Khodri et al., 2001). Here we present a conceptual model which realistically reproduce ice volume variations during the past million years and in particular the timing of the 11 canonical terminations. Exploring our model's parameters exhaustively, we show that obliquity plays a fundamental role in the triggering of termination VI (∼ 530 kyr BP), while precession plays a fundamental role in the triggering of termination VIII (∼ 720 kyr ago).

1 Introduction

Understanding past climates could help us to improve our predictions of future climatic variations. The reconstructions of Earth's climate over the past million years from either ice cores (Jouzel et al., 2007) or marine cores (Lisiecki and Raymo, 2005) show a succession of long glaciations and short deglaciations (or terminations), with a period of ∼ 100 kyr and known as glacial–interglacial cycles. Changes in in-coming solar insolation (Loutre, 1993) due to changes in Earth orbital parameters (Laskar et al., 2004) is the only known major external forcing of the climate system at these time scales. Investigation in the frequency domain suggests that variations in Earth's orbit indeed paced the observed changes (Hays et al., 1976), but the amplitude and sawtooth shape of climatic variations implies that amplifications (e.g., through ice/snow albedo and greenhouse gases changes) and non-linearities exist. To trigger a complete deglaciation, it seems that a large ice volume and appropriate orbital parameters are necessary (Raymo, 1997), while only orbital forcing seems important to trigger a glaciation (Paillard, 1998; Khodri et al., 2001). Paillard (1998) used such ideas to build a 3 states climate system which correctly simulates (within a few kyr, 1000 yr) the timing of terminations (except Termination VI) during the last million years. This idea has been further developed by assuming an additional combination of ice volume and orbital parameters forms the trigger of a termination (Parrenin and Paillard, 2003; Imbrie et al., 2011). It has also been suggested (Parrenin and Paillard, 2003) that ice volume influences the exact timing of deglaciation, and the prediction of this model has been later checked with accurate chronologies of the Dome Fuji and Vostok ice cores (Kawamura et al., 2007). This is a element of proof that such conceptual models are not useless and that they can have some predictive capabilities. More recently, based on slightly different evolution equations but on a similar deglaciation threshold than Parrenin and Paillard (2003), a two-states conceptual climate model was proposed (Imbrie et al., 2011) and suggest that the increase in 100 kyr power during the mid-Pleistocene transition could be caused by changes in Earth orbital parameters and rather than by changes within the climate system. All these simple conceptual models and their accurate data representation suggest that the climate variations of the last million years were deterministic and not stochastic.

Terminations of the last million years (Fig. 1) are all different from one another, with different levels of precession maxima, different phasing between obliquity and precession and different preceding ice volume maximas. In this paper, we will focus on Terminations VI and VIII (TVI and TVIII) which are particular cases. On one hand, the ice volume maximum preceding TVI is probably the smallest of all terminations of the last million years and the corresponding precession maximum is one of the smallest. TVIII, on the other hand, occurred at a time with not a particularly large ice volume and with a defavorable obliquity. For which reason has the termination state been triggered at these periods? To analyze this problem, we will built a conceptual model of ice volume variations which successfully reproduces all canonical 11 terminations of the last million years. With an exhaustive exploration of all the parameters of our model, we will show that terminations VI and VIII (~ 530 and ~ 720 kyr BP) allow to disentangle respectively the role of obliquity and precession in the triggering of deglaciations.

2 Method

2.1 Forward model description

Our study is based on a conceptual model of Quaternary climate which simulates the ice volume from the orbital parameters (Paillard et al., 1996; Laskar et al., 2004). As for the model of Imbrie et al. (2011), this model takes as inputs 3 functions of the orbital parameters which are normalized to zero mean and unit variance on the last million years: $\mathrm{Esi} \sim e \sin \varpi$ (precession, with ϖ the precession angle taken from the vernal equinox), $\mathrm{Eco} \sim e \cos \varpi$ (phase-shifted precession) and $O \sim \varepsilon$ (obliquity). Insolation at most latitudes and seasons can be represented quite accurately by a linear combination of these three orbital functions (Loutre, 1993) . The model of Parrenin and Paillard (2003) was taking as input obliquity and summer solstice insolation at 65° N and this modification allows to disentangle the role of obliquity and precession. For the rest, the model is similar to the one in Parrenin and Paillard (2003) except that the predicted ice volume is now dimensional. It has two different states of evolution: the "glaciation" state g and the "deglaciation" state d and the evolution of ice volume v (expressed in m sea level) in these states is simply described by two linear equations:

$$\text{during stage } g: \frac{\mathrm{d}v}{\mathrm{d}t} = -\alpha_{\mathrm{Esi}}\,\mathrm{Esi}_{\mathrm{tr}} - \alpha\,\mathrm{EcoEco}_{\mathrm{tr}} - \alpha_O\,O + \alpha_g, \tag{1}$$

$$\text{during stage } d: \frac{\mathrm{d}v}{\mathrm{d}t} = -\alpha_P\,\mathrm{Esi}_{\mathrm{tr}} - \alpha_{\mathrm{Eco}}\,\mathrm{Eco}_{\mathrm{tr}} - \alpha_O\,O + \alpha_d - \frac{v}{\tau_d}, \tag{2}$$

where O is obliquity normalized to zero mean and unit variance and $\mathrm{Esi}_{\mathrm{tr}}$ and $\mathrm{Eco}_{\mathrm{tr}}$ are respectively calculated from Esi and Eco the precession parameters using a truncation function:

$$\text{if } x \leq 0 : f(x) = x + \sqrt{4a^2 + x^2} - 2a, \tag{3}$$

$$\text{if} x > 0 : f(x) = x, \tag{4}$$

(where a is a constant) and then normalized to zero mean and unit variance. This truncation is similar to the one used by Paillard (1998) and appears necessary to simulate the lower ice volume sensitivity to precession during cold periods than during warm periods. We now need to define when the model jumps from one state to the other. For this we define thresholds on a linear combination of orbital parameters (and ice volume for the g-to-d transition):

$$g\text{-to-}d : \kappa_{\mathrm{Esi}}\ \mathrm{Esi} + \kappa_{\mathrm{Eco}}\mathrm{Eco} + \kappa_O\ O + v > v_0, (\text{and } \kappa_{\mathrm{Esi}}\ \mathrm{Esi} + \kappa_{\mathrm{Eco}}\ \mathrm{Eco} + \kappa_O\ O \geq v_1) \tag{5}$$

$$d\text{-to-}g : \kappa_{\mathrm{Esi}}\ \mathrm{Esi} + \kappa_{\mathrm{Eco}}\ \mathrm{Eco} + \kappa_O\ O < v_1.(\text{and } \kappa_{\mathrm{Esi}}\ \mathrm{Esi} + \kappa_{\mathrm{Eco}}\ \mathrm{Eco} + \kappa_O\ O + v \leq v_0) \tag{6}$$

We start with $v = v_{\mathrm{init}}$ in the S_{init} state at $t = 1000$ kyr BP and we solve the evolution of v with a Runge-Kutta 4th order method and with a time step of 100 yr.

2.2 Monte-Carlo fitting of parameters

To infer the value of the 14 parameters of this model, we fit it to an ice volume reconstruction (Bintanja et al., 2005) based on the LR04 marine isotopic stack (Lisiecki and Raymo, 2005). In the time space, the good agreement of the LR04 with the independent glaciological EDC3 age scale (Parrenin et al., 2007) for the last 400 kyr suggests that the age scale errors do not exceed ~ 3 kyr. In the ice-volume space, the errors of the Bintanja et al. (2005) reconstruction are taken into account as follow. We define the density of probability of an ice volume simulation $v(t)$:

$$P = k \cdot \exp\left(-\frac{1}{2}\boldsymbol{R}^T \mathbf{C}^{-1} \boldsymbol{R}\right), \tag{7}$$

where k is a multiplicative constant and where:

$$\boldsymbol{R}^T = \left(v\left(t_0\right) - v_D\left(t_0\right), \ldots, v\left(t_N\right) - v_D\left(t_N\right)\right) \tag{8}$$

is the transposed residual vector with $t_0 = 1000$, $t_1 = 999$, ... $t_N = 0$ kyr BP, $v_D(t)$ is the observed sea level over the last million years (Bintanja et al., 2005; Lisiecki and Raymo, 2005) and **C**, the covariance matrix, takes into account both the modeling and data errors (Tarantola, 1987). **C** is inferred iteratively with a residual approach. First, we assume that the errors are independent (**C** is diagonal) and with a confidence interval $\sigma_D = 20$ m. We then explore the parameters space using a 10 000 000 experiments random walk based on the Metropolis-Hastings algorithm (Metropolis et al., 1953; Hastings, 1970). We find a most probable experiment called "First" (not shown here) and analyze the residuals. We find that the residuals have approximately a gaussian distribution (Fig. 2) with a standard deviation of 12.5 m. Figure 3 shows that the correlation of the residuals decreases as the time Δt separating the residuals increases and vanishes for $\Delta t = 26$ kyr. We therefore feed the **C** matrix with this information and run again our optimization algorithm.

We find a most probable experiment called Best (see Table 1 for the values of the parameters and Fig. 1 for a visual comparison with the data). Note that it was not necessary to update the **C** matrix once again since the residuals have approximately the same statistical properties than for the "First" experiment.

3 Results and discussion

3.1 Simulation of the last million years ice volume

This experiment called "Control" is in good agreement with the data and in particular reproduces correctly all the 11 terminations of the last million years. The agreement with the data is slightly better than for the model described by Parrenin and Paillard (2003) because of the use of phase-shifted precession and of the Monte-Carlo optimization algorithm. The data have ~ 90 extremas (two per precessional cycle), that is ~ 90 degrees of freedom (the degree of a fitting polynomial). The model has 14 parameters. Among those, two are boundary conditions that could be fixed according to the data and two other are optional (a similar agreement with the data is found with $\alpha_{\mathrm{Eco}} = 0$ and $\kappa_{\mathrm{Eco}} = 0$). So the complexity of the system is significantly reduced from 90 to 10 degrees of freedom. Considering the timing of the 11 terminations, the 3 parameters that matter are κ_{Esi}, κ_O and v_0, which represent a reduction of the complexity from 11 to 3 degrees of freedom.

3.2 Experiments without obliquity influence on deglaciation threshold

The question now is: how necessary are precession and obliquity to simulate the last million year ice volume? In our model representation, there is no point in assuming $\{\alpha_{\mathrm{Esi}}$ and $\alpha_{\mathrm{Eco}} = 0\}$ or $\alpha_O = 0$ since we know from frequency analysis that both precession and obliquity are present in the sea level observations (Lisiecki amd Raymo, 2005). We thus reformulate our question in: how necessary are precession and obliquity in the *d*-to-*g* and *g*-to-*d* triggers? In other words, are we able to find a model simulation in good agreement with the observations (in particular with the right timing of terminations) and with $\{\kappa_{\mathrm{Esi}} = 0$ and $\kappa_{\mathrm{Eco}} = 0\}$ or $\kappa_O = 0$?

We thus apply our Monte-Carlo optimization algorithm assuming $\kappa_O = 0$ and find a more probable experiment called Best-wo (see Table 1 and Fig. 1). In this experiment, all the terminations are correctly placed except termination VI. It is not surprising that the model fails to reproduce termination VI, since it has devaforable precession (low Esi maximum) and ice volume (low ice volume at MIS14.2) configurations and only a favorable obliquity configuration.

We now try to trigger a deglaciation at termination VI by increasing the influence of precession in the deglaciation threshold (parameters κ_{Esi}, Eq. 4). Unfortunately (see experiment Test-wo1, Table 1 and Fig. 1), the first deglaciation that appears is at ~ 270 kyr BP, a period with a precession maximum larger than that of termination VI, a slightly larger ice volume, but a lower obliquity. We might think at this stage that there is some long term trend in one of the model's parameters (Paillard, 1998) which we have not taken into account. We thus continue our exercise and increase the parameters κ_{Esi}. Unfortunately, the next deglaciation to appear is at ~ 890 kyr BP (see experiment Test-wo2, Table 1 and Fig. 1), i.e. this time *before* termination VI. It is a period with a higher precession maximum with respect to that of termination VI, a comparable ice volume, but a lower obliquity.

3.3 Experiments without precession influence on deglaciation threshold

We now apply our Monte-Carlo optimisation algorithm with $\kappa_{\mathrm{Esi}} = 0$ and $\kappa_{\mathrm{Eco}} = 0$. We find a best-guess experiment called Best-wp (see Table 1 and Fig. 1). Interestingly, this experiment simulates a lot more terminations than the Best experiment, but some do not last very long. All the 11 canonical terminations are reproduced, except TVIII which is shifted ~ 20 kyr toward younger ages and TXI which does not exist at all (we do not discuss TXI because it is too much influenced by our initial condition). It is not surprising that the model fails to reproduce termination VIII, since it has a devaforable obliquity configuration but a favorable precession configuration.

4 Conclusions

A comparison of termination VI with two periods in the past (~ 270 kyr and ~ 890 kyr BP) with comparable or larger ice volume, comparable or larger precession parameter, but lower obliquity, therefore suggests that obliquity played a role in the triggering of last million year deglaciations. Symetrically, termination VIII, which occurred during an obliquity minima, emphasizes the role of precession in the triggering of deglaciations. We have illustrated our findings with a conceptual model which cannot simulate last million years terminations assuming that only precession or obliquity plays a role in the trigger of deglaciations. TVI and the precursor of TVIII have already been emphasized by their lag of CO_2 to global ice volume (Lisiecki, 2010). By this article, we hope to stimulate further studies focused on these terminations.

Acknowledgements. E. Wolff, G. Krinner and V. Masson-Delmotte provided helpful comments to this manuscript. K. Kawamura stimulated this new development on conceptual models of Quaternary climate.

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The publication of this article is financed by CNRS-INSU.

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Table 1. Values of model parameters for the different experiments described in this study.

	Best	Best-wo	Test-wo1	Test-wo2	Best-wp
α_{Esi} (m kyr^{-1})	1.45461	1.79764	1.79764	1.79764	3.01576
α_{Eco} (m kyr^{-1})	0.38764	0.05285	0.05285	0.05285	0.224614
α_O (m kyr^{-1})	1.13662	1.30443	1.30443	1.30443	0.677997
α_g (m kyr^{-1})	0.97825	0.95246	0.95246	0.95246	1.02301
α_d (m kyr^{-1})	−0.7469	−1.3081	−1.3081	−1.3081	−1.52991
$\log(\tau_d/12\,\mathrm{kyr})$	−0.3634	0.28003	0.28003	0.28003	0.964344
a	0.68034	0.26721	0.26721	0.26721	0.484304
κ_{Esi} (m)	14.6348	9.88356	16	18	4.58774
κ_{Eco} (m)	2.28061	6.68405	6.68405	6.68405	−6.20925
κ_O (m)	18.5162	23.8152	23.8152	23.8152	2.99041
v_0 (m)	122.918	111.197	111.197	111.197	98.8498
v_1 (m)	3.10301	−8.2606	−11.3	−12.3	−0.165086
v_{init} (m)	42.2217	53.6324	53.6324	53.6324	26.3206
S_{init}	g	g	g	g	g

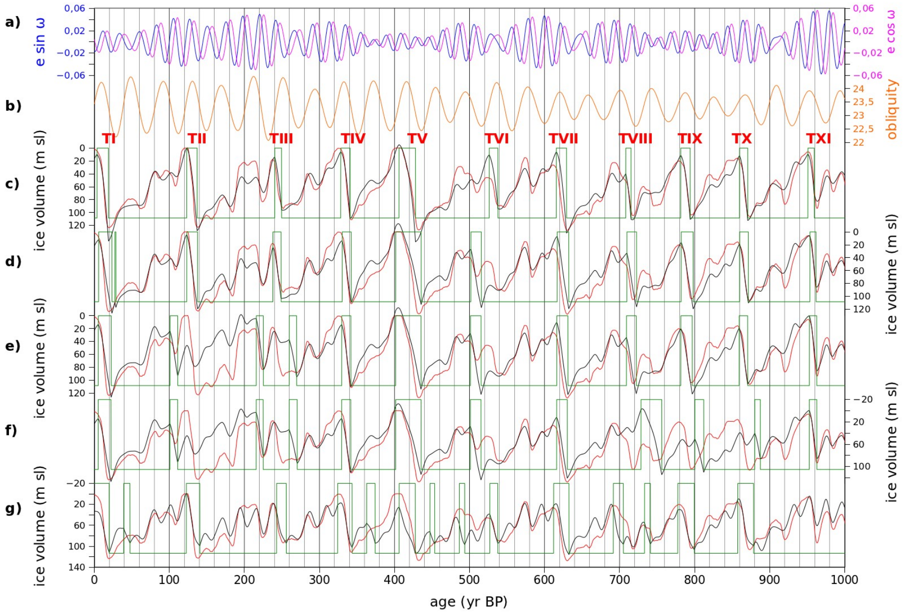

Fig. 1. Model forcings, ice volume data, and model experiments. Terminations are marked with red roman numbers. From top to bottom: **(a)** precession parameters $e\sin\varpi$ and $e\cos\varpi$[1,9]. **(b)** obliquity parameter[1,9]. **(c)** red: ice volume data[10]; black: best model experiment, with obliquity influence on deglaciation trigger; green: model state. **(d)** red: ice volume data[10]; black: best-wo model experiment without obliquity influence on deglaciation trigger; green: model state. **(e)** red: ice volume data[10]; black: test-wo1 model experiment without obliquity influence on deglaciation trigger; green: model state. **(f)** red: ice volume data[10]; black: test-wo2 model experiment without obliquity influence on deglaciation trigger; green: model state. **(g)** red: ice volume data[10]; black: best-wp model experiment without precession influence on deglaciation trigger; green: model state.

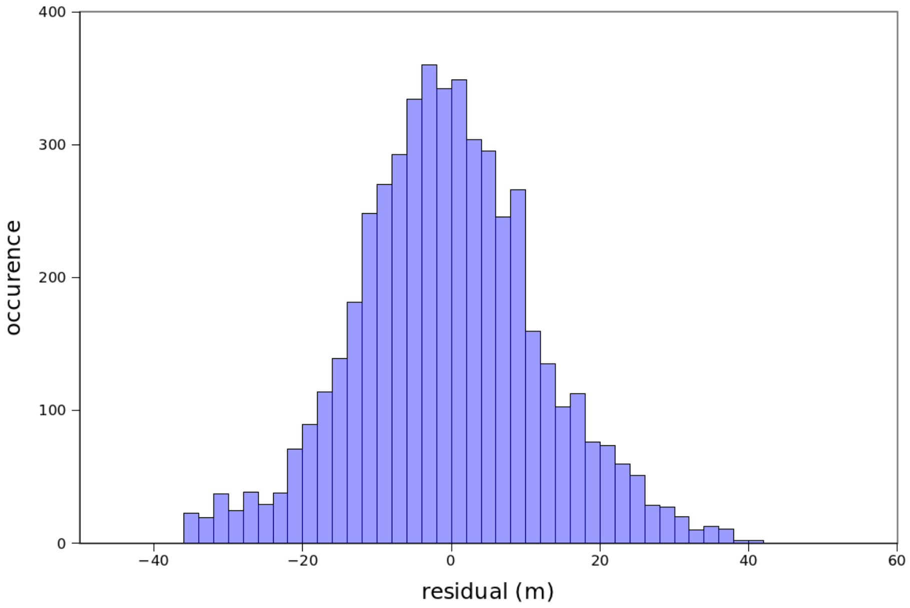

Fig. 2. Distribution of the residuals to the data for the “First” experiment.

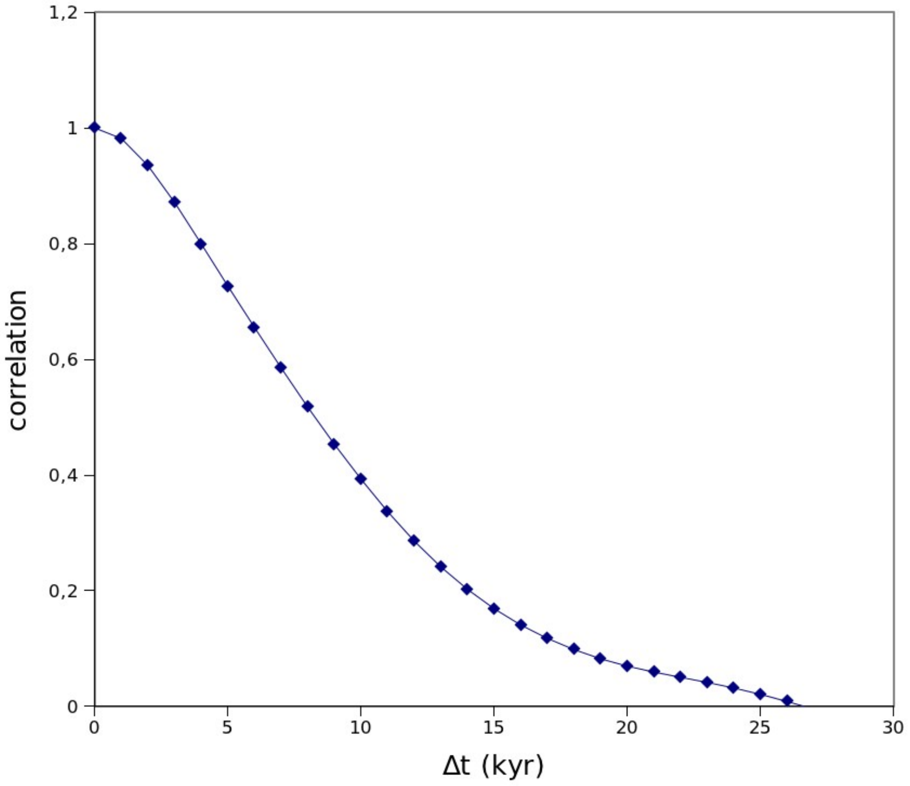

Fig. 3. Correlation of the residuals to the data as a function of the time Δt for the "First" experiment.