

Interactive comment on “Why could ice ages be unpredictable?” by M. Crucifix

M. Crucifix

micHEL.crucifix@uclouvain.be

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First of all I would like to thank the anonymous referee for his useful comments. Two comments need to be addressed: the positioning of the paper with respect to De Saedeleer et al. 2012, and the depth of the comparison with other models.

Positioning of the paper. This paper belongs to a line of research, including Crucifix (2012), De Saedeleer, Crucifix, Wieczorek (2013), and the present one, which aims at understanding the behaviour of simple dynamical system models of ice ages. The first article studies limit cycles and bifurcations in several models, with a focus on their autonomous (i.e., non forced) behaviour; the second focuses on the van der Pol oscillator, and discusses Lyapunov exponents (finite-time and long-term) and basins of attractions; this paper, finally, discusses more systematically the consequences of the progressive introduction of the different components of the astronomical forcing, vi-

C430

visualises the existence of strange non-chaotic attractors in palaeoclimate models, visualises the non-autonomous bifurcations, discusses the possibility of locking on the eccentricity, and finally applies the proposed diagnostics to different models. None of this was presented in the previous articles. In addition to this scientific discussion, a significant amount of technical work has been achieved with respect to De Saedeleer et al. 2012, by coding the different models and compare them with the original publications, and finally publishing all the relevant codes (models and analysis). None of the figures presented here has been published elsewhere.

It is correct that the counting of pullback attractors in the van der pol oscillator was proposed in De Saedeleer et al. 2012 and that the present article takes some time in explaining again how this works. It is common practice in the scientific literature to have some redundancy in the explanation of methods (think how many times a model as HadCM3 was described in methodology sections !). It has been this author experience that the palaeoclimate community, the primary audience of the Climate of the Past, is not always familiar with dynamical system concepts. In fact, strange non-chaotic attractors and pullback attractors are not so common even in the mathematical literature, hence the perceived need to insist on these concepts in order to make the paper sufficiently accessible. However, be it the nature of the introduction, the way the astronomical forcing is introduced, and the discussion of the conclusions, this is a very different paper to the two previous ones. Taken together the three papers provide a consistent piece of research that suggests that structural instability of ice ages should be considered as a serious possibility.

The second remark concerns the depth of the model intercomparison. At the IPICS workshop a proposal was indeed made of preparing an article that would cover the aspects that the reviewer precisely suggests. Thinking of it this is a very ambitious task. The models have important structural differences (some are hybrid models, other are continuous deterministic dynamical systems; other at last were introduced by their authors as stochastic dynamical systems). Some were introduced to defend plausi-

C431

ble physical mechanisms, while others aim at a more abstract understanding of the dynamical behaviour. The discussion of the necessary number of parameters is admittedly an interesting one, but one should also consider that it may either be tackled from a statistical point of view (model selection based on marginal likelihood estimates) or physical point of view, necessarily subjective given the high level of conceptualisation.

This would be a great and ambitious paper, been seen as a collaborative effort, and clearly the objective of the present article is more modest: show that the behaviour found in the van der Pol model, which is not strongly physically motivated as a model of ice ages (this is the main weakness of De Saedeleer et al), is found in other conceptual models of ice ages that previously passed the review. The tongue structure is different from one model to the next, but the overall pattern of synchronisation is found in all the models discussed here, which suggests that it may reasonably be seen as a plausible aspect of the theory of ice age cycles.

As a last remark, Dr Takahito Mitsui and Kazuyuki Aihara recently submitted an article very complementary to the present one. Their paper, entitled "Dynamics between order and chaos in conceptual models of glacial cycles", is already available from the arXiv (<http://arxiv.org/abs/1302.0915>). As the present article, it discusses several models of ice ages, reveals the existence of strange non-chaotic attractors and show stroboscopic sections. Mitsui and Aihara show metrics confirming the strange non-chaotic nature of the attractors (not done here), while the present article shows bifurcations diagrams and discusses more systematically the effects of progressively introducing different components of the astronomical forcing on the bifurcation structure. Both articles have been written independently, without previous concerting, but were submitted almost the same day. Their complementary character and converging conclusions would make it fair to have them both published.

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