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Nonlinear Processes in Geophysics
Discussions
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Interactive comment on "Oscillations in a simple climate–vegetation model" *by* J. Rombouts and M. Ghil

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Referee: The paper presents a simple conceptual climate vegetation model exhibiting oscillatory behavior for a certain parameter setting. In particular including an ocean with ice cover saw tooth-like oscillation are observed similar to the glaciation-deglaciation cycles in the quaternary. The model consists of two coupled ODEs and can be handled analytically. Therefore stationary states and their stability are determined being the main advantage of simple conceptual models. Overall the paper is organized and written very well and fits into the scope of the journal. On the other hand, such models have their limitations. On a global scale vegetation albedo is not the main driver of the climate, clouds play also an important role. In reality other effects might result in climate oscillations observed in the last 800kyr with a different

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periodicity.

AUTHORS: We thank this referee for the very positive assessment of our paper and for the constructive request of placing it in the broader context of other important mechanisms and feedbacks that play a role in Quaternary glaciation cycles in particular and, more generally, in climate variability on long time scales. These concerns overlap with some of those of **Referee 2 (M. Crucifix)** and have led us to add a subsection to the paper's final section.

The paper's final section is now entitled **"4 Concluding remarks"** and it has the following three subsections: **4.1 Summary**, **4.2 Discussion of the results**, and **4.3 Broader context**. The latter had to be kept reasonably brief, given the overall satisfaction of both referees with the writing and especially the conciseness of the paper. **Section 4.3** therefore mainly refers to reviews and other papers that cover the topics at greater length; It is attached to this reply as a supplement.

The more specific comments of **Referee 1** are answered forthwith, along with the pertinent additional references.

REFEREE: More specific comments:

In the introduction two types of models area presented. On the one hand simple models like the presented one, on the other hand complex general circulation models. Models of intermediate complexity define a third type of models considerably faster than the GCMs. This has to be mentioned.

AUTHORS: Thank you for the suggestion to include intermediate models in our review of climate-vegetation modeling. The paragraph straddling pp. 147-148 in the original version has been expanded and broken up into two paragraphs , as follows. Intermediate-complexity models are now also discussed in **Section 4.3** (see supplement).

Although vegetation plays an essential role in the climate system, it has only been

NPGD
2, C91–C94, 2015

rather recently included as an active player in climate models. The hierarchy of climate models (Schneider and Dickinson, 1974; Ghil and Robertson, 2000; Ghil, 2001) ranges from simple, conceptual ordinary differential equation (ODE) models — through intermediate models of varying complexity — all the way up to full-scale general circulation models or global climate models (GCMs).

Across this whole range, vegetation can be included to better explain various climatic phenomena and trends. In some cases, the predictions of models that couple atmosphere, ocean and vegetation dynamics – often referred to as Earth system models (ESMs) – differ radically from models that exclude the vegetation (Meir et al., 2006). It follows that it is of the essence to include vegetation in our models to obtain a better understanding of climate evolution and variability.

[Additions or modifications to the text of the original version are in red.]

REFEREE: Page 159: The sawtooth like behaviour is driven by internal oscillations of the system with a 1000yr periodicity, while the glaciation/deglaciation cycles of the Earth are driven by external perturbations due to the Milankovitch cycle. In models of intermediate complexity the sawtooth-like behaviour can be explained by a positive feedback (see, e.g.," The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles", Ganopolski and Calov, Clim. Past, 7, 1415–1425, 2011). Results of their experiments support the notion that 100 kyr cycles represent a direct, strongly nonlinear response of the climate-cryosphere system to orbital forcing and they are directly related to the corresponding eccentricity period. In terms of nonlinear dynamics, this link can be interpreted as the phase-locking of the long glacial cycles to the shortest (100 kyr) eccentricity cycles. Please comment on that.

AUTHORS: The modeling of the dominant, 100-kyr peak in the power spectrum of Quaternary proxy records and of its asymmetric, sawtooth character goes back at least four decades, to the Hays et al. (Science, 1976) paper, and there is still no generally accepted explanation. In the paragraph of p. 159 to which the referee alludes, we have simply added the particular explanation that s/he prefers, as well as two additional references that include the work of the PIK group , as follows.

Such sawtooth-like behavior characterizes the ice volume evolution during Quaternary glaciations; see, for instance, Ghil and Childress (1987, Ch. 11 and references therein). This behavior has been modeled using relaxation oscillations, cf. Le Treut and Ghil (1983), Ghil (1994) and Crucifix (2012), among others. In these studies, the sawtooth shape is due to a quick melting and slow build-up of the ice sheets, whereas in Gildor and Tziperman (2001), the sea ice plays a key role. In the intermediate-complexity model of Ganopolski and Calov (2011), like in the early conceptual model of Imbrie and Imbrie (1980), it is the strongly nonlinear response of the climate-cryosphere system to orbital forcing. In the present model, it is the surge in vegetation growth accompanying a temperature rise that provides the characteristically asymmetric nature of the oscillation.

Additional references

- Ganopolski, A., and Calov, R.: The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles, Clim. Past, 7, 1415–1425, 2011.
- Imbrie, J., and Imbrie, J. Z.: Modeling the climatic response to orbital variations, Science, 207, 943–953, 1980.

References already included in the original version of the paper and cited in the reply here are not listed in full.

Please also note the supplement to this comment:
http://www.nonlin-processes-geophys-discuss.net/2/C91/2015/npgd-2-C91-2015-supplement.pdf

Interactive comment on Nonlin. Processes Geophys. Discuss., 2, 145, 2015.