Answer to RC4 :

We thank the reviewer for her/his helpful comments and suggestions that will help us revise and improve the manuscript. We hope the answers and modifications proposed satisfactorily address her/his remarks.

In the following, the reviewer's comments are in black, our answer in blue and suggested corrections in green.

The additional figures performed are labelled Qa-b with a the number of the reviewer's question and b the number of the corresponding figure in the original manuscript.

G. Leloup and D. Paillard

General comments

1. I think that it should be clearly stated in the abstract, introduction and conclusions that the paper will focus on the deglaciation threshold V0, while keeping all the other 4 model parameters constant. In particular, I find the sentence "to be able to reproduce the frequency shift over the Mid Pleistocene Transition, the deglaciation threshold needs to increase over time, independently of the summer insolation used as input" misleading if it is not pointed out that all the other parameters are fixed. If temporal changes in the other parameters were also allowed, then the frequency shift over the MPT could potentially also be reproduced via other changes.

We fully agree with the reviewer's comment. This will be made clearer in the next version of the manuscript.

We propose the following modification of the abstract (l. 7) :

"Here, we use a simple conceptual model to test and discuss the influence of the use of different summer insolation forcings, having different contributions from precession and obliquity, on the model results. We show that some features are robust. Specifically, to be able to reproduce the frequency shift over the Mid Pleistocene Transition, while having all other model parameters fixed, the deglaciation threshold needs to increase over time, independently of the summer insolation used as input."

We propose the following modification of the end of the introduction (l.61) :

"In particular, we are able to reproduce a switch from 41 kyr oscillations before the MPT to 100 kyr cycles afterwards in agreement with the records for all insolation forcings, by varying a single parameter, the deglaciation threshold V_0, and keeping all the other model parameters constant"

We propose the following modification of the conclusion (l.291)

"More specifically, we are able to represent the Mid Pleistocene Transition and the switch from a 41 kyr dominated record to a 100 kyr dominated record, by raising the deglaciation threshold and keeping the other model parameters constant."

2. How do the results change if you consider the insolation at 50°N, as in Caulder's model, instead of 65°N?

This is an interesting question. In his article, Calder used the latitude of 50° N and not 65° N. However, even if we choose the 50° N latitude for our input forcing, our results would hardly be comparable to the one of Calder's model, as the astronomical solutions have changed since. Calder used the Vernekar tables (1972), while we use the Laskar 04 (Laskar, 2004) solution. For the latitude of 50° N, the question of which definition of the summer insolation to choose (insolation at the summer solstice, caloric season or Integrated Summer Insolation above a threshold) would remain, leading to a new set of experiments that is outside of the scope of this paper.

Here, we have performed a new experiment, in the case of the summer solstice insolation at 50° N, and compared it with the results previously obtained with the 4 different summer insolation types at 65° N.

The new figures, corresponding to the one of the original manuscript with the additional experiment (summer solstice insolation at 50° N used as input) are labeled Q2-1 to Q2-5 (following the number of the figure in the original manuscript).

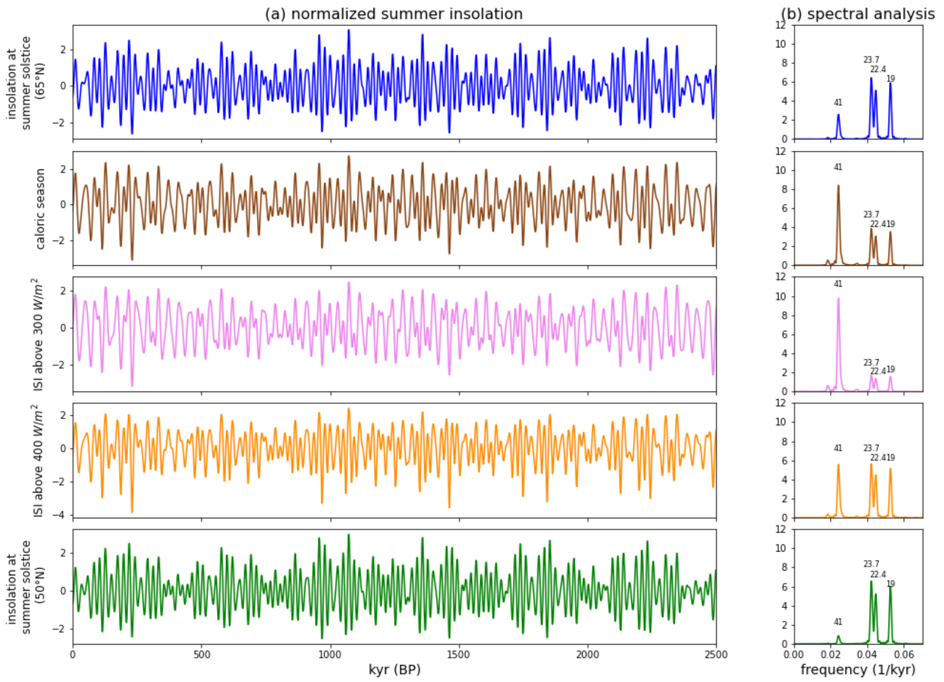


Figure Q2-1: [Fig. 1 of the manuscript with summer solstice insolation at 50°N]

(a) The four different summer insolation types at 65° N and the summer solstice insolation at 50° N, displayed over the Quaternary period. (b) Corresponding spectral analysis, normalized by the standard deviation.

The summer solstice insolation at 50° N has a lower obliquity component than the summer solstice insolation at 65° N.

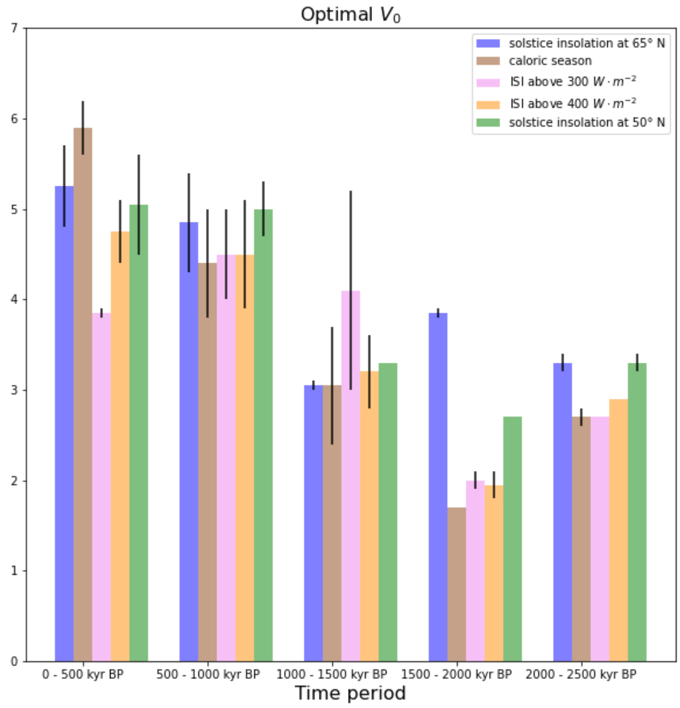


Figure Q2-2: [Fig. 2 of the manuscript with summer solstice insolation at 50°N]

Optimal deglaciation threshold V_0 over the five different periods for the four different summer insolation forcings at 65° N and the summer solstice insolation at 50° N. When several values of the deglaciation threshold V_0 maximize the accuracy criteria, the mean value is plotted and the other possible values are represented with errorbars.

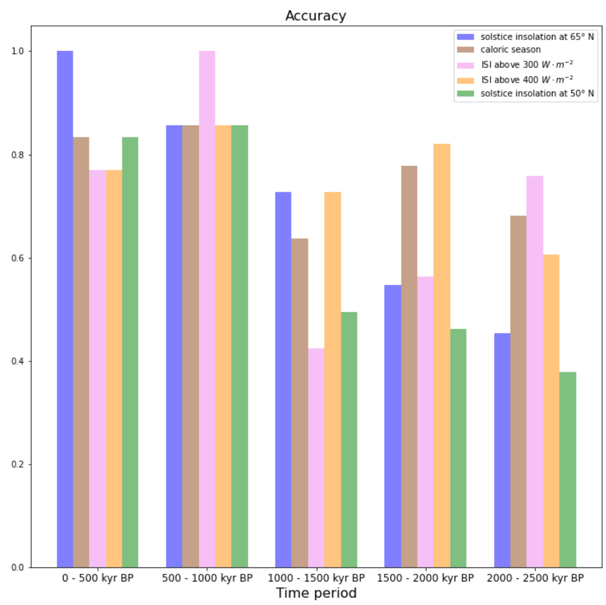


Figure Q2-3: [Fig. 3 of the manuscript with summer solstice insolation at 50°N]

Accuracy over the five different periods for the four different summer insolation forcings at 65° N and the summer solstice insolation at 50° N.

Please note that in Figures 2 and 3, the values over the period [1000 - 1500]kyr BP for the four initial summer forcings (at 65° N) have changed compared to the first version of the manuscript, due to an error in the plot. However, this does not change the main results : the optimal deglaciation threshold V_0 increases over the Quaternary, and the accuracy is generally higher on the latter part of the record.

With the summer solstice insolation at 50° N, we obtain the same conclusion as in the case of forcings at 65° N. The optimal deglaciation V_0 (obtained while keeping all other model parameter constants), increases over the Quaternary, with lower values around 3 at the start of the Quaternary and values around 5 after the MPT.

As in the case of the summer solstice insolation at 65° N, the accuracy values of the results with the summer solstice insolation at 50° N are higher on the later part of the Quaternary. Compared to the solstice insolation at 65° N, the solstice insolation at 50°N always leads to a lower accuracy on the earliest part of the record. This seems logical as the insolation at 50° N has a weaker obliquity component, and the pre MPT period is dominated by obliquity (41 kyr cycles). Following the accuracy criteria defined in the manuscript, their performances on the post MPT part are comparable.

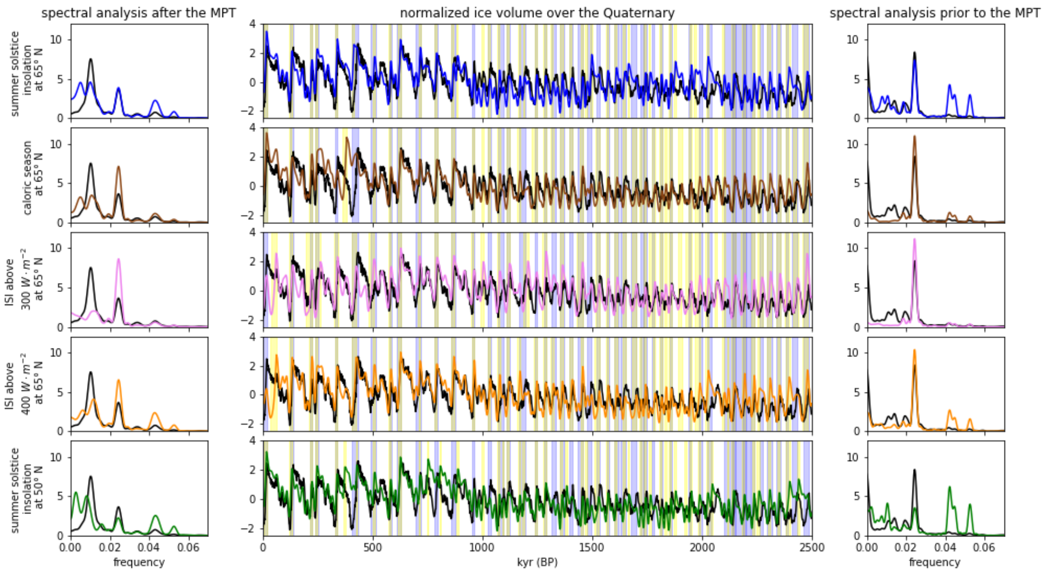
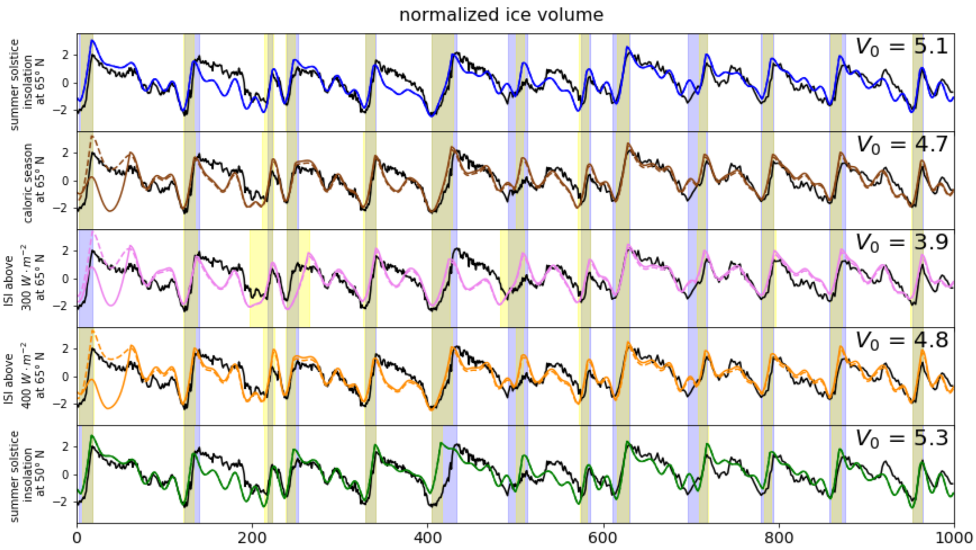


Figure Q2-4: [Fig. 4 of the manuscript with summer solstice insolation at 50°N]

Best model fit over the whole Quaternary and corresponding spectral analysis. The middle panel represents the best fit of the model for the different summer insolation used as input, compared to the data. The data (normalized LR04 curve) are in black. The blue shading represents deglaciation periods in the data and the yellow shading deglaciation periods in the model. This results in a green shading when deglaciations are seen in the model and data at the same time.The left panel represents the spectral analysis of the best fit solution over the last million year. The right panel represents the spectral analysis over the more ancient part of the Quaternary (before 1 Ma BP)

On Figure Q2-4, the best guess over the Quaternary was obtained (see answer to Q7 for a definition and corresponding modification suggestions), and the spectral analysis over the pre MPT ([1000 - 2500] kyr BP) and post MPT ([0 - 1000] kyr BP) was carried out.

The spectral analysis over the pre MPT period shows that model results with the summer solstice insolation at 50° N as forcing fail to reproduce the dominance of the obliquity cycle that is visible on the data on that part of the record. As for the accuracy value on this period, this is not surprising, as the summer solstice insolation at 50° N has a low obliquity component. On the post MPT part, larger cycles are produced, but their frequency do not match the data.



<u>Figure Q2-5</u> : [Fig. 5 of the manuscript with summer solstice insolation at 50°N]

Normalized model results over the last million year, with the four different summer insolation forcings at 65° N and the summer solstice insolation at 50° N . The full line is the best fit computed over the 100 - 1000 ka BP period. The dashed line represents the same solution, but with an increased V_0 threshold for the last deglaciation. The data (LR04 stack curve normalized) are in black. The yellow shading represents deglaciation periods in the model (case of the increased V_0 threshold) and the blue shading represents deglaciation periods in the data. This results in a green shading when deglaciations are seen in the model and data at the same time

On the last million year, the model output with the summer solstice insolation at 50° N as forcing reproduces quite well the data. As in the case of the summer solstice insolation at 65° N, there is no need to increase the V_0 threshold over the last 100 kyr in order to reproduce the last cycle. This is visible in Figure Q2-5, where the best fit over the [0 - 1000] kyr BP period with a constant V_0 threshold on this period is shown in full lines. The dashed lines represent the case where the V_0 threshold is increased over the last 100 kyr. For the summer solstice insolation at 65°N and 50°N, the full and dashed curve overlap, as increasing the V_0 threshold over the last 100 kyr does not change the results.

In this manuscript, we aim at comparing “classical” insolation types that could be used to force conceptual models at the latitude of 65° N. We could have chosen different latitudes and definitions of summer insolation, and the amount of possible experiments is infinite. Here, we have shown that the main results of the manuscript do not change with the summer solstice insolation at 50° N. Indeed, we are able to produce a frequency shift of the cycles by increasing the V_0 threshold over the MPT. As it contains less obliquity, the results with this forcing are poorer on the earliest part of the Quaternary, where the record is dominated by obliquity. For the clarity of the manuscript, we prefer to stick to the four initial forcings used, at the same latitude of 65° N.

We suggest to add a sentence l.124 in the presentation of the input forcings used, and to refer to the answer to RC4.

“Experiments were also conducted for the summer solstice insolation at 50° N instead of 65° N but are not presented here as they do not change the conclusions obtained with the forcings at 65° N.”

3. What happens if you decompose the summer solstice insolation into its precession and obliquity components and use each of them as forcing in your model? By the results shown in the manuscript, the ISI above 300W/m2 forcing (which contains almost no precessional signal) still produces what the authors deem a "good fit to data". Therefore, I think that a clean separation into the precessional and obliquity components of, let's say, summer solstice insolation could be a clean experiment to compare with.

We did not use precession and obliquity as direct forcings, since we intend to have a model forced by the "Milankovitch" forcing, that is a forcing based on "summer insolation". Summer insolation has indeed two main components (obliquity and precession) with varying power depending on insolation definition, but there is no "summer insolation" without precession, nor without obliquity.

Still, in the following, we have compared the model results with 3 different forcings :

- the summer solstice insolation at 65°N as in the manuscript
- the "fixed obliquity / precession only" forcing. This forcing was obtained by computing the summer solstice insolation at 65° N but with a constant obliquity value (equal to the current value)
- the "fixed precession / obliquity only" forcing. This forcing was obtained by computing the summer solstice insolation at 65° N but with a constant value of the precession parameter (equal to the current value)

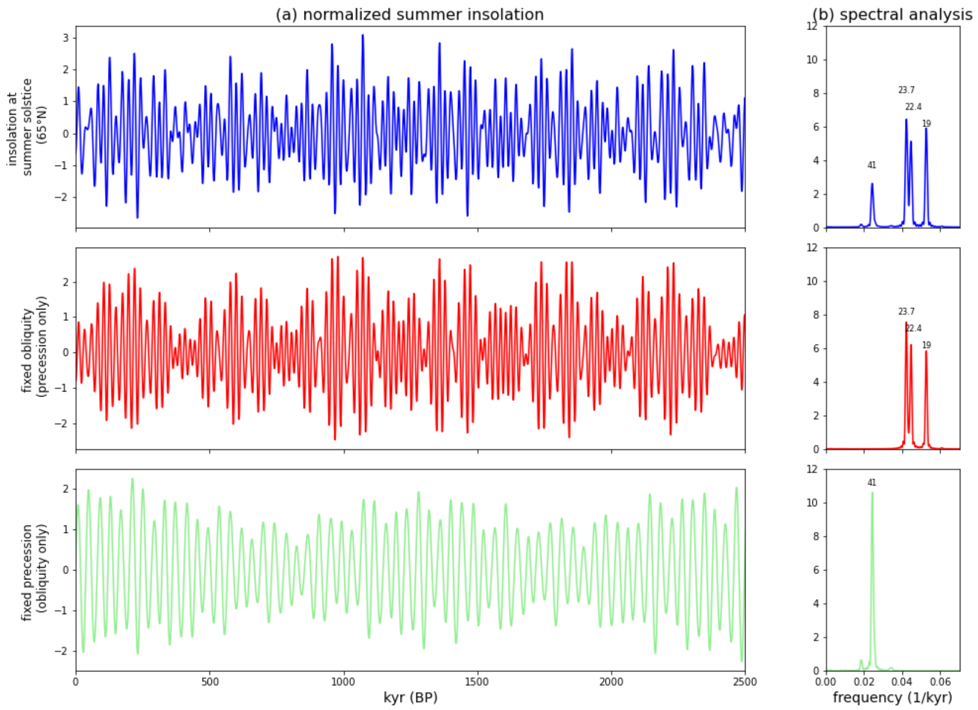
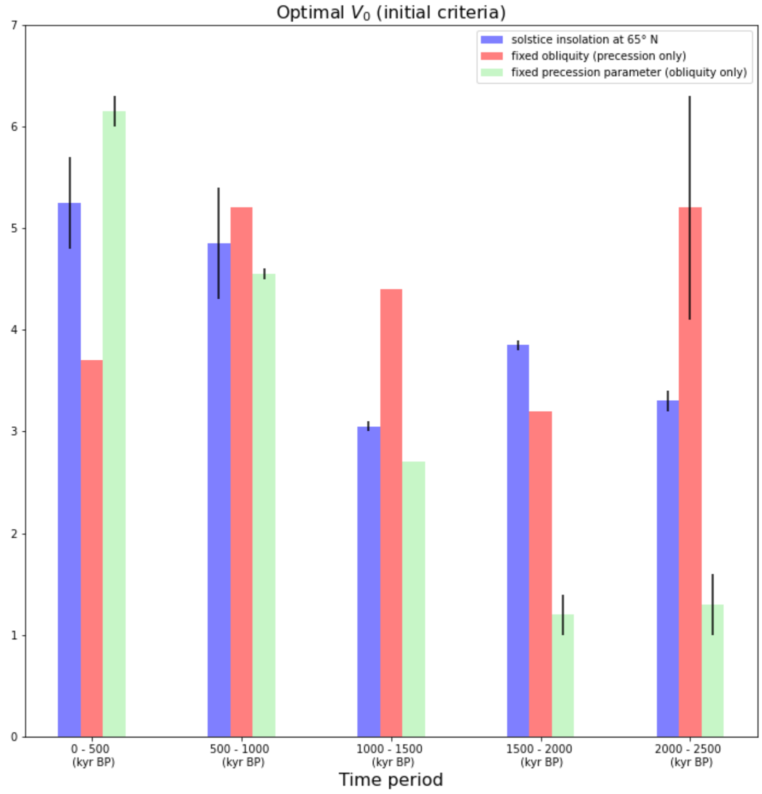


Figure Q3-1: [Fig. 1 of the manuscript with summer solstice insolation, fixed obliquity and fixed precession forcing]

(a) Summer solstice at 65°N, fixed obliquity and fixed precession forcings, displayed over the Quaternary period. (b) Corresponding spectral analysis, normalized by the standard deviation.

Figure Q3-1 represents these forcings. As expected, the spectral analysis of the “fixed obliquity” forcing has only components from the precession, and conversely the “fixed precession” forcing has only an obliquity component.



<u>Figure Q3-2</u>: [Fig. 2 of the manuscript with fixed obliquity and fixed precession forcings]

Optimal deglaciation threshold V_0 over the five different periods for the summer solstice at 65°N, fixed obliquity and fixed precession forcings. When several values of the deglaciation threshold V_0 maximize the accuracy criteria, the mean value is plotted and the other possible values are represented with errorbars.

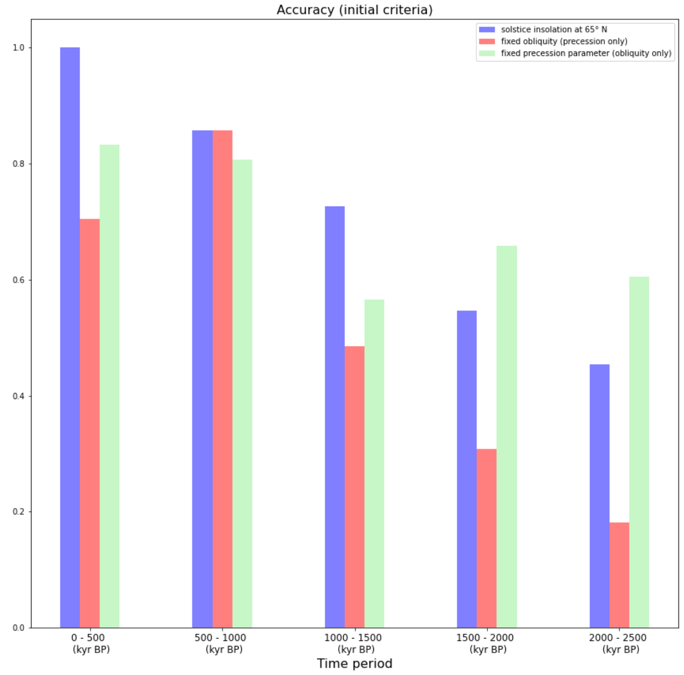
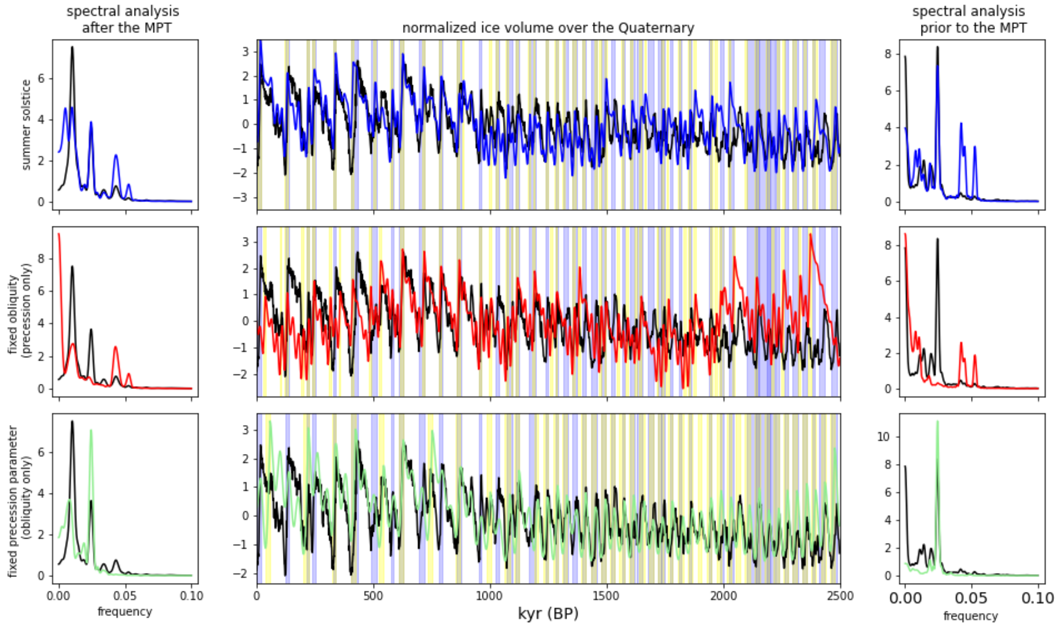


Figure Q3-3: [Fig. 3 of the manuscript with fixed obliquity and fixed precession forcings]

Accuracy over the five different periods for the summer solstice at 65°N, fixed obliquity and fixed precession forcings.

Figure Q3-3 shows that the summer solstice insolation allows a better accuracy in reproducing the last part of the record than the fixed obliquity and fixed precession forcings.

The Figure Q3-4 shows the best fit over the whole Quaternary. With a fixed obliquity (precession only) forcing, our model is not able to reproduce the pre-MPT 40 kyr signal, whereas this is possible with the fixed precession (obliquity only) forcing. It is not surprising that an input forcing with no obliquity component does not allow to reproduce the pre MPT, obliquity-dominated record. On the latest part of the Quaternary, the results obtained are less satisfying with the fixed precession and fixed obliquity forcings than with the summer solstice insolation. Concerning the spectral analysis, for the fixed precession (obliquity only) forcing, obliquity continues to dominate after the MPT. For the fixed obliquity (precession only) forcing, there is a 100 kyr peak after the MPT. However, concerning the terminations placement, both of these forcings fail to successfully represent the post MPT part of the record.



<u>Figure Q3-4</u>: [Fig. 4 of the manuscript with fixed obliquity and fixed precession forcings]

Best model fit over the whole Quaternary and corresponding spectral analysis. The middle panel represents the best fit of the model for the different insolation used as input, compared to the data. The data (normalized LR04 curve) is in black. The blue shading represents deglaciation periods in the data and the yellow shading deglaciation periods in the model. This results in a green shading when deglaciations are seen in the model and data at the same time.The left panel represents the spectral analysis of the best fit solution over the last million year. The right panel represents the spectral analysis over the more ancient part of the Quaternary (before 1 Ma BP)

Figure Q3-5 shows the best fit over the [0 - 1000] kyr BP period. When the optimization is done over the [0 - 1000] kyr period, the respective accuracy over this period is 0.92 for the summer solstice forcing and 0.67 for both the fixed obliquity and fixed precession forcings. With the fixed obliquity, and fixed precession forcing, some terminations are misplaced.

For instance, with the fixed obliquity (precession only) forcing, Termination V (around 420 kyr BP) is triggered too late. With the fixed precession (obliquity only) forcing, Termination VII and Termination IX (around 620 and 790 kyr BP) are misplaced.

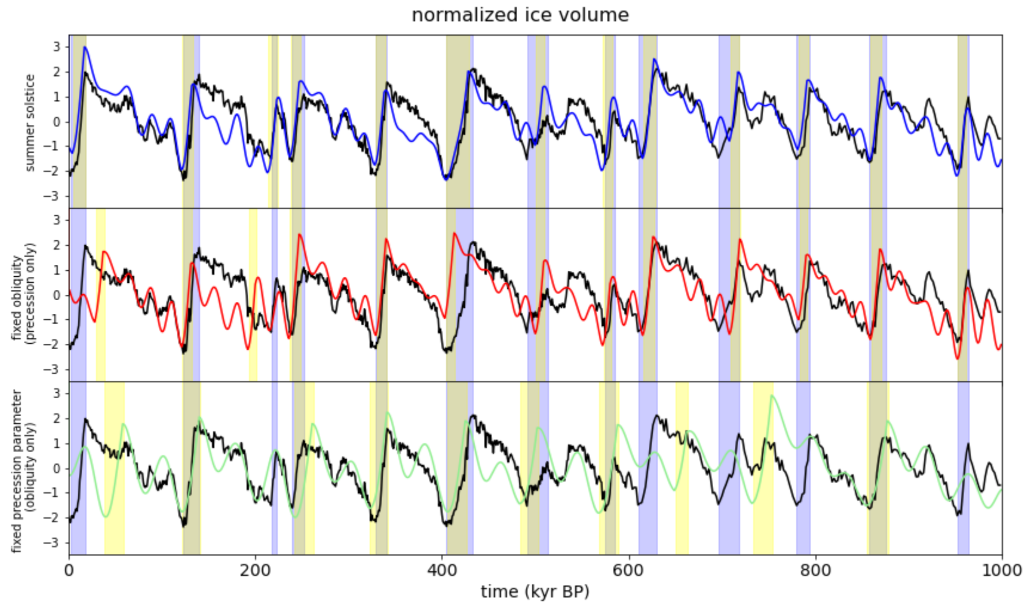


Figure Q3-5 : [Fig. 5 of the manuscript with fixed obliquity and fixed precession forcings]

Normalized model results over the last million year, with the summer solstice at 65°N, fixed obliquity and fixed precession forcings. The colored lines are the best fit computed over the 0 - 1000 ka BP period. The data (LR04 stack curve normalized) is in black. The yellow shading represents deglaciation periods in the model and the blue shading represents deglaciation periods in the data. This results in a green shading when deglaciations are seen in the model and data at the same time

These results show that when an obliquity only or precession only forcing are used, our model is not able to represent the latest part of the Quaternary record as well as when forcings with contributions from both the precession and the obliquity are used.

In the case of the ISI 300 W/m^2 forcing, the precession component is small, but is not absent, and allows a better fit to data. With our accuracy criteria, the accuracy of this forcing is comparable to the other forcings, but differences are indeed noticeable when looking at the record.

We have proposed modifications (see answer of question 3 of RC2), and among those, to add the sentence :

“Especially for the ISI above 300 W/m^2 forcing, the agreement is not as good as for the other forcings : Termination V (around 420 kyr BP) is triggered later compared to the data, while Termination III (around 240 kyr BP) is triggered too early. For the ISI above 300 W/m^2 forcing, the range of V_0 values allowing to reproduce correctly most of the terminations on the last million year is reduced (only values of V_0 = 3.9 - 4.0), whereas the results are more robust for the three other insolations forcings, with a broader range of working V_0 values. The ISI above 300 W/m^2 forcing has a low precession component, which explains why it is less successful in reproducing the data over the last million year. Experiments with our model setup have shown that a summer forcing with no precession component could not successfully reproduce the data over the post MPT period as well as the four forcings presented here, that contain both precession and obliquity*.

** Here we will refer the reader to the answer of question 3 of RC4*

4. Will the results be the same with a different fitting criterion? For example, if instead of the defined c, the criterion for the optimisation is to maximise the correlation between time-series of normalized paleo and modelled ice volume, how do the results change? It is obvious that the correlation measure will penalise the ISI above 300W/m2 forcing, as it clearly cannot reproduce the variability at the 100 kyr frequency.

The figure corresponding to the case where we try to maximize the coefficient correlation instead of our initial accuracy criteria are displayed below, with the initial figures for comparison. Please note that in Figures Q2 and Q3, the values over the period [1000 - 1500]kyr BP have changed compared to the first version of the manuscript, due to an error in the plot. However, this does not change the main results : the optimal deglaciation threshold V_0 increases over the Quaternary, and the accuracy is generally higher on the latter part of the record.

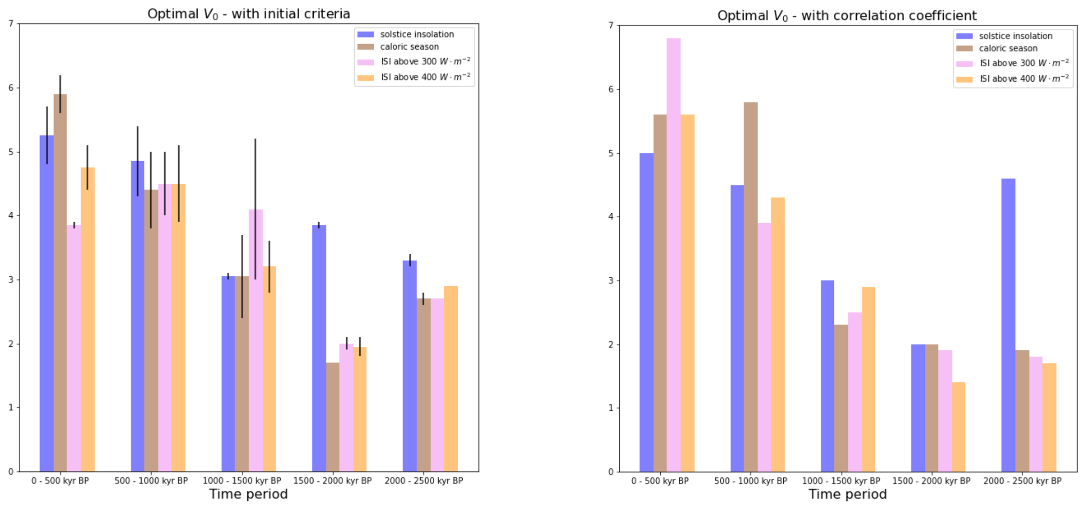


Figure Q4-2 : [Figure 2 of the manuscript and corresponding figure with the correlation coefficient as fitting criteria]

Optimal deglaciation threshold V_0 over the five different periods for the four different summer insolation forcings at 65° N. The left part displays the result when the initial accuracy criteria of the manuscript is used. The right part displays the result when the correlation coefficient is used as accuracy criteria. When several values of the deglaciation threshold V_0 maximize the accuracy criteria, the mean value is plotted and the other possible values are represented with errorbars.

Changing the accuracy criteria from the initial criteria proposed in the manuscript to the correlation coefficient changes the value of the optimal V_0 threshold, as visible in Figure Q4-2. However, this does not change the general tendency : lower values of the V_0 threshold allow to better fit the earliest part of the record, while higher values lead to a better fit on the post MPT period. For all insolation forcings (except the summer solstice insolation, detailed below), there is a clear tendency of increase of the V_0 threshold over the different time periods.

The correlation coefficient is better on the latest part of the record compared to the pre MPT part for all insolation forcings, and the summer solstice insolation leads to poorer results than all the other forcings on the pre MPT period, as visible in Figure Q4-3.

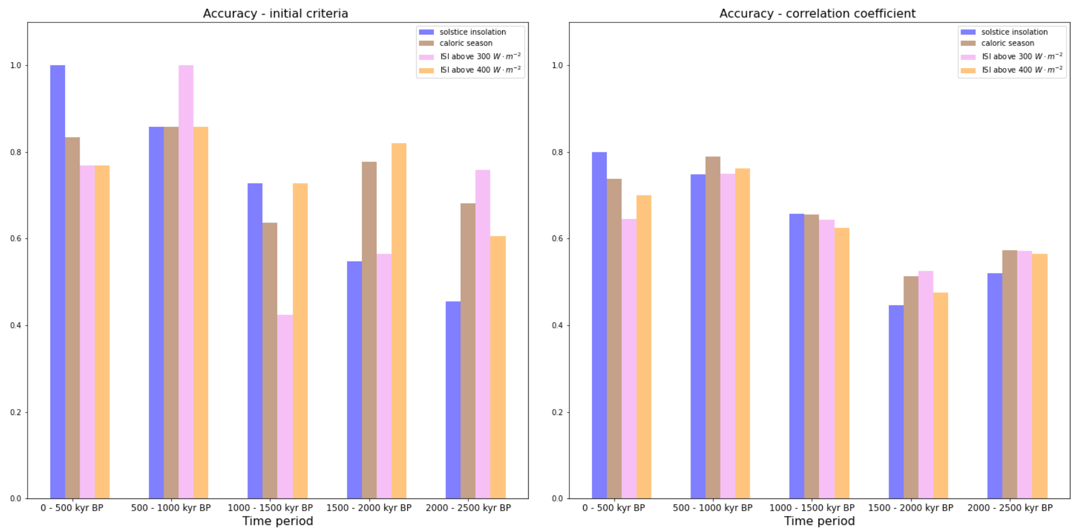


Figure Q4-3: *[Figure 3 of the manuscript and corresponding figure with the correlation coefficient as fitting criteria]*

Accuracy over the five different periods for the four different summer insolation forcings at 65° N. The right part displays the result when the correlation coefficient is used as accuracy criteria.

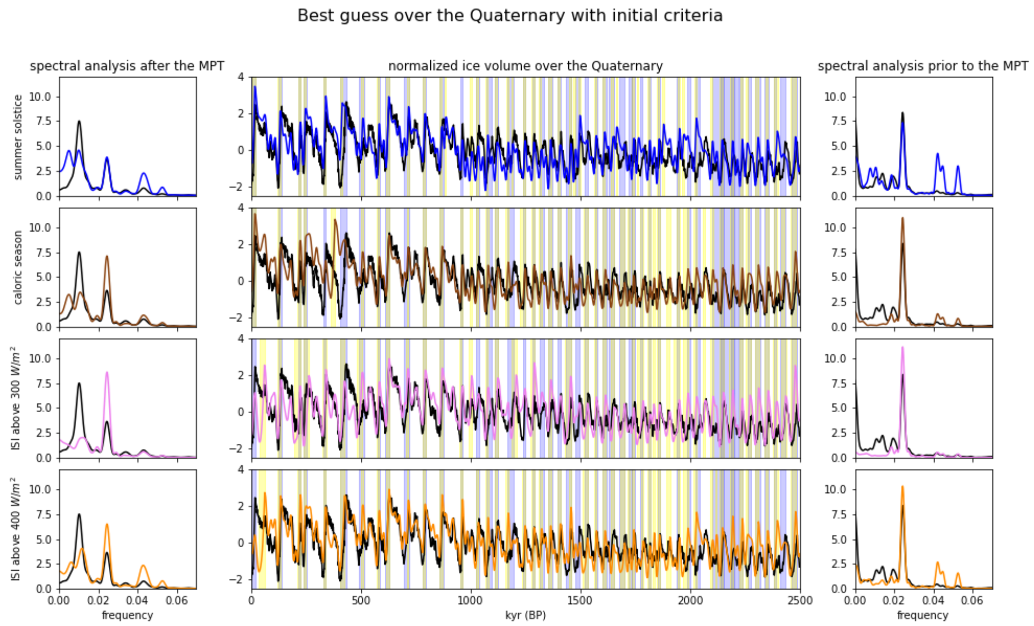


Figure Q4-4a: [Figure 4 of the manuscript] Best model fit over the whole Quaternary and corresponding spectral analysis when the accuracy criteria is the initial criteria

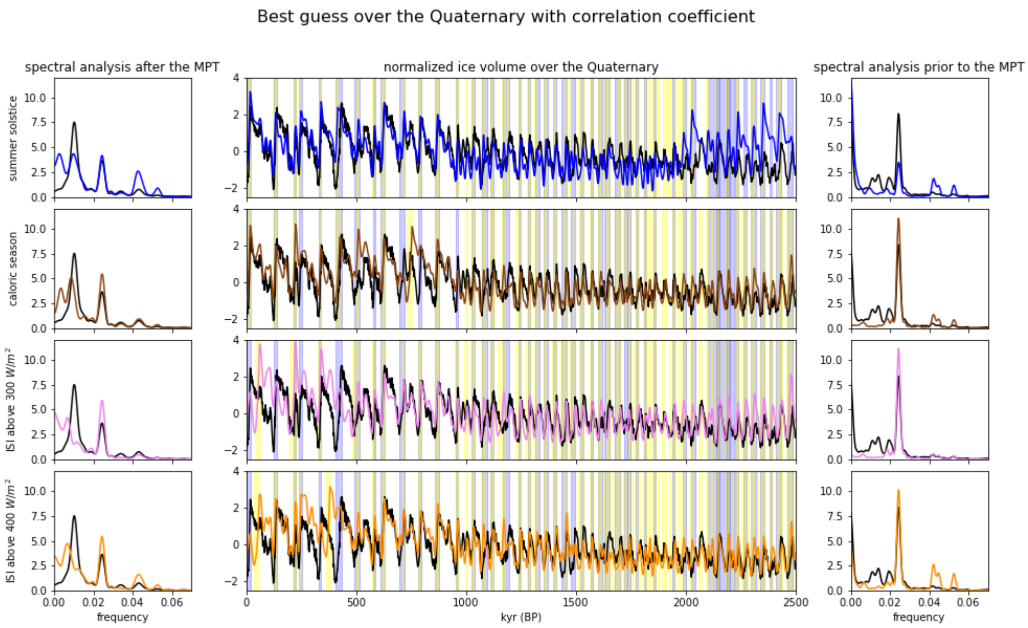


Figure Q4-4b: [Figure 4 with the correlation coefficient as fitting criteria]

Best model fit over the whole Quaternary and corresponding spectral analysis when the accuracy criteria is the correlation coefficient.

On Figure Q4-4a, the optimal fit over the Quaternary when the initial criteria is used as the fitting criterion is displayed. Please note that we have changed the normalization of the spectral analysis (it was normalized by the maximum value in the manuscript, and is now normalized by the standard deviation). On Figure Q4-4b, the optimal fit over the Quaternary when the correlation criteria is used as the fitting criterion is displayed. When the caloric season and the ISI above 300 W/m^2 and 400 W/m^2 are used as input forcing, the spectral analysis over the pre MPT period does not change much. However, for the summer solstice insolation, the spectral analysis shows a less pronounced obliquity peak than in the case of the initial fitting criteria. This is due to the fact that the model output do not match well the data on the [2000 - 2500] kyr BP period, where the optimal V_0 threshold is high in comparison to all other forcings.

This shows us that the correlation coefficient might not be the best criteria to determine which model output best fits our data. In this case (for the summer solstice insolation forcing on the [2000 - 2500] kyr BP period), the highest correlation coefficient is obtained for a relatively high V_0 threshold value (V_0 = 4.6), that leads to too large ice volumes compared to the data on this period.

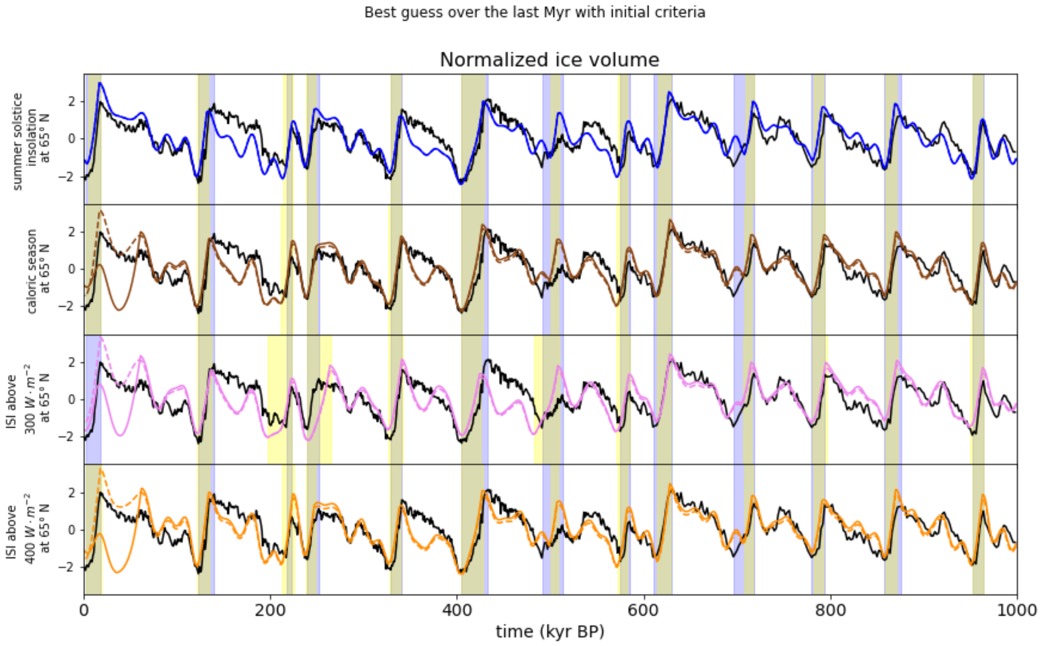


Figure Q4-5a : *[Figure 5 of the manuscript]*

Normalized model results over the last million year, with the four different summer insolation forcings at 65° N when the accuracy criteria is the initial criteria of the manuscript.

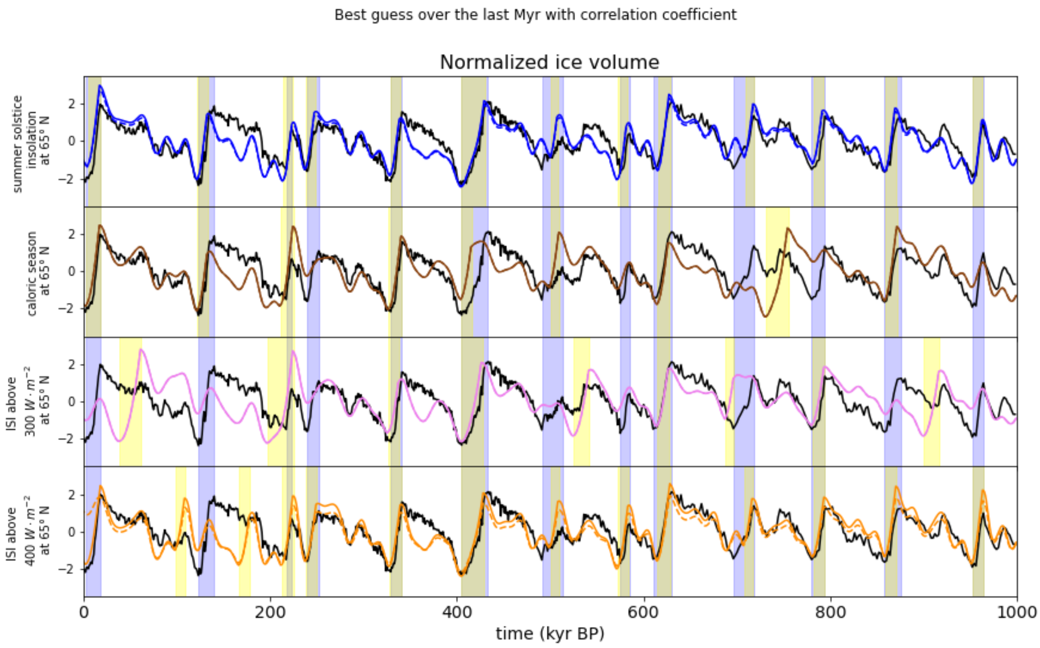


Figure Q4-5b : *[Figure 5 of the manuscript with the correlation coefficient as fitting criteria]*

Normalized model results over the last million year, with the four different summer insolation forcings at 65° N when the accuracy criteria is the correlation coefficient.

On Figures Q4-5, the best fit over the last Myr period is displayed. Figure Q4-5a corresponds to the original figure of the manuscript, where the initial accuracy criteria is used, whereas Figure Q4-5b corresponds to the case where the correlation coefficient is used as fitting criteria.

On the [0 - 1000] kyr BP period, the optimal V_0 values obtained with the correlation coefficient as a fitting criteria lead to a greater model-data mismatch than in the case of our initial accuracy criteria. The deglaciations are not all at the right place.

To summarize, the exact values obtained with the coefficient correlation for the V_0 threshold and the corresponding model realizations are different from the values obtained when our initial accuracy criteria is used. However, this does not change the main results of the paper, as we are able to produce a shift from 41 kyr to larger cycles, by increasing the V_0 threshold, and thus for all insolation forcings.
Our criteria is better suited for this model (that is threshold - based) and the choice of the solution corresponding to the highest initial criteria gives better results than when choosing the one maximizing the correlation coefficient, in terms of deglaciations placement.

We suggest to add a reference to the answer to the reviewer when we describe the choice of the accuracy criteria l.154.

5. I am interested in knowing more about the optimisation procedure. For each period and insolation forcing, did you any optimisation algorithm or trial and error?

For the optimisation procedure for each period and insolation forcing, we used an optimisation algorithm, based on a trial and error method in an automated manner.

For each insolation forcing and period we have performed several simulations, with different V_0 and different initial conditions. For each of these simulations, we computed our accuracy criteria and selected the simulation that gave the highest accuracy criteria.

In more details, the V_0 values considered are between 1 and 8 with a step of 0.1. The initial condition corresponds to the couple (V_{init}, init_state) with V_{init} the initial volume and init_state the initial state of the simulation (glaciation or deglaciation). The initial volume is taken between 0 and 5, with steps of 0.2. For every (V_0, V_{init}, init_state) possible triplet, we perform a simulation. This corresponds to 3500 simulations for each time period and insolation forcing. Then, we select the simulation with the highest accuracy criteria. This gives us the 'best V_0' value for a given period and insolation forcing. Here, we should stress that the use of different initial conditions (V_{init}, init_state) is done in order to compensate for the fact that we do not know the initial conditions at each time. Over periods of time containing relatively few cycles (like our 500 kyr periods), to start the model with initial conditions far from the data (for example with an high initial ice volume when the data at this time show a low volume and in the wrong state) would lead to a low accuracy coefficient as the first cycle will be 'misplaced', influenced by the initial conditions.

We propose to rephrase this part in the manuscript, and replace l.170- 171 by :

"The V_0 values that maximize the accuracy criteria for each time period and insolation forcing are called 'optimal V_0'. To determine the optimal V_0 threshold corresponding to each period and insolation forcing, several simulations were carried out and the parameter values maximizing the accuracy criteria *c* were selected. More precisely, for each insolation and period, 3500 simulations corresponding to different V_0 thresholds (from V_0=1.0 to V_0=8.0 with a step of 0.1) and different initial conditions (initial volume V_{init} ranging from 0.0 to 5.0 with a step of 0.2, and initial state - glaciation or deglaciation) were performed."

6. How do you define the “Best fit over the Quaternary”? (Section 3.2) This is not explained. I assume the authors use a V0 that changes with time (5 different values, in the 5 different periods considered), is that correct? Please, make explicit.

The reviewer is right in the interpretation of the “best fit over the Quaternary”, and we agree that it is not clearly stated in the manuscript.

We suggest to add explanatory sentences at the end of section 2.3 (after the modification proposed above for l.170-171). In section 3.2, we will refer the reader to the definition given in section 2.3.

“For each insolation forcing, the best fit over the Quaternary is defined as the simulation over the whole Quaternary (0- 2500 kyr BP) with a V_0 changing with time, and that is equal to the corresponding optimal V_0 at each time period.”

7/ For the “Best fit over the Quaternary” the authors use a V0 that changes with time. As a benchmark, I think the authors should also show how the performance with a changing V0 compare with the one of a constant V0. Please, repeat the optimisation procedure using the whole 0-2500 kyr BP period and provide the optimised constant V0 and corresponding model output. Please add these curves for each forcing in Figure 4. Also add in Figs. 1 and 2 the corresponding optimal constant-over-time V0 and accuracy when considering the entire 0-2500 kyr period.

In the next paragraphs, we call V_0^Q the optimal V_0 threshold that is obtained when the optimization procedure is carried out over the whole Quaternary. The results in the case of a changing V_0 (corresponding on each period to the optimal V_0 threshold obtained on that period) are compared to the results in the case of a constant V_0 over the whole Quaternary (V_0^Q).

We repeated the optimization procedure over the whole quaternary.

Figure Q7 - 2 compares the optimal V_0 obtained for the whole Quaternary (V_0^Q) to the optimal V_0 for each period.

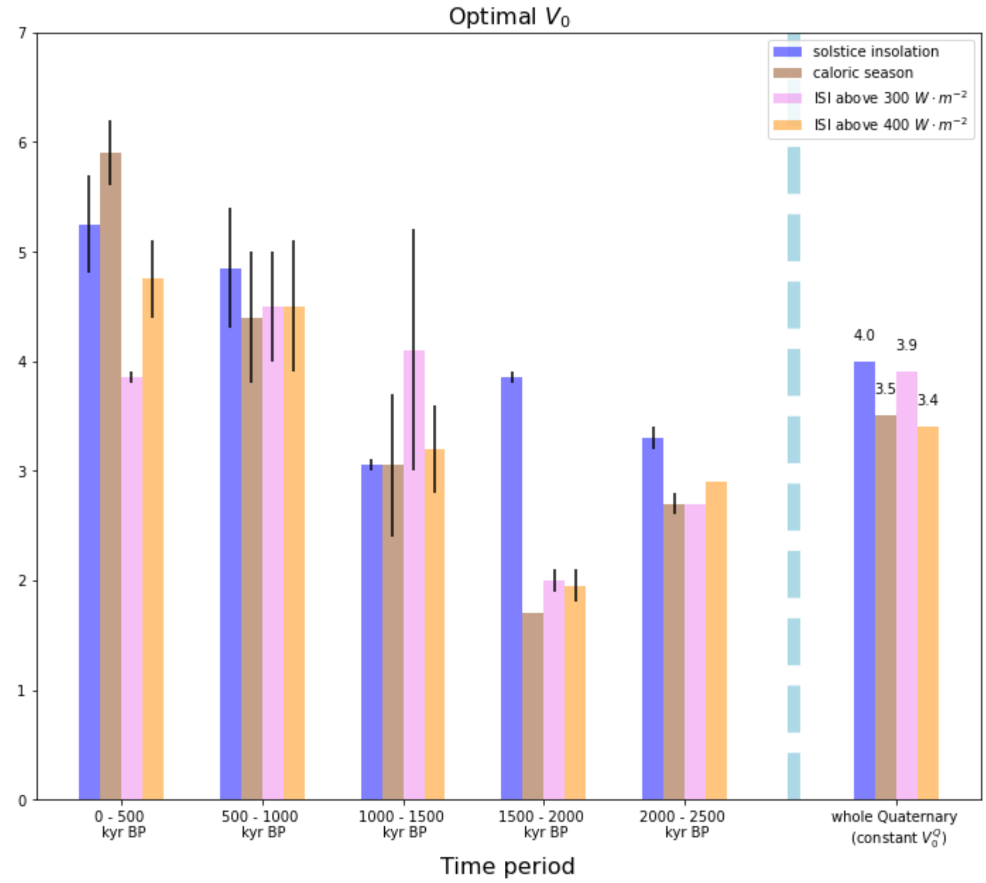


Figure Q7-2 : Optimal deglaciation threshold V_0 over the five different periods for the four different summer insolation forcings at 65° N, as well as the optimal constant V_0 threshold obtained when the optimization procedure is done over the whole Quaternary (V_0^Q). When several values of the deglaciation threshold V_0 maximize the accuracy criteria, the mean value is plotted and the other possible values are represented with errorbars.

The V_0^Q is between 3.4 and 4 for each insolation type. It is a value in the middle of the highest values that best fit the latter part of the record and the lowest values that best fit the earliest part of the record.

Figure Q7-3a represents the corresponding accuracy obtained on the whole Quaternary with a constant V_0^Q value (values represented by diamonds), as well as the accuracy when the V_0 value is varied over each period (initial case of the manuscript, represented by full bars). To obtain this figure, we used the V_0^Q value previously obtained corresponding to each forcing, and performed simulations with this value over each 500 kyr period, with several initial conditions. The highest value of the accuracy criteria obtained was selected and corresponds to the diamonds values.

As expected, the accuracy with a fixed V_0^Q value (diamonds) on each period and for each forcing is lower than or equal to the case when V_0 is being optimized (full bars). It is the case by definition, as the 'optimal V_0' were choosen maximizing the accuracy criteria. Indeed, the V_0^Q value being in the middle of highest value that best fit the latest part of the record and lowest values that best fit the earliest part of the record, the model outputs with a constant V_0^Q value have globally a poorer fit on all the record.

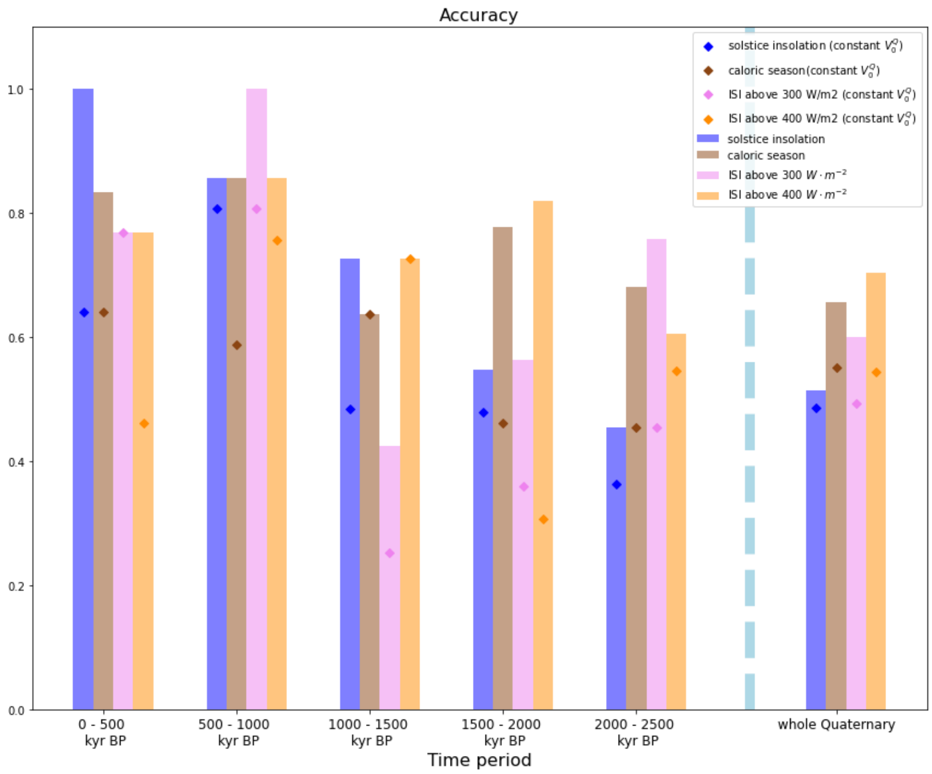


Figure Q7-3a: Accuracy over the five different periods for the four different summer insolation forcings at 65° N, as well as the corresponding accuracy criteria over the Quaternary when the optimization procedure is done over the whole Quaternary. The diamonds correspond to the accuracy obtained on each period when taking the optimized constant V_0 on those periods instead of the optimal V_0.

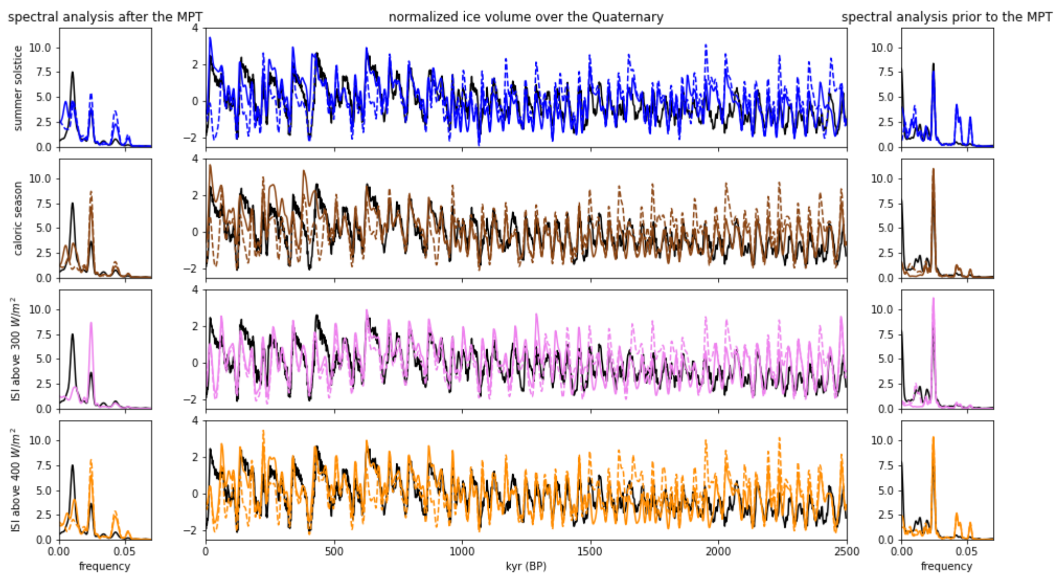


Figure Q7-4: Best model fit over the whole Quaternary and corresponding spectral analysis when V_0 is varied over time (initial case of the manuscript displayed in full lines) and when V_0 is taken equal to V_0^Q (dashed line).

Figure Q7-4 displays the results over the whole Quaternary in the case where the V_0 value is changed over each period (full lines) and when it is kept to the constant value optimized over the whole Quaternary, V_0^Q (dashed lines)

In the case of constant V_0^Q value, the ice volume values obtained prior to the MPT are too high in comparison to the record. This is not surprising, as the V_0^Q values for each insolation are globally higher than the optimal V_0 values over the pre-MPT period, leading to larger ice volume (as the deglaciation threshold is higher, larger volumes can form before the deglaciation takes place). On the contrary, on the latest part of the record, the model tends to deglaciate too often when using the fixed V_0^Q values. This is also not surprising as the V_0^Q values for each insolation are globally lower than the optimal V_0 values over the post-MPT period, allowing deglaciations to happen more often, when a lower ice volume is reached.

Figure Q7-5 displays the results over the last million year period, in the case where the V_0 value is set to its optimal value over the [0 - 1000 kyr] period (initial case of the manuscript, represented by full lines) and when it is set to the constant value optimized over the whole Quaternary, V_0^Q (dashed lines). For all insolation forcings except the ISI above 300 W/m2, the fit to the data is better in the case where the V_0 value is set to its optimal value over the [0 - 1000] kyr BP period and not the whole Quaternary. In the case of the ISI above 300 W/m2 forcing, the results are identical as the optimal V0 value over the [0 - 1000] kyr BP period is equal to the V_0^Q value.

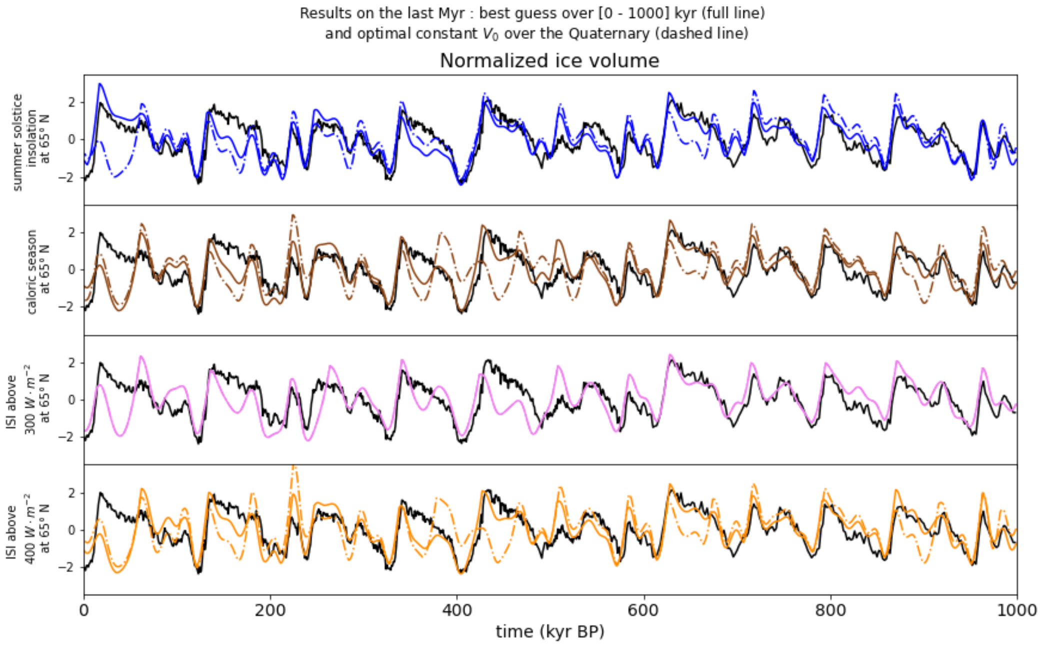


Figure Q7-5 : Normalized model results over the last million year, with the four different summer insolation forcings at 65° N when the accuracy criteria is the initial criteria of the manuscript (full line) and when the V_0 value is taken equal to V_0^Q (dashed lines).

We thank the reviewer for his/ her helpful suggestion to compare the results obtained to a fixed V_0 value over the whole Quaternary (V_0^Q). In the following, we propose additions to the manuscript to take into account this suggestion.

Concerning the figures, we prefer to keep Figure 4 and Figure 5 as in the original version of the manuscript, in order not to overload them.

However, we suggest to modify Figure 2 and Figure 3 of the manuscript. We suggest to replace Figure 2 by Figure Q7-2, to display the V_0^Q values. We suggest to replace Figure 3 by Figure Q7-3b. In comparison to Figure Q7-3a, the diamonds values are not displayed anymore in Figure Q7-3b. We think that displaying the accuracy values for both cases (varied V_0 and fixed V_0^Q) would overload the figure, and we therefore prefer to add to the manuscript only the accuracy value over the whole Quaternary when V_0 is being optimized over the whole Quaternary (V_0^Q).

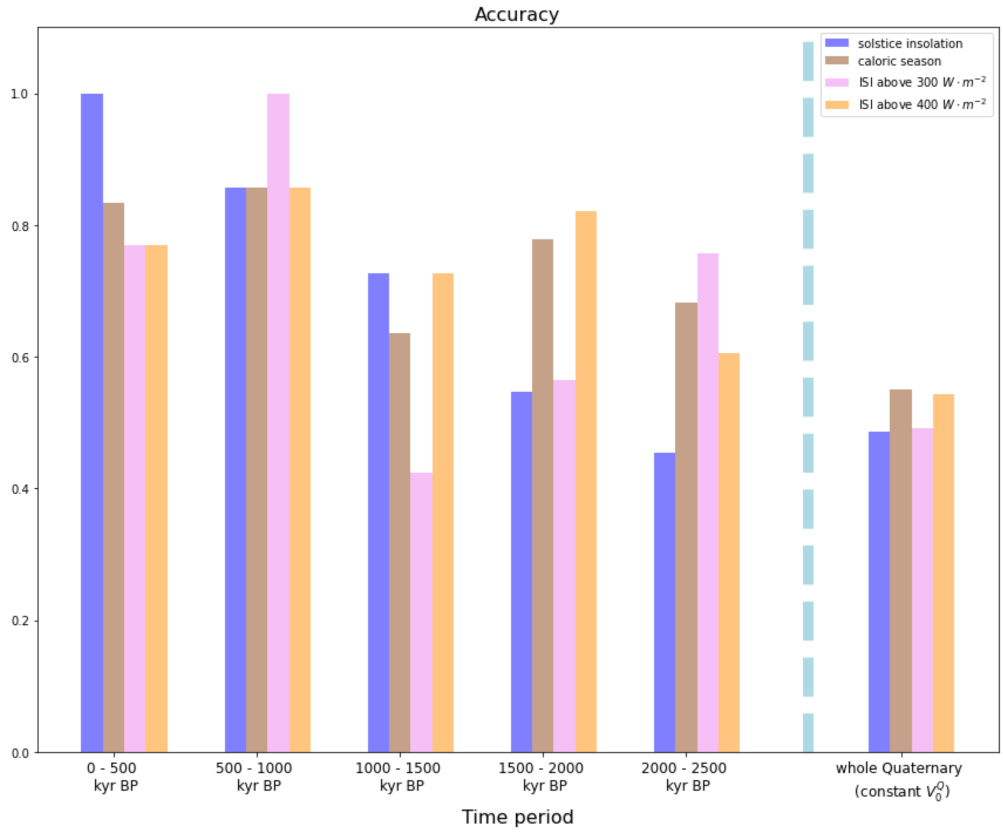


Figure Q7-3b: Accuracy over the five different periods for the four different summer insolation forcings at 65° N, as well as the corresponding accuracy criteria over the Quaternary when the optimization procedure is done over the whole Quaternary.

We suggest the following additions to the text of the manuscript, following the suggested additions in question 5 and 6 of the reviewer (in square brackets in the following) :

"[The V_0 values that maximize the accuracy criteria for each time period and insolation forcing are called 'optimal V_0'. To determine the optimal V_0 threshold corresponding to each period and insolation forcing, several simulations were carried out and the parameter values maximizing the accuracy criteria *c* were selected. More precisely, for each insolation and period, 3500 simulations corresponding to different V_0 thresholds (from V_0=1.0 to V_0=8.0 with a step of 0.1) and different initial conditions (initial volume V_{init} ranging from 0.0 to 5.0 with a step of 0.2, and initial state - glaciation or deglaciation) were performed. For each insolation forcing, the best fit over the Quaternary is defined as the simulation over the whole Quaternary (0- 2500 kyr BP) with a V_0 changing with time, and that is equal to the corresponding optimal V_0 at each time period]. Additionally, simulations were performed to determine the optimal V_0 threshold that is obtained when the optimization procedure is carried out over the whole Quaternary. It is called V_0^Q in the following."

Additionally, we rephrase l.186 :

"For each insolation, the deglaciation threshold V_0 maximizing the accuracy for each of the five 500 kyr periods, as well as the fixed V_0^Q value maximizing the accuracy over the whole Quaternary were computed. The results are displayed in Fig. 2."

We add at the end of l.194 :

“The optimal V_0 over the whole Quaternary, V_0^Q is between 3.4 and 4 for each insolation type. It is a value in the middle of the highest values that best fit the latter part of the record and the lowest values that best fit the earliest part of the record.”

We rephrase l.194 :

For each insolation, the accuracy corresponding to the optimal V_0 threshold for each time period as well as to the fixed V_0^Q value maximizing the accuracy over the whole Quaternary is displayed in Fig. 3.

We add at the end of l.198 :

“The accuracy obtained on the whole Quaternary period (fixed V_0^Q value) is globally lower than the accuracy on each time period. This is due to the fact that the V_0^Q values obtained are lower than the optimal V_0 values on the later part of the Quaternary and higher than the optimal V_0 values on the earliest part of the Quaternary, leading to a poorer representation of both of these periods”

In the following tables, values of the experiments are displayed.

	Optimal V_0 over the [0 - 1000] period	whole Quaternary V_0^Q value and corresponding accuracy over the [0 - 1000] period
summer solstice	5.1	4.0
caloric season	4.65	3.5
ISI > 300 W/m2	3.9	3.9
ISI > 400 W/m2	4.75	3.4

	Corresponding accuracy to the optimal V0 over the [0 - 1000] period	corresponding accuracy to the whole Quaternary V0Q value over the [0 - 1000] period
summer solstice	0.92	0.73
caloric season	0.82	0.48
ISI > 300 W/m2	0.87	0.87
ISI > 400 W/m2	0.82	0.48

Table : optimal V_0 threshold over each period

	summer solstice	caloric season	ISI above 300 W/m2	ISI above 400 W/m2
[0 - 1000] kyr BP	5.1	4.65	3.9	4.75
[0 - 500] kyr BP	5.25	5.9	3.85	4.75
[500 - 1000] kyr BP	4.85	4.4	4.5	4.5
[1000 - 1500] kyr BP	3.05	3.05	4.1	3.2
[1500 - 2000] kyr BP	3.85	1.7	2.0	1.95
[2000 - 2500] kyr BP	3.3	2.7	2.7	2.9
[0 - 2500] kyr BP (whole Quaternary)	4.0	3.5	3.9	3.4

Table : highest accuracy obtained over each period and accuracy on each period corresponding to the V_0^Q value (in parenthesis)

	summer solstice	caloric season	ISI above 300 W/m2	ISI above 400 W/m2
[0 - 1000] kyr BP	0.92 (0.73)	0.82 (0.48)	0.87 (0.87)	0.82 (0.48)
[0 - 500] kyr BP	1.0 (0.64)	0.83 (0.64)	0.77 (0.77)	0.77 (0.46)
[500 - 1000] kyr BP	0.86 (0.81)	0.86 (0.59)	1.0 (0.8)	0.86 (0.76)
[1000 - 1500] kyr BP	0.73 (0.49)	0.64 (0.64)	0.42 (0.25	0.73 (0.73
[1500 - 2000] kyr BP	0.55 (0.48)	0.78 (0.46)	0.56 (0.36)	0.82 (0.3)
[2000 - 2500] kyr BP	0.45 (0.36)	0.68 (0.45)	0.76 (0.45)	0.61 (0.55)
[0 - 2500] kyr BP (whole Quaternary)	0.51 (0.49)	0.65 (0.55)	0.60 (0.49)	0.70 (0.54)

Specific comments

L 25-26: "…due to reduced summer insolation, at latitudes typical of Northern Hemisphere ice sheets, 65° N." I suggest to change for "…due to reduced summer insolation, at latitudes of the Northern Hemisphere critical for ice sheet growth (65°N)."
We accept the suggested change.

L 38: independent --> independent
This will be modified in the next version of the manuscript.

L 49: the more insolation --> the highest insolation
This will be modified in the next version of the manuscript.

L 53: more adapted --> better
This will be modified in the next version of the manuscript.

L 71: explicitely --> explicitly
This will be modified in the next version of the manuscript.

L 77-77: In Equation (1) the labels (g) and (d) are misplaced
This will be modified in the next version of the manuscript.

L 80: "…a typical latitude for Northern Hemisphere ice sheets." This part of the sentence has already been used in the introduction, no need to repeat it.
We will remove this part of the sentence in the next version of the manuscript.

L 93-93: "The importance of orbital forcing alone seems able to start a glaciation" This sentence does not make sentence, please reformulate.
We propose to rephrase the sentence and to invert the order of the paragraph for clarity. This gives :
"A critical point is to define the criteria for the switch between the glaciation and deglaciation states. To enter the deglaciation state, both ice volume and insolation seem to play a role (Raymo, 1997; Parrenin and Paillard, 2003, 2012), as terminations occur after considerable build-up of ice sheet over the last million year. To represent the role of both ice volume and insolation in the triggering of deglaciations, the condition to switch from (g) to (d) state uses a linear combination of ice volume and insolation. The deglaciation is triggered when the combination crosses a defined threshold V_0 : the deglaciation threshold. As in the work of Parrenin and Paillard (2003), this allows transitions to occur with moderate insolation when the ice volume is large enough and reciprocally. On the contrary, glacial inceptions seem to depend on orbital forcing alone (Khodri et al, 2001; Ganopolski and Calov, 2011). Therefore, the condition to switch from the deglaciation state to the glaciation state is based on insolation only : it is possible to enter deglaciation when the insolation becomes low enough."

L 169: "In order to study the evolution of the optimal model parameters over the Quaternary…" Please correct to indicate that only V0 is being optimised.
We suggest to replace the sentence by : "In order to study the evolution of the optimal deglaciation threshold V_0 over the Quaternary, it was divided into five 500 kyr periods."

L 170: periods --> period
This will be modified in the next version of the manuscript.

L 173: "…the best fit parameters…" please modify to indicate only V0 is being fit
We suggest to replace the sentence by : "To calculate our accuracy criteria c and therefore determine the optimal V_0 threshold over a given period, a definition of the deglaciation in the data is needed."

L 183-184: “The model state was compared to the middle of the deglaciation.” I don’t understand this sentence
We suggest to rephrase in this way :
“To determine if a deglaciation is well reproduced by our model, we look at the state of the model (glaciation or deglaciation) at the time halfway between the start of the deglaciation and the end of the deglaciation. If the model state at that time is “deglaciation”, the deglaciation is considered as correctly reproduced.”

L 233: varying --> varying
This will be modified in the next version of the manuscript.

L 242: varies --> varies
This will be modified in the next version of the manuscript.

L 273-274: “To model future natural evolutions of the climate system, one would need to take into account for possible evolutions of the V0 threshold.” Please acknowledge that, possibly, the other parameters might as well change.
Indeed. We suggest to add an additional sentence l.274 :
“To model future natural evolutions of the climate system, possible evolutions of the V_0 threshold should be considered. However, we do not exclude the fact that variations of other parameters, that were kept constant in this study, could vary in the future. For instance, different I_0 thresholds have to be considered.”

L 283: Also add here Talento and Ganopolski, 2021 as reference.
This will be done in the revised manuscript.

L 287: “…very few tunable parameters… ” in fact, you should clarify that you tune only 1 parameter.
We suggest adding the following sentence at the start of l.288. “Only one parameter was varied, the deglaciation threshold parameter V0, while the other were kept constant.”

Section 2.4: I think a plot of the d18O record used with indications of the start and end of deglaciations, according to your criterion, is due here. Or at least refer the reader to this information in figure 3.
We would prefer not to add a plot here, in order to keep the figures for the core message of the paper. However, we agree that we should more clearly refer the reader to this information in the existing figures Figure 4 and Figure 5. We suggest to add a sentence at the end of line 182 : “the deglaciation periods in the data corresponding to the time between the deglaciation starts and deglaciation ends are displayed with a blue shading in Fig. 4 and Fig. 5”.
In the legend of Fig. 4 and Fig 5. the label of the blue and yellow colors have been swapped. The blue color corresponds to the deglaciation in the data, and the yellow color to the deglaciation state in the model. This will be corrected in the next version.

Figure 1: Normalized to what? by standard deviation? Please clarify. The ylabel in blue line must be corrected.
The insolation plots are centered and normalized to their standard deviation. For the spectral analysis curves in the new figure proposed, the spectral power is normalized by the standard deviation. The spectral analysis is performed using insolation curves over the [0 - 2500] kyr BP. This will be clarified in the legend of Fig 1.

Why show only until 1000 kyr BP when the totality of the Quaternary (0-2500 kyr BP) is the focus on the rest of the paper? Please show the plot considering 0-2500 kyr BP.
While the spectral analysis was carried out on insolation on the totality of the Quaternary ([0 - 2500] kyr BP), the insolation was initially only plotted on the [0 - 1000] kyr BP period, to make it easier for the reader to see the differences between the differents curves. However, we agree that this might be confusing as the paper focuses on the whole Quaternary period and suggest to modify Figure 1 accordingly.
The new figure is displayed below.

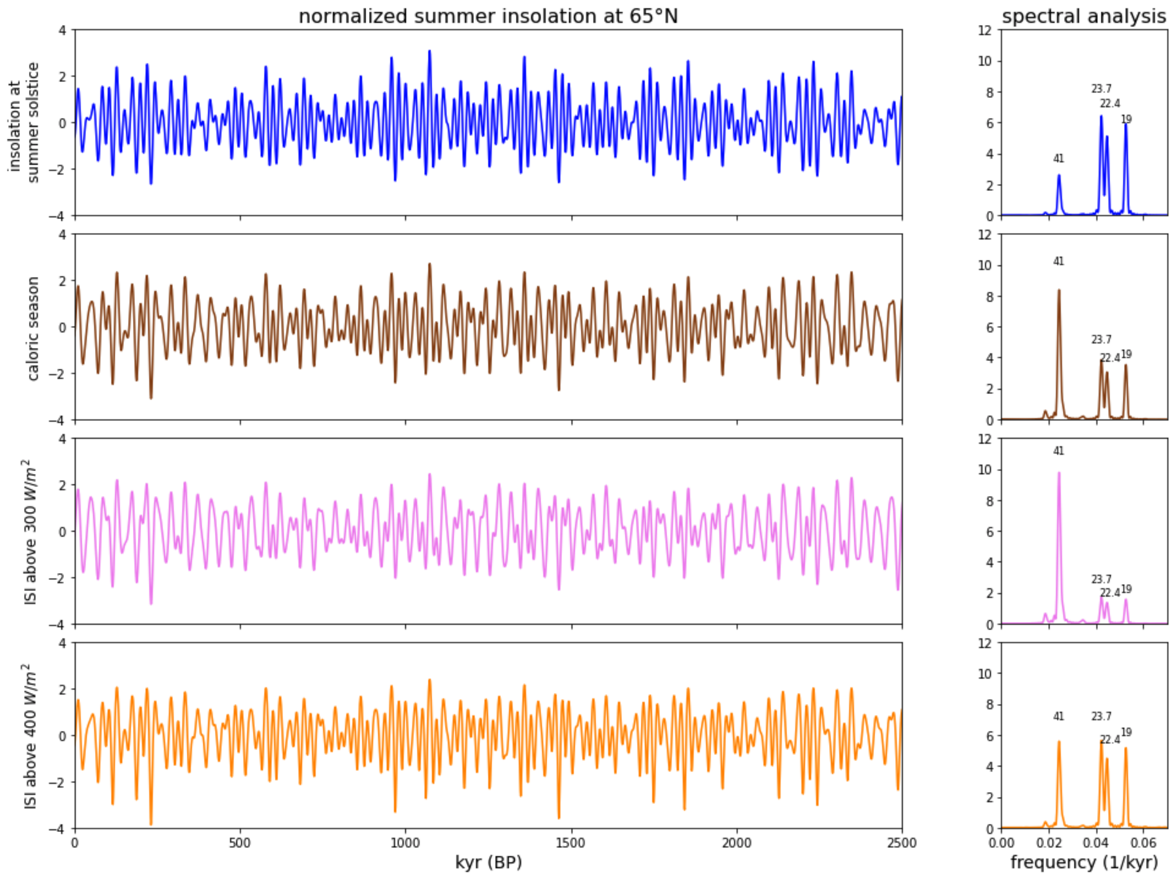


Figure : [New version of Fig. 1 of the manuscript]

(a) The four different summer insolation types at 65° N (centered and normalized by standard deviation). (b) Corresponding spectral analysis, normalized by the standard deviation.

In all the text: The acronym ISI was introduced in line 5, but frequently not used afterwards.
Indeed, we will use it more frequently after its definition in the revised manuscript.

When starting a new paragraph, sometimes there is an indent, sometime there is not.
We will modify it in the revised manuscript.