Reply to Dr. Andrey Ganopolski

Thank you very much for these very valuable comments. In what follows, we respond to them, point by point, and propose several according changes to our manuscript. We consider that these changes will substantially improve the quality and clarity of our manuscript.

In order to improve the readability of our replies we applied a color/type coding to discriminate our replies from your comments. We have attached our replies as a pdf document since color coding is not available in the browser based text editor.

Color/type coding:
Comment by Dr. Andrey Ganopolski.
Reply from the authors.

The authors acknowledged my comments on their work. However, these comments were made on an early version of the manuscript which did not include the important finding of the manuscript published in ESDD, namely, the existence of self-sustained oscillations in the CLIMBER-2 model. This is why I would like to use an opportunity to provide additional comments on this aspect of the manuscript by Mitsui et al.

Thank you for pointing out this. We should have stated that you gave us comments on an early version of the manuscript. We again acknowledge your new comments on the present ESDD manuscript.

The manuscript is based on the version of the CLIMBER-2 model which was used in Willeit et al. (2019) (hereafter W19), and which is very similar to the version used in Ganopolski and Brovkin (GB17) but with somewhat different values of several model parameters. Similar to W19, the GB17 version of CLIMBER-2 simulates self-sustained oscillations with the constant orbital forcing and CO_2 for regolith covering all continents (as in REG simulation in Ganopolski and Calov, 2011), although, in a rather narrow range of CO_2 concentrations (220-240 ppm). However, the GB17 model does not simulate any appreciable (more than several meters in sea level equivalent) self-sustained oscillations for the present regolith cover neither with constant CO_2 for the entire range of CO_2 concentration from 180 to 300 ppm nor with the interactive CO_2 for a wide range of orbital parameters. In principle, such a difference between similar model versions is not very surprising – CLIMBER-2 is a strongly nonlinear model, and even small changes in model parameter values can cause the appetence or disappearance of some dynamical regimes. Moreover, the time-dependent regolith map used in W19 is slightly different at time 0K from that was used in GB17. Two questions arise in this regard: (i) What are the mechanisms of long self-sustained oscillations seen in the W19 (but not in GB17) model, and (ii) whether these oscillations with a typical periodicity of several hundred kiloyears arising under constant orbital parameters (Fig. 2c) are related to the strongly asymmetric glacial cycles with the periodicity close 100 kyr simulated in CLIMBER-2 under the influence of real orbital forcing (Fig. 2d)?

Thank you for the valuable information: The GB17 version of CLIMBER-2 is not self-oscillatory for the present regolith conditions, but it can be self-oscillatory for particular conditions (the regolith covering all the continents and 220-240-ppm CO_2). This information and our results show that CLIMBER-2 has the potential to be self-oscillatory. This fact is, however, not known in the community so far. We believe it is important to report that comprehensive Earth system models have a possibility to exhibit orbital-scale self-sustained oscillations.
There are a few notable differences in the model used in W19 and our study compared to GB17:

(i) W19 includes an interactive dust cycle following Bauer and Ganopolski (2010 and 2014), while the dust deposition fields in GB17 are interpolated between pre-industrial and last glacial maximum fields, using sea level as weighting factor,

(ii) W19 includes the deep permafrost model of Willeit and Ganopolski (2015), which explicitly considers the effect of a coupled heat conducting bedrock on ice sheets basal conditions, accounting also for the latent heat of phase changes of water in the sediments,

(iii) as already mentioned above the present-day regolith mask differs slightly between W19 and GB17.

In particular (i) and (ii) introduce additional feedbacks in the model that may have impacts on the simulation of internal oscillations.
We will run additional simulations to try to isolate the model difference(s) between W19 and GB17 that are fundamental for the different model behavior, in particular with respect to the long internal oscillations simulated with the W19 version for present-day regolith.

1. The appearance of very long glacial cycles (in the case of the orbital parameters corresponding to 21 ka, the periodicity reaches 500 kyr) is puzzling since none of the climate components of CLIMBER-2 has such a long time scale. The only suspect is the negative silicate weathering feedback with just the right time scale. The parameters of the carbon cycle model in CLIMBER-2 are selected in such a way that the average during glacial cycle weathering compensates for volcanic outgassing. However, under interglacial (warm) climate conditions, weathering exceeds volcanic outgassing and CO_2 *drifts down, while under glacial (cold) climate conditions, weathering is smaller than volcanic outgassing and* CO_2 *rises slowly, which, of course, is opposite to what is observed during real glacial cycles. A combination of several strong positive feedbacks with the slow negative weathering feedback, in principle, can give rise (but not in the GB17 version) to the oscillations with periodicities order of several hundred thousand years. Fig. 6 in Mitsui et al. provides some support for this hypothesis.*

The very long glacial cycles are simulated under present and LGM orbital configurations, respectively (Fig. S6 and S7). For the time scale of these oscillations, CO_2 feedback is more relevant than the glaciogenic dust feedback. We also consider that the gradual increases in CO_2 in glacial states in these simulations correspond to the difference between volcanic outgassing and silicate

weathering. However, it is difficult to attribute the emergent periodicity to a few feedbacks. The period of limit cycle oscillations can be arbitrarily large near bifurcation points, even if the time constants defined by the system's parameters are all finite.
We will perform a set of additional simulations with different values for the prescribed volcanic CO_2 outgassing rate in order to investigate the role of a long-term drift in atmospheric CO_2 resulting from an imbalance between volcanic outgassing and silicate weathering, in the appearance of the internal oscillations in the model.

2. Whatever the mechanism of such long self-sustained oscillations, more important is whether the existence of these oscillations is relevant for the 100-kyr glacial cycles simulated in CLIMBER-2 under realistic orbital forcing. I do not believe that this is the case.

The simulated glacial cycles under realistic orbital forcing are relevant for the internal sustained oscillations. We fully agree that self-sustained oscillations are not mandatory for generating 41-kyr or ~100-kyr cycles. Indeed, in the manuscript, we have not claimed that this is mandatory. **Instead we have proposed that _if self-sustained oscillations exist_, the dominant frequency of glacial cycles under the forcing is related to the period of the self-sustained oscillations.** As shown in Figs 2 and S4, the frequency of the simulated glacial cycles under the presence of realistic orbital forcing is related to the internal time scale of self-sustained oscillations.

First, the shape and typical periodicity of these self-sustained oscillations are very different from the forced 100-kyr cycles.

We have not claimed that the underlying self-sustained oscillations explain all the aspects of ~100-kyr cycles. We agree that the underlying self-sustained oscillations are different from the actual glacial cycles. On the other hand, we can identify common aspects in the self-sustained oscillations and the actual glacial cycles:

- Shape: The self-sustained oscillations are already asymmetric. Glaciations are slightly slower than deglaciations (Figs 4 and 6).

- Periodicity: The mean periodicity of the post-MPT self-sustained oscillations (~250 kyr) is not very different from ~100-kyr. If we focus solely on glaciation and deglaciation phases ignoring quasi-stable glacial intervals, the joint period is closer to ~100 kyr. The orbital forcing may help deglaciations shortening the quasi-stable glacial periods.

Thus we consider that the underlying self-sustained oscillations can be a backbone, allowing asymmetric ~40-to-100-kyr glacial cycles when the system is forced.

Second, the GB17 version does not possess such oscillations but simulates strong 100 kyr periodicity both with constant (sufficiently low) CO_2 concentrations and with interactive CO_2 (Ganopolski and Calov, 2011; GB17). Moreover, other models, which, unlike CLIMBER-2, do not include glaciogenic dust feedback and thus *unlikely to possess similar self-sustained oscillations, also simulate 100-kyr cycles (e.g. Berger and Loutre, 2010; Abe-Ouchi et al. 2013). Thus, although the existence of self-sustained oscillations within a certain range of external boundary conditions may amplify nonlinear system response to orbital forcing at some frequencies, they are not essential for reproducing the main features of the late Quaternary glacial cycles.*

You say that self-sustained oscillations are not essential for actual glacial cycles, citing three ice age models without self-sustained oscillations: LLN-2D (Berger & Loutre, 2010), IcIES-MIROC (Abe-Ouchi et al. 2013) and GB17. However we think that the existence of three good non-oscillatory models does not falsify any other model and that it is important to also investigate the possibility of self-sustained oscillations even if considered less likely as the overall paradigm.

The W19 version of CLIMBER-2 exhibits self-sustained oscillations even without glaciogenic feedback if the carbon cycle feedback is active. We will include this simulation result in the revised manuscript. So the carbon cycle feedback alone can be a potential source of oscillatory instability. In the former two models (LLN-2D and IcIES), the atmospheric CO_2 concentration has been prescribed when simulating realistic glacial cycles. Hence we cannot exclude the possibility of self-sustained oscillations in these two models if a carbon cycle model is interactively coupled. Also GB17 has a potential to produce self-sustained oscillations with slight changes in parameters and setting as in W19. So we consider that we cannot exclude self-oscillatory dynamics for the real ice age dynamics.

Nevertheless we fully agree that self-sustained oscillations are not mandatory for generating 41-kyr or ~100-kyr cycles. Actually, in the manuscript, we have not claimed that it is mandatory. **Instead we have proposed that _if self-sustained oscillations exist_, the dominant frequency of glacial cycles under the forcing is related to the period of the self-sustained oscillations. We will make this point clearer in the revised manuscript.**

Regardless of the existence of self-sustained oscillations, we suppose that the dominant frequency of glacial cycles under the forcing can be determined in relation with the internal time scale. The internal time scale is apparent when the self-sustained oscillations are presented, but it is not obvious in non-self-oscillatory systems. Developing a unified explanation for self-oscillatory and non-self-oscillatory systems is left for future work.

References

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