

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

Anonymous Referee #1

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This paper carefully analyzes the response of several simple nonlinear models to different variants of Milankovitch forcing. The common wisdom has been that Milankovitch forcing sets the phase of glacial cycles via some sort of nonlinear phase locking. This paper shows that while this may be the case, such phase locking can be very sensitive to model formulation. The paper introduces several analysis approaches that as far as I can tell are new to this research area, certainly were new to me. I find the paper exceptionally well written, and containing several very interesting and important insights. The analysis is both creative and very carefully and thoroughly done. The combination of the van der pol oscillator and six different glacial models conveys a very robust message. The author has done a great job of delving into the nonlinear dynamics literature, extracting very useful information and methods, and applying them here.

I feel this is an important paper and am recommending publication essentially as is, with a few minor optional points raised below for the author to consider in case he finds

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them relevant.

P 1065, line 17 raises the important question of whether the 100 kyr period is directly due to the orbital forcing or not. I find the discussion following that question interesting, but it would be helpful to have a more explicit answer to this question (even if it is "we don't know"), and the author may want to present this question and answer in the abstract and conclusions as well. A related point: Can the author deduce of the glacial cycles are likely to be due to a self-sustained internal climate oscillation?

Conclusions, p 1071, line 24: regarding the definition of a "pacemaker paradigm". Would it be consistent to present it as being the hypothesis that the ice ages are due to a self-sustained oscillation where the only role of the Milankovitch forcing is to set the phase, or time of terminations? Some of the models analyzed here wont have oscillations without Milankovitch forcing, so I feel the issue of self-sustained vs not is a worth discussing here.

P 1072, line 20: I very much like the approach of not discussing which model is most accurate representation of glacial cycle physics. This continues the line of argument made by Tziperman et al 2006 that a good model fit to the ice volume record is not an indication that the model mechanism for the ice ages is correct, but merely an indication of the powerful role of Milankovitch phase locking. This may be useful to discuss here, as I feel this paper takes this one step further: not only do we not know what the correct mechanism is given a good fit to the observed ice volume record, but this fit may, in fact, be quite sensitive to model parameters. More specifically, I see the important question raised here for future studies being: how robust is the phase locking, in the sense of how deep into the 1 pullback attractor (if at all) is the actual glacial climate system.

There is an interesting connection to the ENSO literature that can be briefly made here. There, the introduction of periodic (annual) forcing readily leads to chaos and unpredictability of long term behavior. Specifically, chaos occurs there when Arnold tongues overlap. Here, the definition of Arnold tongues is actually different, and chaos does not

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seem to develop. Is it clear why? Does this have to do with these glacial models typically being relaxation oscillators, as opposed to just self-sustained nonlinear oscillators in the ENSO case?

Interactive comment on Clim. Past Discuss., 9, 1053, 2013.

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