Response to the review of Andrey Ganopolski (Referee #2)

Dear Referee,
Thank you for reviewing our manuscript and for your effort and time spent on this. Your constructive feedback will help to improve the final revised version of this manuscript.

Based on this feedback, we will substantially revise the manuscript with the following main changes:

- we will reduce the complexity of the used model to rely on fewer parameters
- The benthic δ^{18}O curve (probstack with removed trend) from Clark et al. (2025) will be used as a new main target. Berends and Rohling SL curves will only be shown in SI
- ORB, ABR and GRAD models will be removed to focus on the novel RAMP model. This will make the manuscript more concise and highlight the novelities compared to the Legrain et al. (2023) model

In the following, we respond to your comments and propose several changes to the manuscript, motivated by your suggestions.

Author comments
Referee comments

General comments

Conceptual model. The model used in this study originates from the Paillard conceptual model of glacial cycles (Paillard, 1998). This model was then considerably revised by Parrenin and Paillard (2012) (hereafter referred to as PP12). Firstly, the authors of this paper abandoned Milankovitch theory of glacial cycles and delegated the determination of the 'orbital forcing' to the optimization algorithm. Secondly, they introduced two completely different 'orbital forcings': one determines the linear response of the global volume while another one determines nonlinear response, namely transitions between glacial and deglaciation regimes. However, since they tune the model only to glacial cycles of the late Quaternary, both 'orbital forcings' at least qualitatively resembles each other and boreal summer insolation. Unfortunately, the authors did not explain why they need two orbital forcings instead of one. In Legrain et al. (2023) (hereafter referred to as L23), the same model has been applied already to the entire Quaternary, and the model parameters were fitted to Berends global ice volume simulations. Since Berends ice volume contains very little precession even for the late Quaternary, the result of such tuning is easy to understand. The 'linear orbital frorcing' (I_α) is dominated by obliquity while 'nonlinear orbital forcing' (I_k) by presession. (How such a situation could occur in the real world is not explained). Without strong precessional component in Ik, it would not be possible to simulate glacial cycles of the 100-kyr world, but too much precession disturbs the 41-kyr world. This is why, the optimization algorithm chooses model parameters for the early Quaternary in such a way that another central element of Pallard's conceptual model - the existence of two distinct glaciation and deglaciation regimes - also vanishes. As can be seen in Fig. 2, the model switches several times between glaciation and deglaciation regimes during a single glacial cycle. As the results, what is described in the paper is not a conceptual model but rather a mathematical immolator of glacial cycles, where a good agreements with 'reconstructions' is achieved by using 16, 17 or even 19 model parameters, the physical meaning of which is hard to understand.

We accept the critique of relying on too many model parameters and on two different orbital forcings. Hence, we set up a reduced version of the RAMP model (described below), which allows us to show the effects of a ramp-like change in the deglaciation parameter.
The necessity of having I_α and I_k arises from using non-normalised units and dimensions for the target. This is discussed in more detail below (see comments on Model performance). However, for the reduced model, we circumvent this issue by scaling the orbital forcing to the ice volume, which allows us to rely on a single insolation metric for the model.

Model description. Although the model used in the study has been described in several papers, some aspects require clarifications and corrections. Firstly, it is unclear whether conditions for regime changes denoted by (i) and (ii) should be met simultaneously. According to PP12 it seems that both conditions must be met :

$$\begin{aligned} \text{g to d: } & k_{\mathrm{Esi}}\mathrm{Esi}(t) + k_{\mathrm{Eco}}\mathrm{Eco}(t) + k_{\mathrm{Ob}}\mathrm{Ob}(t) + v \geq v_0 \\ & (\text{and } k_{\mathrm{Esi}}\mathrm{Esi}(t) + k_{\mathrm{Eco}}\mathrm{Eco}(t) + k_{\mathrm{Ob}}\mathrm{Ob}(t) \geq v_1) \end{aligned}$$

but it is unclear to me why the second condition is in brackets.

In this model, as well as for the PP12 and L23 models, both conditions must be met simultaneously. We agree that writing the second condition in brackets is misleading. However, in this manuscript, it is clearly stated that both conditions must be met simultaneously (see Eq. 6 and 7). Having a look into the source code of the Leloup and Paillard (2022) model reveals that both conditions must be fulfilled there as well, although not being mentioned in their model description (their Eq. 2).

Secondly, the model employs two different times denoted by the same letter 't'! One time, used in the differential equation for ice volume has 'physical' (i.e. normal) direction, while the second time, which determines the evolution of model parameters, goes in the 'paleo' (i.e. reverse) direction. This is very confusing. Using of the same notations (v_0 and τ_d) for two different characteristics (one constant and another time-dependent) is also not a good idea.

We agree. We followed the convention used in Legrain et al. (2023), but we agree that this can lead to misunderstandings. Therefore, we propose to use the following formulation for the RAMP model:

$$v_0(t) = \begin{cases} v_{0,1}, & \text{if } t > t_1 \\ v_{0,1} - \frac{v_{0,2} - v_{0,1}}{t_1 - t_2}\left(t - t_1\right), & \text{if } t_1 \geq t \geq t_2 \\ v_{0,2}, & \text{if } t_2 > t \end{cases} \tag{1}$$

where $v_{0,1}$ denotes the constant value prior to the onset of the ramp at time t_1 and $v_{0,2}$ the constant value after the ramp at time t_2. The time t is given in paleo units (kyr BP).

Improved model. The title of the paper begins from "*An improved conceptual model*", but, surprisingly, it is not clear from the manuscript what they meant under "improved model". The manuscript makes an impression that the 'improved model' is RAMP-l but in page 27 it is written *'we constructed an improved conceptual model of Quaternary global ice volume, including four different internal forcing scenarios, alongside another model configuration... We showed that the RAMP-l model...'* I am not sure how this should be interpreted. The improvements compared to L23 are also not clearly described. Only after the comparison of the equations in Pollak and L23, one can understand that 'deprecated truncation function' means that the authors decided not to use truncation of insolation introduced in Paillard (1998) and then uses in PP12 and L23. Why the authors consider this an improvement is not explained.

In the manuscript, we sometimes refer to the ORB, ABR, GRAD and RAMP models as different scenarios of one model, and sometimes we refer to them as individual models. We agree that this can lead to misunderstandings. In the revised manuscript, we will only present one model, which will eliminate this misunderstanding. By improved model, we refer to improvements in each of the individual models that were already performed in Legrain et al. (2023) (ORB, ABR and GRAD), i.e. the ORB/ABR/GRAD model in this study outperforms the ORB/ABR/GRAD model in Legrain et al. (2023). Furthermore, the RAMP and RAMP-l models yielded better results than the GRAD model.
One major improvement compared to the Legrain et al. model is of technical nature regarding the improved tuning strategy and the improved speed of the code. However, this was barely mentioned in the manuscript, since we wanted to focus on the model output rather than on these technical details. The model speed was significantly increased by translating the code into JAX (a python library which allows for accelerated computation and just-in-time compilation). Furthermore, we added three additional solvers, namely ptemcee (parallel-tempered MCMC), dynesty (dynamic nested sampling) and PyMC. With the improved tuning procedure and with the increase in speed, which allows a more rigorous tuning, we could already reduce the model data mismatch compared to the original Legrain et al. model, without any changes in the parameterisations. We propose to add a paragraph in the model section of the revised version of the manuscript, where we highlight the increase in speed and the newly added solver to the model.
The increase in speed and the refined tuning allowed us to test various parameterisations in the model and come up with a new version of the RAMP model with reduced complexity. For the revised version of the manuscript, we propose to only present this reduced RAMP model (described below), which relies on fewer model parameters and uses only one orbital forcing. The other models will be dropped in the revised manuscript. By doing so, we can clearly indicate the changes in parameterisation compared to the Legrain et al. (2023) model and discuss its improvements.

At the same time, the author introduced a new time-dependent parameter td which is the relaxation time scale during deglaciation and which is in Paillard (1998) model determined the duration of glacial termination. However, what is the meaning of this parameter in Pollak et al. is unclear: during the early Quaternary its value in GRAD, RAMP and RAMP-l models is about 40 kyr, i.e. close to the duration of the entire glacial cycles. Even worse, in ABR model version, the relaxation time scale is -113 kyr, but the 'relaxation time scale' cannot be negative by definition. The meaning of negative v0 in the RAMP model is equally hard to interpret.

τ_d cannot be directly compared to values obtained in the P98 or the Leloup and Paillard (2022) model, since the constant α_d was added in the PP12 model. Therefore, it always has to be considered with the corresponding value of α_d. The initial idea in the P98 model was that once the model enters a deglaciation state, the term $\frac{v}{\tau_d}$ can quickly decay large ice volumes. This only works for positive values of τ_d. Therefore, it is in fact questionable why a negative value of -113 kyr appears in the ABR model. The negative sign of τ_d makes the whole $-\frac{v}{\tau_d}$ term positive, which reduces the rate of change in $\left(\frac{dv}{dt}\right)_d \left(= -I + \alpha_d - \frac{v}{\tau_d}\right)$. However, α_d is highly negative for the ABR model ($\alpha_d = -0.81$), compensating the positive $-\frac{v}{\tau_d}$ term and still leading to a fast deglacial decay. To avoid this behaviour in the model and improve the physical interpretability of the τ_d parameter, we will remove the α_d parameter in the reduced model version. Furthermore, we will remove the time dependency of τ_d to focus on the change in the deglaciation parameter and reduce the number of parameters. Since we are using a non-normalised ice volume reconstruction, negative values for the ice volume appear during the early Quaternary and prior to ~2.8 Ma, before the onset of NH glaciations. In the Berends SL curve, the values are reported with respect to present-day conditions. This can result in negative values for $v_0(t)$ during early time periods.

Insolation. According to the Milankovitch theory, changes in boreal summer insolation is the driver of glacial cycles, but since PP12 abandoned Milankovitch theory, it is rather surprising that the term 'insolation' appears in section 3.5. The term 'insolation' has a very clear meaning: 'insolation' is the abbreviation for 'incoming solar radiation' and is measured in W/m^2 (or equivalent units). The 'orbital forcings' I_α and I_k used in the paper have nothing to do with the real insolation and therefore the terms 'insolation' and 'insolation maximum' in the context of the paper is misleading.

We agree. We will instead use the term *orbital forcing* in the revised manuscript

Ice volume reconstruction. The author used the Berends reconstruction of global ice volume. Like any other reconstruction, the Berends reconstruction contains significant uncertainties and deficiencies. For example, for the Last Glacial Maximum, for which there are numerous independent data, Berends underestimates global ice volume by more than 20% and also underestimates ice volume variability during MIS5. For MIS3 different reconstructions for global ice volume range between 30 and 90 meters (Farmer et al., 2023 PNAS), i.e. the uncertainties are about 50%. It is very likely that for the early times, the uncertainties are even larger. This makes reported improvements in RMSE order of several meters completely insignificant.

We agree. We will follow the advice from all three referees and no longer use the Berends or Rohling sea level curves as our main tuning targets in the revised manuscript, but only show them in the SI. To discuss the limitations of these model-based sea level reconstructions, we

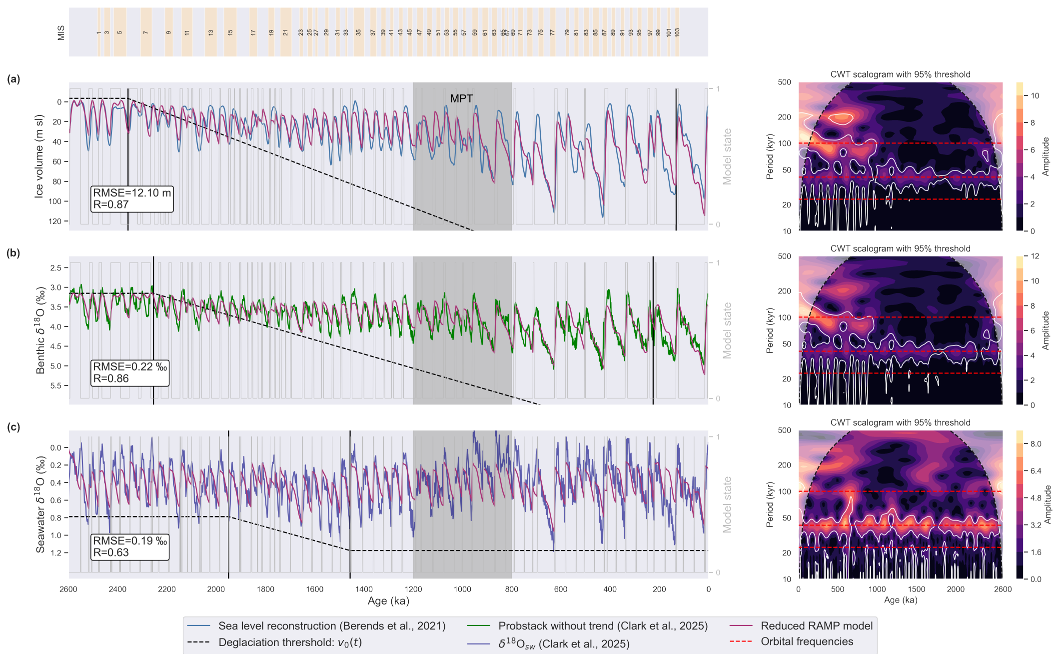

Figure 1: Reduced RAMP model tuned on three different tergets: a) Berends et al. (2021) sea level curve, b) Clark et al. (2025) benthic $\delta^{18}O_b$ (probstack with trend removed) and c) Clark et al. (2025) sea water $\delta^{18}O_{sw}$.

propose to add the following paragraph to our discussion:

"Available global mean sea level data exhibit large uncertainties. Between 50 and 30 ka, geological and geochemical reconstructions of GMSL vary up to 60 m and above (Farmer et al., 2023). Model-based deconvolutions of global $\delta^{18}O$ into GMSL, like for the Berends et al. (2021) and Rohling et al. (2022) sea level reconstructions, exhibit similar large uncertainties. While the Berends curve shows an LGM lowstand of around 100 m, the Rohling curve gives around 108 m. Both values are well below observational-based reconstructions of around 130 - 135 m for the LGM (Austermann et al., 2013; Lambeck et al., 2014; Yokoyama et al., 2000). These large uncertainties limit the usability of sea level reconstructions as targets for conceptual models, as presented in this study."

Instead of using the Berends sea level curve, we will follow the advice from Referee 1 and use the benthic $\delta^{18}O$ record (probstack with trend removed) from Clark et al. (2025) as our main target. Furthermore, we will discuss the model performance on the newly available seawater $\delta^{18}O_{sw}$ record from Clark et al. (2025), based on a benthic $\delta^{18}O$ deconvolution motivated by an ocean temperature data compilation. It gives a contrasting view compared to the Berends and Rohling deconvolutions by exhibiting a rise in $\delta^{18}O_{sw}$ during the MPT, interrupting a previous period of increasing values and showing larger glacial-interglacial amplitudes in the pre-MPT cycles. However, a final reconstruction of this $\delta^{18}O_{sw}$ record into sea level is not yet available. That's why we will mainly focus on the benthic record. Following your advice, we reduce the complexity of the RAMP model (discussed later). The results of this reduced RAMP model for the three different tuning targets (Berends SL, Clark $\delta^{18}O_b$, Clark $\delta^{18}O_{sw}$) can be seen in Fig. 1. Our reduced RAMP model yields similar results for this target, i.e. a long-lasting trend for the ramp, which started over 2 Ma. While the model performs well on this target, it has more difficulties with the seawater δ^{18}O record from Clark et al. (2025) (Fig. 1c), as can be seen by comparing the R values. In general, the model cannot accurately reproduce the larger pre-MPT amplitudes of the glacial-interglacial cycles and the decreasing trend of $\delta^{18}O_{sw}$ during the MPT. The RAMP formulation seems to be less suited for this target, as can be seen by the identified ramp period, which lies now in the interval $\sim$ 400 - 200 ka. For the $\delta^{18}O_{sw}$ target, the model also cannot reproduce the shift towards the 100-kyr periodicity correctly, since it only shows a 100-kyr signal for the last 200 ka.

Even more strange to see 6, 7 and even 8-digit numbers in Table A1. It is clear that so many digits originate from Monte Carlo, but in natural sciences, it is customary to report only significant digits. The paper also says nothing about the robustness of the modelling results with respect to the choice of model parameters.

We are well aware that it is not conventional to use so many digits in natural science. The reason behind this was to report the exact parameter values that were used in the model, since the model output can be sensitive to specific parameters. Hence, in order to allow interested readers who want to re-run the simulations, it is important to report the exact set of parameters used. However, since they are also documented in the available GitHub repository, we accept this critique and will change the number of significant digits in this Table to enhance readability.

Simulation of MPT. The main objective of the paper (similarly to L23) is to simulate MPT. Clearly, MPT cannot be explained by orbital forcing alone; therefore, the purpose of the ORB version is unclear.

One reason to include the ORB model, similarly including the ABR and GRAD models, was to show the effects of the new tuning strategy in combination with changes to the initial parameterisation as described in Legrain et al. (2023). The improved tuning strategy alone could already reduce the model-data mismatch (not shown in the manuscript). The other reason for including the ORB model was to have a 'baseline' model, which can be used to compare the RAMP model with and to see the effects of adding a ramp-like change to the model.
Actually, there are recent studies linking the occurrence of the MPT to orbital forcing alone. Ma et al. (2024) introduce the *integral of annual mean insolation anomaly* (IAMIA), which quantifies successive small step-wise insolation changes over a given period of time. The authors show that IAMIA exhibits a large shift around 935 ka, which they hypothesise to have enabled the onset of the MPT. Another recent preprint by Verbitsky and Omta (2025) discusses the idea that the MPT is due to a delayed relaxation process, which can lead to an abrupt-like jump in the dominant period. This shift in periodicity can be highly sensitive to the initial conditions, and the sensitivity depends on the amplitude of the orbital forcing.

However, since our model yields the same result as in Legrain et al. (2023), namely that orbital forcing alone cannot explain the MPT, we will, to keep the manuscript concise, drop the ORB model from the revised manuscript and just refer to the Legrain et al. (2023) paper.

Secondly, even without modelling, it is clear from data analysis alone that the MPT (Mid-Pleistocene Transition) was a transition, not an event, and that it lasted for at least several hundred thousand years. This is why the purpose of the repeating of ABR scenarios is unclear. Regarding the mechanism(s) of the MPT (which are still debatable), it is unclear how the experiments presented in this manuscript can shed light on the cause of the MPT transition. The problem with strongly nonlinear systems, such as the Earth system, is that even gradual changes of the controlling parameters can cause a rather abrupt regime changes (e.g. Willeit et al., 2019).

To highlight the novel RAMP model and the differences compared to the Legrain et al. (2023) paper, we will remove the ABR and GRAD models from the revised manuscript. Indeed, these conceptual models cannot shed light on the underlying physical mechanisms directly (e.g. whether a long-term trend in v_0 is due to regolith removal or a gradual CO_2 decrease, etc.), since they do not include the involved physical or chemical processes directly. However, their strength lies in their capability to investigate the underlying temporal structure of such a change. While the ORB, ABR and GRAD models all rely on a specific scenario, the RAMP model selects the most likely scenario to reconstruct the observed paleo record, i.e. the benthic δ^{18}O record from Clark et al. (2025). Multiple scenarios are possible in the RAMP model:

- $v_{0,1} = v_{0,2}$ (or almost; Eq. 1 above): (almost) no change in the deglac. threshold $\rightarrow$ (almost) purely orbitally forced $\widehat{=}$ ORB model
- $t_1 = t_2$ (or almost): abrupt-like scenario $\widehat{=}$ ABR model
- $t_1 = 2.6$ Ma and $t_2 = 0$ Ma (or almost): gradual scenario over the entire Quaternary $\widehat{=}$ GRAD model
- a scenario in between with a gradual change limited over a specific time period

Hence, the RAMP model already incorporates the ORB, ABR and GRAD scenarios and selects the one which can best reproduce the target record (another reason why we agree to drop these models from the revised manuscript). This yields interesting information about how such a temporal change could have looked like.
So, actually, the outcome of our RAMP model is that it supports the idea of a long-lasting change that started already very early in the Quaternary, more than 2 Ma, instead of a rather short and limited change (e.g. which only lasted during the MPT).
An alternative approach is presented in Ganopolski (2024), where the author prescribes the change in the critical ice volume parameter v_c (similar to our v_0) by relating it to the regolith-free scenario described in Willeit et al. (2019). This shows that the regolith-free scenario can reproduce the MPT, but since it relies on a single prescribed temporal structure for this change in v_c, it gives no information on how likely such a temporal structure is.

It is quite possible that the gradual decline in CO2 and landscape evolution (including regolith removal) began not only well before the MPT but also before the Quaternary, and there is no way to derive this from the experiments described in the manuscript.

This is exactly the strength of the RAMP model, since it gives information about a potential start and end of such a gradual change. The L23 GRAD model was only run for the past 2 Ma, therefore, it does not allow earlier changes in v_0, but our RAMP model reveals that the change in v_0 likely started even before 2 Ma. In contrast, other models either use a gradual trend over the entire simulation period (e.g. GRAD model, P98 model, Leloup model) or use one specific temporal structure (e.g. Model 3 in Ganopolski (2024)). While these models give no information about when such a gradual trend could have started and ended, the RAMP model does.

The role of precession. Firstly, the model used in the study of Pollak cannot be used to study the role of precession and obliquity. This is not a physically-based model and the model parameters are just chosen by the optimization algorithm in such a way that glacial termination of late Quaternary occur in the right times. And this 'right times' coincide with the periods of rising boreal summer insolation. In turn, boreal summer insolation is dominated by precession. This is why the optimization algorithm picked up precession.

The analysis of the RAMP-l model will be removed in the revised manuscript, since we agree to reduce the model complexity and we will only focus on the main parameters to highlight the results coming from the new ramp-like formulation.
While we cannot directly investigate the physical effects of precession and obliquity in the climate system with our model, we can investigate their influence in the dynamics of our model. By using a linear combination of precession and obliquity rather than a single insolation metric, we can explicitly see which roles these two orbital quantities play in the model. In the reduced RAMP model, we will only rely on a single orbital forcing (instead of having I_α and I_k), which e.g. allows us to investigate the spectral power of the obtained orbital forcing in this model (Fig. 3a).

Secondly, the fact that glacial terminations of the late Quaternary are mainly determined by precession has been known well before Barker et al. (2025). Already Raymo (1997) noted that 'the length between subsequent terminations is either four or five precessional cycles long'. This idea was further developed by Ridgewell et al. (1999) who wrote that 'the spectral signature of δ^{18}O records are entirely consistent with Milankovitch mechanisms in which deglaciations are triggered every fourth or fifth precessional cycle'

Barker et al. (2025) presents the most recent analysis on the role of precession and obliquity for glacial cycles in the 100 kyr and 41 kyr world. Therefore, as Referee 1 also points out, a special focus should be on this paper.

Future glacial cycle simulations. The authors also used their models to simulate future glacial cycles. According to these simulations, the next glacial cycle has either already begun or will begin soon in the absence of anthropogenic influence. The authors are, of course, aware that this contradicts to the results of the physically-based models and is therefore likely to be incorrect. This is why they attempted to defend their model by arguing that in Ganopolski et al. (2016) glacial inception occurs with the current orbital forcing if pre-industrial CO_2 were 240 ppm. This is absolutely correct, but among many uncertainties, there is one thing which we know for sure – the preindustrial concentration was 280 ppm, and this value is typical for post-MBT interglacials. Therefore, the unprecedently long Holocene is the robust and most striking feature of the next 100 kyr. Since this feature is not reproduced by Pollak et al., the value of such modelling exercises is called into serious doubt.

While neglected in most other conceptual models, we believe that extrapolating at least the next glacial cycle reveals important model dynamics. The extrapolated curves do not resemble nature, as they lack anthropogenic CO_2 emissions. Therefore, they must be interpreted as purely academic thought experiments. More complex models, coupled to the carbon cycle, project, even without any anthropogenic influence, an unprecedentedly long interglacial, lasting for another 50 kyr (Ganopolski et al., 2016; Talento and Ganopolski, 2021). In contrast to this, all of our models, no matter of which simulation period, project that the next glacial cycle has just started or is about to start. In their recent study, investigating the influence of precession and obliquity on glacial interglacial cycles, Barker et al. (2025) estimate that the current interglacial conditions would last for 11 kyr, when obliquity reaches its next minimum and the succeeding glacial would be interrupted in around 66 kyr (again neglecting anthropogenic effects). Other conceptual models similarly predict a contrasting view for the next glaciation: Calder (1974) projected a start 5 ka and an end in around 119 kyr (see his Fig. 2), Imbrie and Imbrie (1980) estimated a start 6 ka (see their Fig. 7) and Fig. 5 in Paillard (2015) reveals that only a large enough glaciation threshold can lead to a prolonged Holocene in the Paillard (1998) model, while a lower threshold would have terminated the Holocene already a few kyr ago. While other models like the L23, Model 3 (Ganopolski, 2024) and Leloup and Paillard (2022) were not extrapolated for the next glacial cycle, it can be expected that they would yield similar results (i.e. a short Holocene) compared to our model, since they are based on similar model dynamics. Therefore, we believe that the failure in simulating a prolonged Holocene in our model, as well as in other conceptual models or studies, is a striking feature, which is worth mentioning, and might be due to the missing carbon feedback in the model or a glaciation threshold which only depends on orbital forcing or parameters.

Model performance. The authors compared their version of the PP12 model with the L23 model, as well as the 19-parameters RAMP-l with the 16-parameters RAMP and using BIC, they claimed significant improvements. However, the MiM (minimal model which I reported in my 2024 paper), which is a simplification of the Leloup and Paillard (2022) model (which in turn is a simplification of original Paillard 1998 model) simulates the last 800 kyr (arguably the most interesting and difficult period of climate history) as good as RAMP ($R2=0.73$). But MiM has only 4 parameters (nondimensional version of MiM described in Ganopolski 2024 has three parameters). By contrast, RAMP uses 12 parameters to simulate the late Quaternary. The natural question is for what purpose we need models with so many parameters and what can we learn from them.

The MiM model and Model 3 described in Ganopolski (2024) present impressively how few parameters are needed to simulate the 100-kyr world or the entire Quaternary. These models were specifically designed to show how few parameters are needed to achieve this goal. If these models indeed present the minimal models required to reconstruct the 100-kyr world or the Quaternary, any other conceptual model which tries to investigate some specific feature during the Quaternary will need to add further complexity to the model. While not all extra parameters are needed, we highlight the main differences in the following:

- MiM and Model 3 are normalised, while the RAMP model has units of global ice volume. Due to the normalisation, the MiM model does not need a v_0 and v_1 parameter, but can simply apply state changes whenever $v = 0$ or $v = 1$. Such a threshold also leads to unrealistic 'flat' interglacials, which always result in full deglaciations (see Fig 3, 10 in Ganopolski (2024)). Such a model cannot reproduce shifts in interglacial conditions (e.g. interglacial values of $\delta^{18}O_{sw}$ in Clark et al. (2024) differ significantly).

- MiM model uses a single metric for the orbital forcing, while RAMP depends on a linear combination of precession, co-precession and obliquity. It can be expected that the RAMP model would work equally well when using normalised summer solstice insolation at 65° N (or an equivalent measure) as an input for the orbital forcing. However, as Leloup and Paillard (2022) have shown, the model-data agreement depends on the selected forcing and can pose a bias to the results, since the different orbital metrics have different weights of precession and obliquity. Hence, we explicitly do not want to use a single metric in our model to remove any source of bias to the model. Instead, we use the same approach as in Imbrie et al. (2011) and Legrain et al. (2023), where orbital forcing is obtained as a linear combination of precession, co-precession and obliquity. This adds three extra parameters to the RAMP model ($\alpha_{\text{Esi}}, \alpha_{\text{Eco}}, \alpha_{\text{O}}$)

- In a normalised and dimensionless model, there is no need for I_α and I_k, but just one forcing would be sufficient. First off, I_α (m/kyr) and v (m) have different units, therefore, the threshold $I_\alpha + v$ is not possible. Secondly, I_α has values between -2 and 2 in our RAMP model, which is much smaller compared to v, which has values between 0 and 120. Hence, the influence of the orbital forcing in the threshold $I_\alpha + v$ would be negligible. Such an issue does not occur in normalised units, as can be seen in the Leloup and Paillard (2022) model. Here, they use the same threshold $I + v \geq v_0$, but can rely on a single orbital forcing $I(t)$. To circumvent this issue, the k-parameters were originally introduced in the Parrenin and Paillard (2012) model. This adds three extra parameters to the RAMP model: $k_{\text{Esi}}, k_{\text{Eco}}, k_{\text{O}}$

- The objective of the RAMP model is to investigate the temporal structure of an internal change in the system causing the MPT. Hence, we explicitly want to have freely adjustable time points t_1 and t_2 in the model, as well as $v_{0,0}$ and $v_{0,1}$. In contrast, Model 3 prescribes the temporal structure of its change in v_c, by using the regolith-free scenario from Willeit et al. (2019), which requires two parameters less (no t_1 or t_2), but therefore, it only tests one specific temporal structure.

- Note: the initial ice volume v_i is also counted as a model parameter, since it has to be adjusted for different simulation periods and targets. If we neglect this parameter, as done in Ganopolski (2024), we always have one parameter less than reported in the manuscript

To reduce the complexity of the model (formulas shown below), we will remove the following parameters from the model, which we identified to be less important or that reduce the interpretability of the results:

- α_{Eco}: While we will still use a linear combination of precession and obliquity for our forcing, which allows the model to adjust its obliquity and precession signals on its own, we found that precession and co-precession are not needed both, but just one of them is sufficient to obtain this goal. Hence we will drop co-precession (Eco) and its related parameters ($\alpha_{\mathrm{Eco}}, k_{\mathrm{Eco}}$) from the reduced RAMP model

- $k_{\mathrm{Eco}}, k_{\mathrm{Esi}}, k_{\mathrm{O}}$: We will adjust our threshold ($I + v \geq v_0$) in such a way that it is possible to rely on a single orbital forcing and that we no longer require these three parameters

- α_d: free model parameter which was first introduced in the PP12 model. While it allows more flexibility in the model by adding a constant offset to $\left(\frac{\mathrm{d}v}{\mathrm{d}t}\right)_d$ it does not alter the general findings of the RAMP model. It also reduces the physical interpretability of τ_d, since it always needs to be considered in combination with α_d. Therefore, it will be removed

- τ'_d: to focus on the change in the deglaciation parameter $v_0(t)$ and to show how a ramp-like change of it can affect the simulation output, we will remove the time dependency in τ_d and use it as a constant parameter again

The objective of the RAMP model was not to overfit the model to some target record by successively adding more parameters. Instead, the objective was to use a ramp-like change in v_0 to obtain information on how the temporal structure of a gradual change could have looked like and, doing so, to reduce the model data mismatch, compared to the L23 model. To accept the critique of relying on too many model parameters and to show that the ramp formulation yields similar results, we set up a reduced RAMP model (shown below). This reduced RAMP model uses only 10 parameters (9 if the initial ice volume is not counted). Hence, it has 4 parameters less than the GRAD model of L23, 6 less than the original RAMP model and 9 less than the RAMP-l model.

Reduced RAMP model:

- Orbital forcing:

$$I(t) = \alpha_{\mathrm{Esi}}\mathrm{Esi} + \alpha_{\mathrm{O}}\mathrm{Ob} \tag{2}$$

- Differential equations:

$$\mathrm{g}: \frac{\mathrm{d}v(t)}{\mathrm{d}t} = -I(t) + \alpha_g, \tag{3}$$

$$\mathrm{d}: \frac{\mathrm{d}v(t)}{\mathrm{d}t} = -I(t) - \frac{v(t)}{\tau_{\mathrm{d}}}, \tag{4}$$

- State transition **(g)** $\rightarrow$ **(d)**:

$$\text{(i)} \quad v(t) \cdot \tilde{I}(t) + v(t) > v_0(t) \qquad \& \qquad \text{(ii)} \quad v(t) \cdot \tilde{I}(t) > v_1, \tag{5}$$

- State transition **(d)** $\rightarrow$ **(g)**:

$$\text{(i)} \quad v(t) \cdot \tilde{I}(t) + v(t) < v_0(t) \qquad \& \qquad \text{(ii)} \quad v(t) \cdot \tilde{I}(t) < v_1, \tag{6}$$

- Dimensionless orbital forcing: $\tilde{I}(t) = \frac{I(t)}{[I]}$
- Ramp-like change in v_0:

$$v_0(t) = \begin{cases} v_{0,1}, & \text{if } t > t_1 \\ v_{0,1} + \frac{v_{0,2}-v_{0,1}}{t_2-t_1}\,(t-t_1)\,, & \text{if } t_1 \geq t \geq t_2 \\ v_{0,2}, & \text{if } t_2 > t \end{cases} \tag{7}$$

- 9 model parameters: $\alpha_{\mathrm{Esi}}, \alpha_{\mathrm{O}}, \alpha_{\mathrm{g}}, \tau_d, v_{0,1}, v_{0,2}, t_1, t_2, v_1$
- Note on the changed threshold: as mentioned above, $I + v > v_0$ does not work for a non-normalised model as presented here. To circumvent this, we firstly use the dimensionless orbital forcing $\tilde{I}$ for the threshold. Secondly, we have to scale the orbital forcing, s.t. it has a similar order of magnitude as the ice volume $v(t)$. Hence, we multiply $\tilde{I}(t)$ with v. Now, both terms have same units and order of magnitude. The term $v \cdot \tilde{I}$ can also be interpreted as an ice volume dependent orbital forcing, effectively making large ice sheets more sensitive to orbital forcing
- We propose including the above model description and the discussion about which model parameters to drop from the new model and why in the revised manuscript. This will highlight the changes made with respect to the L23 model and underline the novelities

Specific comments

L10. The meaning of '*internal focing*' is unclear. The authors prescribed temporal evolution of several model parameters, not forcing.

Will be corrected to '... a ramp-like change in the temporal evolution of the deglaciation parameter.'

L.12 '*support the idea of a long-term climatic shift as a cause of the MPT*'. In fact, MPT is the climate shift, whereas the cause(s) of MPT may have nothing to do with climate, like the 'regolith hypothesis'.
Will be corrected to: '... long-term shift in the underlying Earth-climate system as a cause of the MPT'.

L.131. Unclear what the authors meant under 'versatile model' since even a slight change in the temporal scenario (GRAD to RAMP) causes significant changes of all other model parameters.

The term 'versatile' refers to the easy-adjustability of the model. We propose to replace this sentence with the following:
"The new RAMP model is characterised by its easy adjustability. In comparison with the L23 model (Legrain et al., 2023), it can be run on different time scales, be extrapolated into the future, be run on different tuning targets (Berends sea-level, Rohling sea-level, Clark benthic $\delta^{18}\mathrm{O}_b$, Clark seawater $\delta^{18}\mathrm{O}_{sw}$) or climatic variables (sea level, $\delta^{18}O$), and it can be easily re-tuned for new parameterizations (e.g. allowing to test the effects of changes in the

state thresholds, model forcing, etc.)."

L. 147. '*a linear combination of three orbital parameters normalized to zero mean and unit variance that can reproduce the insolation at most latitudes and seasons*'. This is incorrect. An arbitrary combination of these three parameters does not reproduce insolation at any latitude and at any time.

This approach is not new and has been used in previous models (Imbrie et al., 2011; Parrenin and Paillard, 2012; Legrain et al., 2023). The emphasis in the sentence is on *most*, it does not state *any*.
Imbrie and Imbrie (1980) explain this approach: "Combinations of orbital functions ϵ (obliquity), $e \sin \omega$ (precession) and $e \cos \omega$ (phase-shifted precession) are used as a forcing for our model, and are taken from (Laskar et al., 2004). Insolation at most latitudes and seasons can be represented quite accurately by a combination of these three orbital functions." (Imbrie et al., 2011, p. 2)
Furthermore, they discuss: "Our model uses orbital forcing which is a linear combination of ϵ (obliquity), $e \sin \omega$ (precession) and $e \cos \omega$ (phase-shifted precession). The choice of which linear combination to use is data-driven, in that a regression analysis is used to determine which combination best explains y', the rate of change in ice volume. In our view, this is preferable to working with a preconceived notion of which latitude and season is the most suitable for use in the forcing function." (Imbrie et al., 2011, p. 16).
We fully agree with Imbrie et al. (2011) that not relying on a specific orbital forcing is preferable. To demonstrate that even two orbital parameters (precession parameter and obliquity) can almost perfectly reconstruct various Insolation curves, we demonstrate this for five exemplary insolation curves (see Fig. 2). Insolation (I), precession (Esi) and obliquity (Ob) values are taken from Laskar et al. (2004) and were normalised. ISI computation was carried out with code from Leloup and Paillard (2022). $I_{aprox} = \alpha_{Esi}\mathrm{Esi} + \alpha_{\mathrm{O}}\mathrm{Ob}$ is the linear combination. We find the following solutions for these five orbital forcings:

- I_{SS}^{65N}: Insolation at 65° N on 21$^{\text{st}}$ June: $\alpha_{\text{Esi}} = -0.917,\ \alpha_{\text{O}} = 0.393$
- I_{WS}^{65N}: Insolation at 65° N on 21$^{\text{st}}$ December: $\alpha_{\text{Esi}} = 0.093,\ \alpha_{\text{O}} = -0.991$
- I_{SS}^{Eq}: Insolation at the Equator on 21$^{\text{st}}$ June: $\alpha_{\text{Esi}} = -0.995,\ \alpha_{\text{O}} = -0.094$
- I_{WS}^{90S}: Insolation at 90° S on 21$^{\text{st}}$ December: $\alpha_{\text{Esi}} = 0.892,\ \alpha_{\text{O}} = 0.451$
- $\mathrm{ISI}(\tau = 300)_{65N}$: ISI above 300 W/m^2 at 65° N: $\alpha_{\text{Esi}} = -0.523,\ \alpha_{\text{O}} = 0.850$

L. 168. '*the model can also incorporate an internal forcing mechanism to account for non-linear feedback mechanisms within the climate system*'. Which forcing and feedbacks are meant here is unclear.

We will no longer use the misleading term '*internal forcing*' or '*internal forcing scenarios*', but rather speak of '*temporal change in the deglaciation parameter*'.

Table 3. Why number of model parameters in Table 3 does not coincide with Table A1.

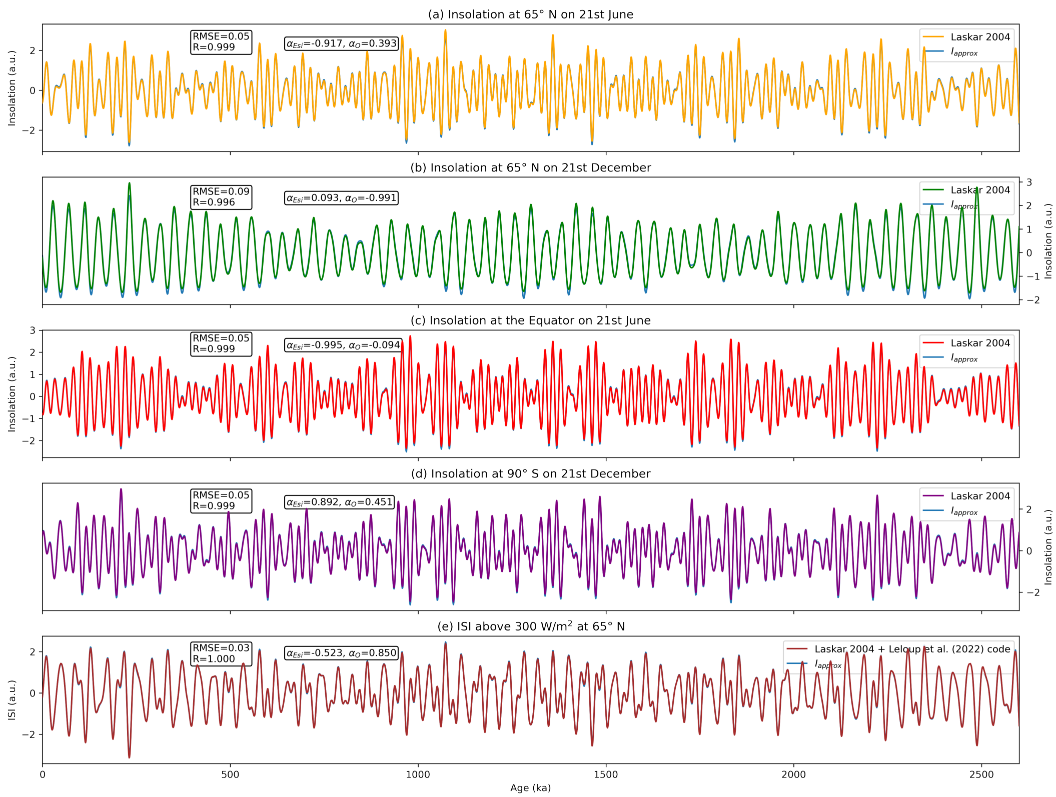

Figure 2: Various Insolation curves from Laskar et al. (2004). ISI computation was carried out with code from Leloup and Paillard (2022). I_{approx} is their optimal linear approximation, based on a linear combination of precession (Esi) and obliquity (Ob): $I_{approx} = \alpha_{\mathrm{Esi}}\mathrm{Esi} + \alpha_{\mathrm{O}}\mathrm{Ob}$.

Perhaps I am overlooking something, but they are the same? ORB has 12, ABR has 15, GRAD has 14, RAMP has 16 and RAMP-l has 19 parameters.

L. 460. 'each or every second insolation peak resulted in a deglaciation'. What is meant under insolation peak is unclear.

Incorrect naming of insolation will be replaced by 'orbital forcing'.

L. 502 'integrated summer insolation (ISI) reported in the literature'. Firstly, this is not an appropriate way to refer to the published concept. ISI was introduced by Huybers in his 2006 Science paper. Secondly, the authors should explain how ISI is defined.

Accepted. We propose to replace the sentence by:
"The integrated summer insolation (ISI) was introduced by Huybers (2006) and is defined as the sum of insulations on days exceeding some threshold τ:

$$\text{ISI}(\tau) = 86,400 \cdot \sum_i \beta_i W_i, \tag{8}$$

where W_i is the mean insolation in W/m^2 on day i, and $\beta_i = 1$ if $W_i \geq \tau$ and 0 otherwise."

Thirdly, ISI was introduced by Huybers to support his (former) idea that glacial cycles are paced primary by obliquity; this is why ISI is defined such a way that it is completely dominated by obliquity. But since I_α, is also dominated by obliquity it is not surprising that two obliquity-dominated curves resemble each other. What can be learned from such a comparison?

Since the model uses a linear combination of three orbital parameters, it is not obvious by looking at these three parameters $\alpha_{\text{Esi}}, \alpha_{\text{Eco}}, \alpha_{\text{O}}$, how the associated orbital forcing looks like. Hence, we think that it is of interest to show how this forcing, which drives the dynamics of our model, looks like. In addition, conceptual models use a variety of orbital forcings, e.g. Model 3 uses the maximum summer insolation at 65° N, P98 relies on the same metric, but with an artificial truncation function added, Tzedakis et al. (2017) uses the caloric summer insolation at 65° N (as introduced by Milankovitch (1941)). Regarding this variety of different orbital forcings in use, it is of interest to see which metric our model selects.
While the Berends SL curve is mainly dominated by obliquity and only shows a small precession signal, this does not imply that the orbital forcing $I(t)$ in the model shows the same pattern. Actually, it can reproduce the sea level by Berends (and thus the same spectral powers for $v(t)$), while being driven by an orbital forcing, which has a different power spectrum. For our reduced RAMP model (as described above), we see that $I(t)$ has a dominant peak in obliquity, but also a significant precessional signal (Fig. 3a). On the other hand, the Berends SL curve, which was used as the tuning target has almost no precession signal (Fig. 3). This shows that it is indeed interesting to investigate the spectral power of $I(t)$ in the model and that it cannot be directly inferred from the tuning target alone. Leloup and Paillard (2022) also showed that their model can reproduce the LR04 target based on four different orbital forcings which vary in their precession and obliquity signals.

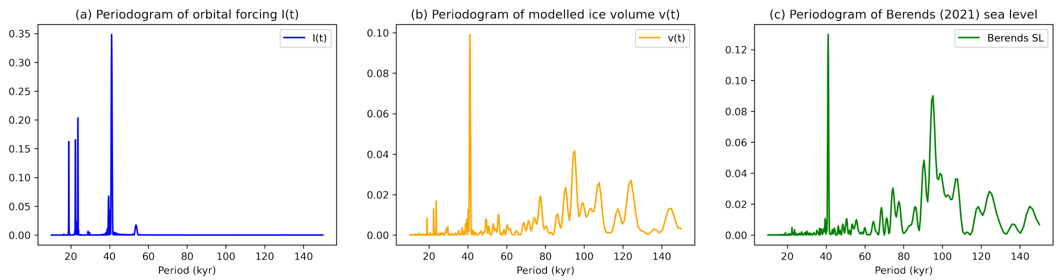

Figure 3: LombScargle periodograms of (a) the orbital forcing I(t) in the reduced RAMP model, (b) the modelled ice volume v(t) and (c) the tuning target, which was the Berends SL curve.

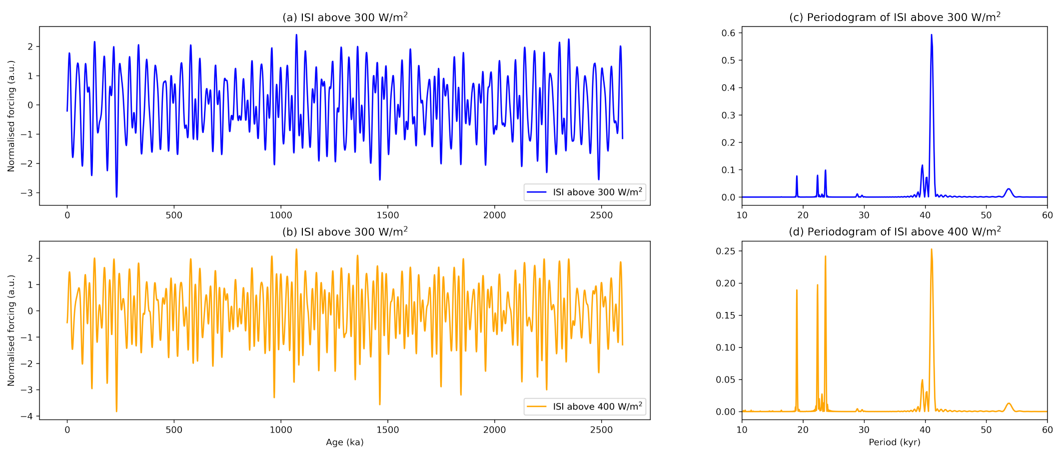

Figure 4: ISI above 300 W/m^2 (a) and its periodogram (c). ISI above 400 W/m^2 (c) and its periodogram (d). Calculations done with code from Leloup and Paillard (2022).

Furthermore, the spectral power of ISI(τ) depends on the chosen threshold τ. While ISI above 300 W/m^2 is mainly dominated by Obliquity (Fig. 4c), ISI above 400 W/m^2 has almost equal contributions of precession and obliquity (Fig. 4d).

L. 565. '*This suggests the presence of non-linearities within the climate system that modify Earth's response to changes in the orbital forcing. This conclusion aligns with findings from other studies (Clark et al., 2006; Leloup and Paillard, 2022; Berends et al., 2021b)*'. I am just curious whether the authors are aware of the works of Weertman, MacAyeal, Oerlemans and others who discussed how nonlinearities modify the Earth's response to orbital forcing already during 1970s and early 1980s?
As for the Berends et al. (2021b) paper, which the authors cited ten times, it is merely a review paper. Although review papers are useful reference material, especially for early career scientists, citing them cannot substitute for reading and citing real scientific papers.

We are aware of earlier work on this topic, e.g. (Hays et al., 1976, p. 1131) already stated that "Unlike the correlations between climate and the higher-frequency orbital variations [...] an explanation of the correlation between climate and eccentricity probably requires an assumption of non-linearity." We agree that review papers should not serve as the sole source of information and the original work therein should be cited as well. In the manuscript, the Berends et al. (2021b) paper was only cited twice as a single source of information, otherwise always multiple citations were given with at least two or three cited papers. In most of these citations, the Berends (2021b) paper is cited as another source of information, since it simply touches a broad range of topics. With over 50 different papers cited in this manuscript, it clearly does not rely on a single source of information.

References

J. Austermann, J. X. Mitrovica, K. Latychev, and G. A. Milne. Barbados-based estimate of ice volume at Last Glacial Maximum affected by subducted plate. *Nature Geoscience*, 6(7):553–557, July 2013. ISSN 1752-0908. doi: 10.1038/ngeo1859. URL `https://www.nature.com/articles/ngeo1859`. Publisher: Nature Publishing Group.

S. Barker, L. E. Lisiecki, G. Knorr, S. Nuber, and P. C. Tzedakis. Distinct roles for precession, obliquity, and eccentricity in Pleistocene 100-kyr glacial cycles. *Science*, 387(6737):eadp3491, Feb. 2025. doi: 10.1126/science.adp3491. URL `https://www.science.org/doi/10.1126/science.adp3491`. Publisher: American Association for the Advancement of Science.

C. J. Berends, B. de Boer, and R. S. W. van de Wal. Reconstructing the evolution of ice sheets, sea level, and atmospheric CO_2 during the past 3.6 million years. *Climate of the Past*, 17(1):361–377, Feb. 2021. ISSN 1814-9324. doi: 10.5194/cp-17-361-2021. URL `https://cp.copernicus.org/articles/17/361/2021/`. Publisher: Copernicus GmbH.

N. Calder. Arithmetic of ice ages. *Nature*, 252(5480):216–218, Nov. 1974. ISSN 1476-4687. doi: 10.1038/252216a0. URL `https://www.nature.com/articles/252216a0`. Publisher: Nature Publishing Group.

P. U. Clark, J. D. Shakun, Y. Rosenthal, P. Köhler, and P. J. Bartlein. Global and regional temperature change over the past 4.5 million years. *Science*, 383(6685):884–890, Feb. 2024. doi: 10.1126/science.adi1908. URL `https://www.science.org/doi/abs/10.1126/science.adi1908`. Publisher: American Association for the Advancement of Science.

P. U. Clark, J. D. Shakun, Y. Rosenthal, C. Zhu, P. J. Bartlein, J. M. Gregory, P. Köhler, Z. Liu, and D. P. Schrag. Mean ocean temperature change and decomposition of the benthic ^{18}O record over the past 4.5 million years. *Climate of the Past*, 21(6):973–1000, June 2025. ISSN 1814-9324. doi: 10.5194/cp-21-973-2025. URL `https://cp.copernicus.org/articles/21/973/2025/`. Publisher: Copernicus GmbH.

J. R. Farmer, T. Pico, O. M. Underwood, R. Cleveland Stout, J. Granger, T. M. Cronin, F. Fripiat, A. Martínez-García, G. H. Haug, and D. M. Sigman. The Bering Strait was flooded 10,000 years before the Last Glacial Maximum. *Proceedings of the National Academy of Sciences*, 120(1): e2206742119, Jan. 2023. doi: 10.1073/pnas.2206742119. URL `https://www.pnas.org/doi/abs/10.1073/pnas.2206742119`. Publisher: Proceedings of the National Academy of Sciences.

A. Ganopolski. Toward generalized Milankovitch theory (GMT). *Climate of the Past*, 20(1):151–185, Jan. 2024. ISSN 1814-9324. doi: 10.5194/cp-20-151-2024. URL https://cp.copernicus.org/articles/20/151/2024/. Publisher: Copernicus GmbH.

A. Ganopolski, R. Winkelmann, and H. J. Schellnhuber. Critical insolation–CO2 relation for diagnosing past and future glacial inception. *Nature*, 529(7585):200–203, Jan. 2016. ISSN 1476-4687. doi: 10.1038/nature16494. URL https://www.nature.com/articles/nature16494. Publisher: Nature Publishing Group.

J. D. Hays, J. Imbrie, and N. J. Shackleton. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. *Science*, 194(4270):1121–1132, 1976. ISSN 0036-8075. URL https://www.jstor.org/stable/1743620. Publisher: American Association for the Advancement of Science.

P. Huybers. Early Pleistocene Glacial Cycles and the Integrated Summer Insolation Forcing. *Science*, 313(5786):508–511, July 2006. doi: 10.1126/science.1125249. URL https://www.science.org/doi/full/10.1126/science.1125249. Publisher: American Association for the Advancement of Science.

J. Imbrie and J. Z. Imbrie. Modeling the Climatic Response to Orbital Variations. *Science*, 207 (4434):943–953, Feb. 1980. doi: 10.1126/science.207.4434.943. URL https://www.science.org/doi/10.1126/science.207.4434.943. Publisher: American Association for the Advancement of Science.

J. Z. Imbrie, A. Imbrie-Moore, and L. E. Lisiecki. A phase-space model for Pleistocene ice volume. *Earth and Planetary Science Letters*, 307(1-2):94–102, July 2011. ISSN 0012821X. doi: 10.1016/j.epsl.2011.04.018. URL http://arxiv.org/abs/1104.3610. arXiv:1104.3610 [astro-ph, physics:physics].

K. Lambeck, H. Rouby, A. Purcell, Y. Sun, and M. Sambridge. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences*, 111(43):15296–15303, Oct. 2014. doi: 10.1073/pnas.1411762111. URL https://www.pnas.org/doi/10.1073/pnas.1411762111. Publisher: Proceedings of the National Academy of Sciences.

E. Legrain, F. Parrenin, and E. Capron. A gradual change is more likely to have caused the Mid-Pleistocene Transition than an abrupt event. *Communications Earth & Environment*, 4(1):1–10, Mar. 2023. ISSN 2662-4435. doi: 10.1038/s43247-023-00754-0. URL https://www.nature.com/articles/s43247-023-00754-0. Number: 1 Publisher: Nature Publishing Group.

G. Leloup and D. Paillard. Influence of the choice of insolation forcing on the results of a conceptual glacial cycle model. *Climate of the Past*, 18(3):547–558, Mar. 2022. ISSN 1814-9324. doi: 10.5194/cp-18-547-2022. URL https://cp.copernicus.org/articles/18/547/2022/. Publisher: Copernicus GmbH.

X. Ma, M. Yang, Y. Sun, H. Dang, W. Ma, J. Tian, Q. Jiang, L. Liu, X. Jin, and Z. Jin. The potential role of insolation in the long-term climate evolution since the early Pleistocene. *Global and Planetary Change*, 240:104526, Sept. 2024. ISSN 0921-8181. doi: 10.1016/j.gloplacha.2024.104526. URL https://www.sciencedirect.com/science/article/pii/S0921818124001735.

M. Milankovitch. Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. *Royal Serbian Academy Special Publication*, 133:1–633, 1941. URL https://cir.nii.ac.jp/crid/1572824499597240704. Publisher: Israel Program for Sceientific Translation, U. S. Department of Commerce.

D. Paillard. The timing of Pleistocene glaciations from a simple multiple-state climate model. *Nature*, 391(6665):378–381, Jan. 1998. ISSN 1476-4687. doi: 10.1038/34891. URL https://www.nature.com/articles/34891. Publisher: Nature Publishing Group.

D. Paillard. Quaternary glaciations: from observations to theories. *Quaternary Science Reviews*, 107:11–24, Jan. 2015. ISSN 0277-3791. doi: 10.1016/j.quascirev.2014.10.002. URL https://www.sciencedirect.com/science/article/pii/S0277379114003898.

F. Parrenin and D. Paillard. Terminations VI and VIII (530 and 720 kyr BP) tell us the importance of obliquity and precession in the triggering of deglaciations. *Climate of the Past*, 8(6):2031–2037, Dec. 2012. ISSN 1814-9332. doi: 10.5194/cp-8-2031-2012. URL https://cp.copernicus.org/articles/8/2031/2012/.

S. Talento and A. Ganopolski. Reduced-complexity model for the impact of anthropogenic CO_2 emissions on future glacial cycles. *Earth System Dynamics*, 12(4):1275–1293, Nov. 2021. ISSN 2190-4979. doi: 10.5194/esd-12-1275-2021. URL https://esd.copernicus.org/articles/12/1275/2021/. Publisher: Copernicus GmbH.

P. C. Tzedakis, M. Crucifix, T. Mitsui, and E. W. Wolff. A simple rule to determine which insolation cycles lead to interglacials. *Nature*, 542(7642):427–432, Feb. 2017. ISSN 1476-4687. doi: 10.1038/nature21364. URL https://www.nature.com/articles/nature21364. Publisher: Nature Publishing Group.

M. Verbitsky and A. W. Omta. Rapid Communication: Middle Pleistocene Transition as a Phenomenon of Orbitally Enabled Sensitivity to Initial Values. *EGUsphere*, pages 1–9, July 2025. doi: 10.5194/egusphere-2025-3334. URL https://egusphere.copernicus.org/preprints/2025/egusphere-2025-3334/. Publisher: Copernicus GmbH.

M. Willeit, A. Ganopolski, R. Calov, and V. Brovkin. Mid-Pleistocene transition in glacial cycles explained by declining CO2 and regolith removal. *Science Advances*, 5(4):eaav7337, Apr. 2019. doi: 10.1126/sciadv.aav7337. URL https://www.science.org/doi/full/10.1126/sciadv.aav7337. Publisher: American Association for the Advancement of Science.

Y. Yokoyama, K. Lambeck, P. De Deckker, P. Johnston, and L. K. Fifield. Timing of the Last Glacial Maximum from observed sea-level minima. *Nature*, 406(6797):713–716, Aug. 2000. ISSN 1476-4687. doi: 10.1038/35021035. URL https://www.nature.com/articles/35021035. Publisher: Nature Publishing Group.