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Effect of the Ordovician paleogeography on the (in)stability of the climate

Dear editor,

Two referees have seen our paper. Both recognized the clarity and the wide interest of our results though the comments of the second reviewer are more nuanced. In the revised version, the text and the content have been modified in order to answer to all major comments raised by both referees.

- Referee 1: We thank the reviewer for having taken the time to entirely correct English errors. We have modified the revised version accordingly to these corrections. We have also followed the referee's requests by adding a discussion about the consistency of the position of Siberia through time within available Ordovician paleogeographical reconstructions. That point is critical in our study, and it undoubtedly deserved specific discussion. The northward drift of Siberia from the Middle to the Late Ordovician is actually based on abundant paleomagnetic data, and it is therefore a robust feature of all available Ordovician paleogeographical reconstructions published so far.
- Referee 2: Remarks made by the second, anonymous referee led us to include supplementary results (slab simulations at 470 Ma), to specify some technical points (the reliability of the sea ice simulation in FOAM) and also to improve the clarity of our iconography (Fig.1 and Fig. 3) and of our discussion. Although the additional simulations suggested by the referee – concerning the land ice and the transient runs – are relevant in the global context of the paleoclimatology, we think that they actually constitute studies as such and we consequently prefer to leave them for future work (we are currently conducting these simulations). We are confident that the present study is substantial enough to be published alone, as the first step of our newly developing research axis.

We consequently hope that this revised version will now be suitable for publication in *Climate of the Past*.

Best regards,

Alexandre Pohl, on behalf of all co-authors.

A. Response to reviewer 1 (Mark Williams)

A.1 Overall comments

This manuscript represents an interesting hypothesis that invokes changes in ocean heat transport to the northern hemisphere as an important driver of change between warm and cold global climate states in the Middle to Late Ordovician. It thus goes beyond those hypotheses that are predicated on CO₂ drawdown as the primary driver to initiate Late Ordovician glaciation.

Thank you for noting the pioneering dimension of our results.

A key observation is that uncertainty in the palaeogeographical position of Siberia in the Middle to Late Ordovician needs further discussion.

It is true that the paleogeographical reconstruction constitutes a critical point in our study, in particular concerning the latitudinal position of Siberia through time. We conducted here the simulations on the reconstructions of Blakey, and the northward drift of Siberia has been proven to favor the increasing climatic stability from the Middle to the Late Ordovician.

It is noteworthy that the northward drift of Siberia from the Middle to the Late Ordovician is a robust feature of all available Ordovician paleogeographical reconstructions published so far, including the maps from Torsvik and Cocks (Cocks and Torsvik, 2007: Fig. 6a (reproduced in Fig. R2); Torsvik and Cocks, 2013: Figs. 2.12, 2.14 and 2.15), Golonka and Gawęda (2012: Figs. 6 and 7) and Scotese and McKerrow (Scotese and McKerrow, 1991: Figs. 4 and 5). Cocks and Torsvik (2007) in particular, reviewed the paleogeographical evolution of Siberia through the Paleozoic. As ever, their continental reconstructions are based on two main data sets. (i) Paleomagnetic studies constrain the latitudinal position of the landmasses and their rotation. They however do not bring any information about the paleolongitude. (ii) The latter is determined through the analysis of the paleobiogeographical relationships that indicate closeness or remoteness of the studied region from other continents. Figure R1 shows the published paleomagnetic record of Siberia. Based on these results, the paleomagnetic constraints on the paleogeography of Siberia seem robust enough to allow reconstruction of the successive latitudinal positions of the continent during the Ordovician, which is on the contrary not the case for the surrounding time periods, between 1 Ga and 600 Ma on one side and between the Silurian and the Permo-Triassic boundary on the other side (Cocks and Torsvik, 2007).

Figure R2 displays the migration of Siberia reconstructed by Cocks and Torsvik (2007) from the Cambrian to the Permo-Triassic boundary. Among the successive latitudinal positions, the Middle to Late Ordovician (470 – 450 Ma on Fig. R2) evolution clearly stands out of the crowd, displaying one of the most prominent northward drifts in the entire period. Cocks and Torsvik (2007) comment it: “During the Cambrian, Siberia drifted slowly

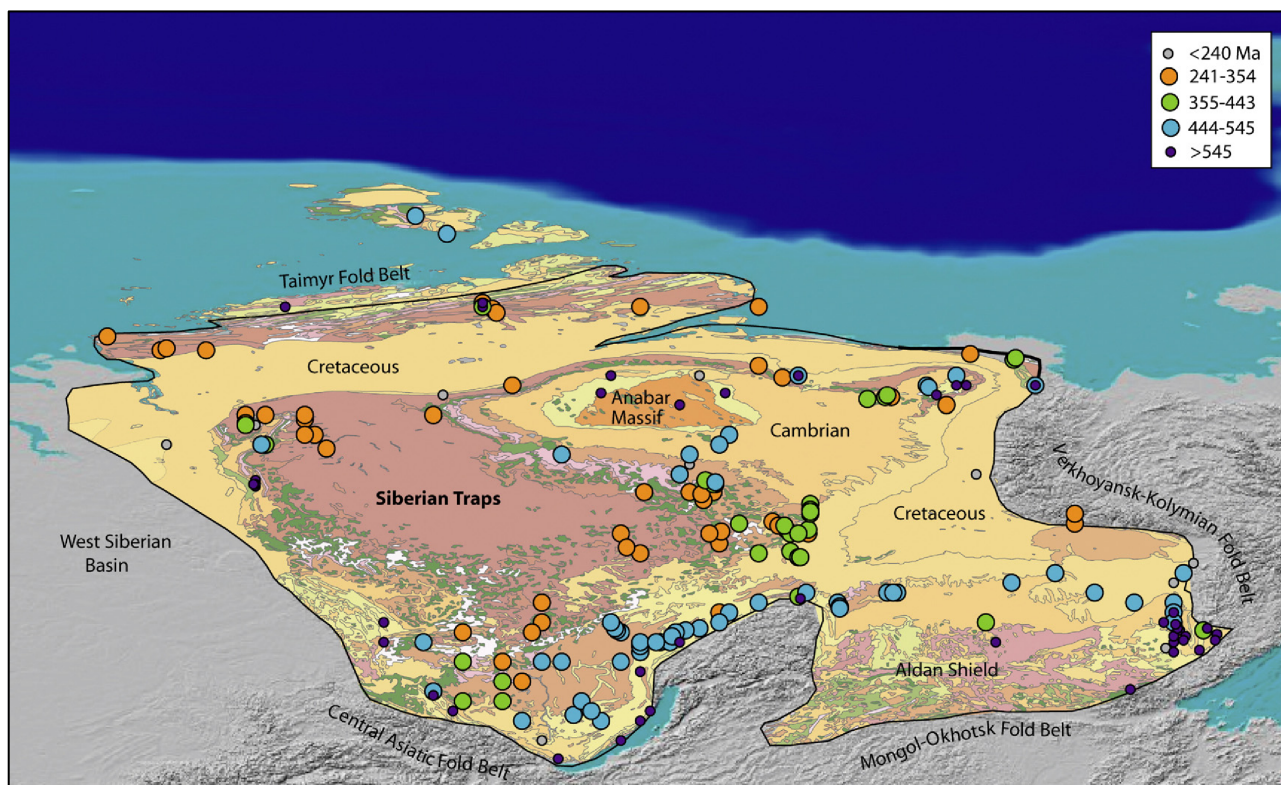


Figure R1. Satellite bathymetry-topography map orthogonal projection on northern Eurasia (Smith and Sandwell, 1997), superimposed on which are the margins of the Siberia Craton and within which is shown the simplified outline geology. The small coloured circles indicate the sampling locations and ages of all published palaeomagnetic data from the Siberia Craton and the Taimyr region, with their colours differentiated by geological time. From Cocks and Torsvik (2007).

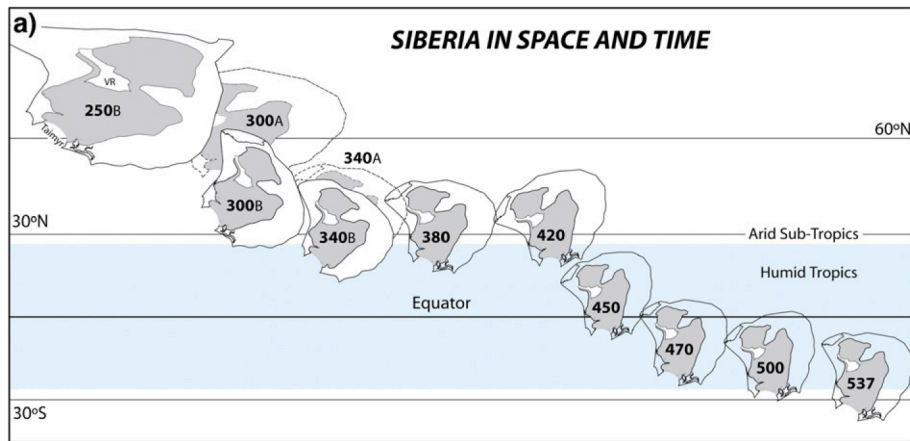


Figure R2. Drift and rotation history for Siberia from 537 Ma to 250 Ma. From Cocks and Torsvik (2007).

northward, but this was followed by more rapid northward drift during the Ordovician and Silurian, peaking at 13 cm/yr near the Ordovician–Silurian boundary”.

It appears that the northward drift of Siberia is thus a reliable, major feature of the continental evolution that took place from the Middle to the Late Ordovician.

A.2 Specific technical and scientific comments

PAGE 1, LINE 14, suggest rewording to ‘The Ordovician Period is characterised by abundant evidence for continental-sized ice sheets.’ OK

PAGE 1, LINE 22, ‘ocean dynamics are taken into account’ OK

PAGE 2, LINE 11 Yes, but perhaps make it clear that this radiation is at the genus and species level and represents the increasing complexity of marine ecosystems: the major organism groups appear in the Cambrian

[Page 2769, Line 11](#)

The remark is totally relevant. The authors are aware that the Great Ordovician Biodiversification Event represents the rapid diversification at the genus and species level of animal phyla that appeared much earlier, during the Cambrian Explosion. The goal of that introduction sentence is however to highlight the binding relationship existing between the global climate and the life’s evolution at the time. Going further into the description of the radiation consequently seems beyond our main purpose here. We propose to maintain the text unchanged to avoid impeding the flow of the argumentation.

PAGE 2, LINE 11 ‘paleoecology’ to be consistent with the rest of the text in the use of ‘paleo’ OK

PAGE 2, LINE 23, I think this would be better worded ‘organismal evolution’ rather than just animal evolution. Likely, changes in the phytoplankton may also have interplayed with global climate OK

PAGE 3, LINE 17 ‘the ocean’ OK

PAGE 4, LINES 5-6, REWORD ‘for two time intervals within the Middle {Dapingian at 470 Ma) and Late Ordovician {Katian at 450 Ma)’ [Neither the Dapingian, nor the Katian represent the whole of the Middle and Late Ordovician respectively] OK

PAGE 5, I think that many (most?) authors now accept that the Early Palaeozoic glaciation was more long-lived than just the Hirnantian acme. Though not inclusive, see for example, Page et al. 2007, and Vandenbroucke et al. 2009, 2010a and b.

[Page 2772, Line 12](#)

Evidence for a long-lived Ordovician glaciation has been accumulating for the last years. We propose here a modeling study. Because there is still no consensus about the duration of the glaciation based on field studies and also because our paper does not bring definitive answers on the duration of the glaciation, we think it is still important to present each scenario.

PAGE 5, LINE 13 It is not clear why the climate of 450 Ma has been chosen to represent the glacial state. I agree that the world was in an icehouse state at this time, but this is not the Hirnantian maximum? Why not choose to model the latter climate of 445 Ma? More explanation here would be useful.

[Page 2772, Line 23](#)

Using the 445 Ma continental reconstruction would be much more logical to study the Hirnantian glacial maximum. However, we can only use published and/or available continental configurations. For the Ordovician, paleogeographies from Ron Blakey (<http://jan.ucc.nau.edu/rcb7/mollglobe.html>) were available for the Middle Ordovician and the Late Ordovician and are indicated as 470 Ma and 450 Ma in absolute age. However, the Late Ordovician continental configuration represents the paleogeography for the whole time interval (i.e. 458 – 443 Ma) and thus includes the Hirnantian. No reconstruction is specifically available for the

latter. As explained in the text, “*The 450 Ma reconstruction is considered here as a good estimate for the Late Ordovician Hirnantian (445 Ma). The paleogeographical changes are limited at that timescale and they are assumed to not critically impact global climate.*” That reasonable approximation makes the discussion of the Hirnantian glacial maximum feasible.

PAGE 5, LINES 22-23, I cannot follow the English for ‘we used a cold summer orbit (CSO) like an orbital configuration’? Thank you. We reworded the sentence.

PAGE 6, LINE 6, ‘undertaken’, not done OK

PAGE 6, LINE 11, ‘well sensitive’ is grammatically incorrect (though sometimes used in the vernacular), simply use ‘sensitive’ here OK

PAGE 6, LINE 23, ‘we must note’ not notice OK

PAGE 7, LINE 6, GCMs OK

PAGE 8, LINE 6 ‘these results’ OK

PAGE 8, LINES 19-20, ‘for the same pCO₂’ OK

PAGE 10, LINE 6 ‘northwards’ OK

PAGE 11, LINE 9, ‘developed’ OK

PAGE 11, LINE 10 ‘these’ OK

PAGE 11, LINE 25 ‘energy balance’

[Page 2780, Line 11](#)

The referee is right: the energy balance actually matters. We however follow the conventions previously established by considering a varying climatic forcing (solar constant, pCO₂...) and maintaining all other things equal. In this manner, the energy balance and the considered climatic forcing vary together. The plots used to describe multiple equilibria and hysteresis within EBMs traditionally give the latitudinal position of the ice front as a function of the solar constant (i.e. the climatic forcing), not the position of the ice front as a function of the energy balance (see for example the review from North et al. (1981)). That is why we prefer here the term “climatic forcing” to “energy balance”.

PAGE 12, LINE 4 ‘for the same climatic’ OK

PAGE 12, LINE 5, do you mean ‘enslaved to’? ‘captured within’ would be better

[Page 2780, Line 27](#)

Thank you for the correction once again. We used here that expression following Rose and Marshall (2009) (e.g. page 2837: “*the ice edge is enslaved to the position of the midlatitude zero wind curl line*”). “Captured within” seems much better. We corrected that.

PAGE 13, LINE 4 ‘enslaved’ OK

PAGE 13, LINE 15 ‘In addition’, not besides OK

PAGE 13 GENERAL OBSERVATION. The text here contains many acronyms that often impede the flow of the argument. Sometimes its better to state key acronyms in full, like SICl on page 13.

[Page 2782, Line 15](#)

Employing the acronym SICl seems exaggerated here. Other acronyms are “GCM” (general circulation model), “EBM” (energy balance model) and “OHT” (oceanic heat transport). They are used throughout the text and constitute the body of the paper. We think that stating them in full would even more impede the flow of the argument. We consequently propose to delete the acronym “SICl” but we wish to maintain the others.

PAGE 13, LINE 31, I am always worried by ‘definite proof’, especially related to modelling studies

[Page 2782, Line 29](#)

We replaced the expression “definitely prove” by “confirm”.

PAGE 13, LINE 32, GCMs OK

PAGE 14, LINE 1, The Ordovician Period (no need for the word ‘time’, since ‘Period’ is a geochronological term that immediately invokes time) OK

PAGE 15, LINE 22, ‘to the mid latitudes’ OK

Page 15, LINE 13, there is widespread evidence for a cooler Late Ordovician climate that persisted well into the Silurian, and began as early as the Sandbian (or earlier).

[Page 2784, Line 20](#)

Thank you for correcting that formulation. We propose to focus that part of the conclusion on the Hirnantian, which seems more logical since our study actually does not bring new results for the rest of the Period. We modified the last paragraph of the conclusion.

PAGE 15, LINE 18, ‘to explain cooling’ not ‘that cooling’ OK

FIGURE 1 (AND ALSO FIGURE 8), do all palaeogeographical reconstructions for the Ordovician show the same northwards drift of Siberia during the interval 470 to 450 Ma? What is the uncertainty in these reconstructions? This needs further discussion because it is of fundamental importance to the model proposed here.

Cf. comments in part A.1 (“overall comments”) for a response to that question. We propose to integrate the discussion in Fig. 8, since the latter shows at best the northward drift of Siberia observed in Blakey’s reconstructions and its consequences on the ocean circulation (see the caption in Fig. 8).

A.3 References cited in review

Vandenbroucke, T.R.A, Armstrong, H.A, Williams, M, et al. 2010a. Polar front shift and atmospheric CO₂ during the glacial maximum of the Early Paleozoic Icehouse. *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.1003220107

Page, A.A., Zalasiewicz, J.A., Williams, M. & Popov, L.E. 2007. Were transgressive black shales a negative feedback modulating glacioeustacy during the Early Palaeozoic Icehouse? In: Williams, M., Haywood, A., Gregory, J. & Schmidt, D. Deep time perspectives on climate change: marrying the signal from computer models and biological proxies. The Micropalaeontological Society. Special Publications. The Geological Society London. 123-156.

Vandenbroucke, T.R.A., Armstrong, H., Williams, M., Paris, F., Zalasiewicz, J.A., Novak, J. & Verniers, J. 2010b. Epipelagic chitinozoan biotopes map a steep latitudinal temperature gradient for the earliest Late Ordovician seas: implications for a cooling Late Ordovician climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, doi:10.1016/j.palaeo.2009.11.026.

Vandenbroucke, T.R.A., Armstrong, H.A., Williams, M., Zalasiewicz, J.A. & Sabbe, K. 2009. Ground truthing Late Ordovician climate models using the paleobiogeography of graptolites. *Paleoceanography*, 24, 4, doi:10.1029/2008PA001720, 2009

B. Response to Anonymous Referee #2

I should note that I have not read the other review of this paper, so my review is independent.

This paper presents a set of climate model simulations designed to test the sensitivity of climate to CO₂ forcing under two different Ordovician palaeogeographies. The model displays non-linearity in its response to CO₂, with a step-change in temperature at a CO₂ threshold which is found to depend on the underlying palaeogeography. This non-linearity is not found with a slab model, and so the authors infer that ocean circulation is playing a role in the non-linearity. The different thresholds for the different palaeogeographies are attributed partly to the presence of more land in the Northern Hemisphere in one palaeogeography, the presence of which precludes a coherent circumglobal circulation.

The paper is fairly straightforward and I have no major problems with the findings.

Thank you.

I think that it could be published with the analysis carried out so far, but that some more analysis (listed as 'Main Comments' below) will uplift this paper from being fairly pedestrian to being very good.

Most of current hypotheses explaining the Late Ordovician glacial onset required a large CO₂ drop up to now (Brenchley et al., 1994; Kump et al., 1999; Lenton et al., 2012; Villas et al., 2002). These kinds of scenarios have motivated numerous modeling studies investigating the sensitivity of the Ordovician climatic system to a CO₂ decrease (Crowley and Baum, 1991; 1995; Crowley et al., 1993; Herrmann et al., 2003; 2004; Poussart et al., 1999). The latest one is now more than 10 years old. For the first time, here we use a general circulation model with coupled components for ocean and atmosphere, thus representing a major step forward into the simulation of the Ordovician climate which was based on slab ocean-atmosphere simulations till now. These simulations cannot capture the impact of large changes in ocean circulation's scheme as slab ocean models do not simulate the oceanic currents and the deep oceanic circulation and use a crude parameterization to represent the ocean heat transport based on the modern ocean. By demonstrating non-linearity within Ordovician climate, we bring for the first time an explanation for the Late Ordovician Hirnantian glacial peak that does not require any sharp CO₂ drop. As a consequence, the amplitude of the CO₂ sinks (Young et al., 2009; Nardin et al., 2011) required to trigger a glaciation during the Hirnantian may be reconsidered. We now suggest that a moderate sink may have been sufficient, thus making relevant some mechanisms that have been neglected so far due to their moderate impact on the CO₂ level (we added this supplementary argument to the final paragraph of the conclusion). Finally, our results are discussed in the light of the recent findings from Ferreira et al. (2011) through an extensive analysis of the oceanic heat transport. Although the demonstration of multiple equilibria and hysteresis has not been undertaken here, our study paves the way for new investigations by suggesting that the existence of multiple equilibria can be extended to realistic continental configurations.

B1. Main comments:

The proposed mechanism appears to rely fairly heavily on the sea ice physics and dynamics. So, does the model simulate sea ice well in the modern climate?

Sea ice effectively plays a critical role in the climatic non-linearity demonstrated in our study. Hopefully, FOAM simulates sea ice correctly in the modern climate. A previous study led by Vincent Lefebvre on the Antarctic Circumpolar Current has already checked this specific point. We refer here to the paper from Lefebvre et al. (2012), from which we quote page 6:

"The modern maximum sea ice area during the winter of the southern hemisphere (SIM) is estimated between 14.2 and 15.2 x 10⁶ km² in September [Gloersen et al., 1992] and the CTRL-1X predicts a SIM equals to 16.5 x 10⁶ km² (assuming a pre-industrial CO₂ level). As a result, FOAM provides a correct representation of the maximum sea ice coverage in winter (September) in the Southern Hemisphere for the control simulation, at least better than a lot of IPCC class model [cf. Arzel et al., 2006]. The seasonality of the sea ice coverage in the CTRL-1X simulation differs from the observations in summer with a 0.2 x 10⁶ km² minimum contrasting to 2 x 10⁶ km² [Gloersen et al., 1992] suggesting a stronger melting of the sea ice in FOAM during the summer of the Southern Hemisphere. While far from perfect, FOAM simulates correctly the modern day extent of the sea-ice cover in the Southern Hemisphere and seems therefore suitable for studying paleoclimate."

We propose to develop that point at the beginning of the results, to make it clear to the reader for the rest of the paper: [Page 2775, Line 15](#)

The slab model is only run for the 450 Ma palaeogeography. To have confidence that the non-linearity is related to the full ocean, it would be helpful to show that the slab model at 470 is also linear.

The slab runs are not the main purpose of our analysis. We decided to show the simulations conducted at 450 Ma to allow comparison with previous studies that are all focused on the Late Ordovician (Crowley and Baum, 1991; 1995; Herrmann et al., 2003; 2004; Poussart et al., 1999). Slab results at 470 Ma however display the same characteristics. The pCO₂-SAT relationship is linear in a log-axis plot. As suggested by the referee, we propose here to add the 470 Ma slab runs in Fig. 2 and into the description of the results:

[Figure 2](#), figure and caption were modified.

[Page 2775, Line 27](#): Comments were adjusted to take the slab runs at 470 Ma into account.

The paper several times refers to a “tipping point”. However, a tipping point implies some form of hysteresis. All that is shown here is that the model displays a non-linearity. The authors should either formally show that the model displays ‘tipping point’ behaviour (i.e. carry out some transient simulations in which CO₂ is ramped up and down slowly), or cut all references to ‘tipping points’ and ‘bifurcation’ and instead use ‘non-linearity’.

It is true that we do not demonstrate multiple equilibria and hysteresis in the Ordovician climate in this study, which will actually be undertaken very soon. We are currently working on a deep-time configuration of the MITgcm in order to address this question. It is also true that the term “tipping-point” has long been exclusively used to refer to bifurcation points between multiple equilibrium states. It has long been seen as a threshold at which the changes undergone by the climatic system were suddenly much faster than the changes in the forcing and presented a certain degree of irreversibility. It seems thus necessary to clarify the usage of this term through 3 points:

(i) Firstly, Lenton et al. proposed in 2008 a broader definition of a “tipping-point” that does not necessarily include neither bifurcation nor hysteresis. From a very formal point of view, it is thus not misleading to use that term here.

(ii) Secondly, it is noteworthy that the two studies from Rose and Marshall (2009) and Ferreira et al. (2011) – about which our entire discussion has been built – do not employ the term “tipping-point”. Employing that term here consequently does not mislead the reader by suggesting that we conducted similar analysis with transient simulations. The expression “tipping-point” is actually found a single time – in the study from Ferreira et al. (2011) – as the authors invite the reader to refer to the paper of Lenton et al. (2008). We quote here Ferreira et al. (2011): *“Multiple equilibrium states, which might be “accessed” suddenly as external forcing parameters slowly change (e.g., orbital parameters, greenhouse gas concentrations, continental drift, etc.) and pass through “tipping points” [see the review by Lenton et al. (2008)], could have played a role in such climate excursions.”*

(iii) Finally, it seems reasonable to use that term even considering its classical implications (bifurcation and hysteresis) in the light of the extensive analysis of the oceanic heat transport conducted in our study. The key points of the mechanisms shown by Rose and Marshall (2009) and Ferreira et al. (2011) to induce multiple equilibria are also found in our simulations: the two equilibria obtained in our study are similar to the ones from Ferreira et al. (2011, compare Fig. 1 with our Fig. 3) and the underlying climatic behavior is similar too (compare the synthesis from Ferreira et al. (2011) and our Fig. 12) with sea ice extending down to the mid-latitudes oceanic heat transport minimum. As we explained before, we plan to strictly demonstrate multiple equilibria and hysteresis in the Ordovician in our next study with the MITgcm. But for now, our analysis is really encouraging and we think that the multiple equilibria found in Ferreira et al. (2011) will be extended to the Ordovician continental configuration.

Because it perfectly describes the climatic behavior demonstrated in our study without misleading the reader, we would like to maintain the term “tipping-point” in our text, unless the editor asks us to change it.

Although it is traditionally used in studies about the Snowball Earth that do not strictly demonstrate multiple equilibria and hysteresis (e.g. Liu et al., 2013), we recognize that using the term “bifurcation” may be misleading, and we consequently propose to replace “bifurcation” by the word “shift”. [Page 2776, Line 14](#) and [Page 2783, Line 26](#)

The model does not include a land-ice component. With the inclusion of a land-ice component, the main results of the paper (e.g. a lower CO₂ threshold for 450 Ma compared with 470Ma) may well change, and even reverse. This should at least be commented on. The Donnadieu modelling group does regularly use a land-ice model, so it is possible that they could incorporate this into their model setup.

Including the land-ice into the modeling procedure constitutes the next step of our work. Actually, we are currently conducting the ice-sheet runs.

From a methodological point of view, it is for now impossible to fully couple an ice-sheet model with our climate models because of the huge computation time required. Several strategies have consequently been developed to overcome this difficulty (see the review from Pollard, 2010). Results substantially differ depending on the experimental protocol chosen (see for example Herrington and Poulsen, 2012), leading to large uncertainties in the simulated ice-sheet associated to the each climatic state (e.g. at 450 Ma and at 8 PAL). Simulating the land ice constitutes a whole study as such and it is consequently left for future work. It is still noteworthy that our preliminary ice-sheet results for 450 Ma display the climatic instability too.

Following the referee’s suggestions, we propose to clarify that point in our methodology section ([Page 2772, Line 3](#)), but we will not include ice-sheet results in our present study.

The authors postulate that the presence of a proto-Siberia in the NH is responsible for the difference between the two paleogeographies. This could be tested more robustly by carrying out a further simulation in which just this one aspect of the palaeogeography is changed.

We conducted such an experiment at the beginning of our work. We had originally 3 paleogeographical reconstructions, from which only 2 are presented in the paper to simplify the demonstration.

We tested the influence of the presence of high-latitude continental masses on global climate at 430 Ma. Using this configuration, the tipping-point is crossed between 4 PAL and 2 PAL. At 4 PAL, climate

consequently belongs to the warm climatic mode (Fig. R3a, global surface air temperature: 19°C). We subsequently truncated all continental masses beyond 40° N by replacing them by oceanic points and kept other boundary conditions the same. The simulation at 4 PAL was repeated with that new configuration. As expected, climate enters the cool climatic mode. Global temperature falls to 4.3 °C and sea ice expands down to the mid-latitudes (Fig. R3b).

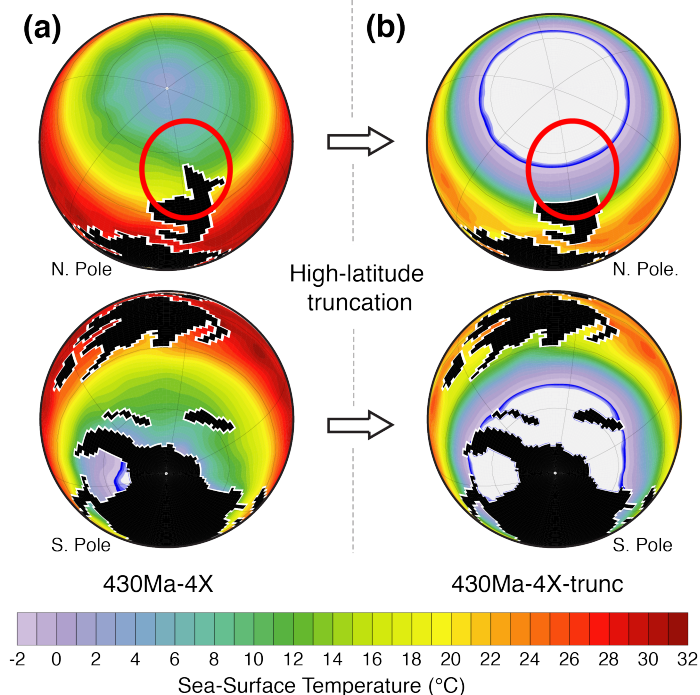


Figure R3. Sensitivity experiment showing the impact of the presence of high-latitude continental masses on the climate system at 430 Ma and for 4 PAL. The paleogeography based on Blakey (2007) is used in (a). In (b), the paleogeography from Blakey is modified by truncating all high-latitude continental masses (red circle). The color shading gives the SST, the blue-white shading the extension of the permanent sea-ice cover. The latter is defined as the sum of all grid points whose at least 80 % of the surface is covered by sea ice during a year, allowing to discard temporary sea ice cover by icebergs or rapidly advancing and retreating ice fronts. Continental masses are in black.

Although such a simulation is quite convincing as such, it does not show the driving mechanisms implicated in the shift from the warm to the cold climatic mode. That is why we preferred presenting a detailed analysis of the oceanic heat transport in the paper, which seems much more instructive and allows to discuss our results in the light of the studies from Ferreira et al. (2011) and Rose and Marshall (2009).

Changes to seaice are postulated as being responsible for several aspects of these simulations. However, this is not proven, just inferred from the fact that there are changes in seaice. To properly nail this, the authors would need to carry out a further simulation in which seaice was held constant whilst other aspects of climate were allowed to change.

Because we use a fully coupled ocean-atmosphere GCM, conducting such a simulation where sea ice is maintained constant seems hazardous, leading to serious problems within the energy conservation and within the SST calculation.

Nevertheless, our analysis is based on the papers from Rose and Marshall (2009) and from Ferreira et al. (2011), these papers being in turn built on numerous studies about multiple equilibria and the positive ice-albedo feedback, going back to Budyko (1969) and Sellers (1969). Abundant scientific literature is available, and you can in particular refer one more time to North et al. (1981) for a review about multiple equilibria and hysteresis within Energy Balance Models.

In addition, as we explained in our discussion by reviewing the historical background of the multiple climatic equilibria, two main mechanisms have been proven so far to induce climatic intransivity: the first one relies on the meridional overturning circulation, the second one on the ice-albedo positive feedback. The paper from Rose et al. (2013) complements previous studies from Rose and Marshall (2009) and Ferreira et al. (2011) by explicitly showing that the changes within the meridional overturning circulation are a “passive response to cooling and ice expansion” and that “transitions are driven by radiative forcing and sea ice feedbacks.”

At the moment, much is made of the changes seen between 450 and 470 Ma in the Northern Hemisphere. However, the changes in the Southern hemisphere are just as large, but of opposite sign, and deserve some more attention.

Fig. R4 displays the SST changes taking place from the 470Ma-12X simulation to the 450Ma-12X simulation (same as Fig. 6c with a rectangular projection to allow comparing with Figs. R5 and Fig. R6).

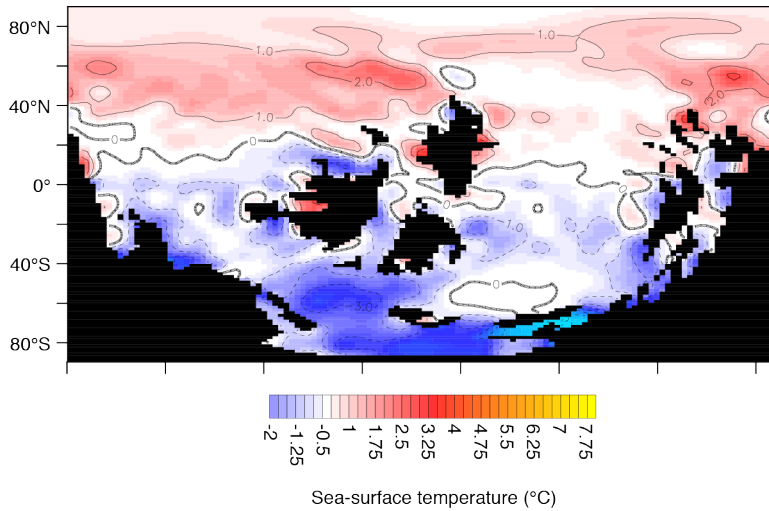


Figure R4. Sea-surface temperature difference between the simulations conducted with 12 PAL at 450 Ma and at 470 Ma (450Ma-12X – 470Ma-12X). The black mask represents all the grid points where the SST difference could not be calculated, cumulating each point that is a continent, either in the 450 Ma or in the 470 Ma configuration.

A cooling is observed in the Southern Hemisphere (up to $-3\text{ }^{\circ}\text{C}$), as noted by the reviewer. A first explanation lies in the changes occurring in the oceanic heat transport (OHT). From 470 Ma to 450 Ma, the OHT decreases at almost all latitudes in the Southern Hemisphere (Fig. 7a). These changes are necessary induced by the paleogeographical evolution since all other things are kept the same between the two simulations. These changes are also sufficient to induce the growth of sea ice in the Southern Hemisphere (Fig. R5). The latter reinforces in turn the cooling due to the sea ice albedo positive feedback, which explains the sharp temperature drop beyond $70\text{ }^{\circ}\text{S}$. The spatial pattern of the Southern Hemisphere cooling is also modulated by the changes occurring in the surface convection (Fig. R6). Cooling culminates where surface convection is decreased from 470 Ma to 450 Ma (compare Fig. R6 [blue circle] with Fig. R4), and cooling is reduced where convection increases (compare Fig. R6 [red circle] with Fig. R4).

It is thus possible to comment and explain the cooling occurring in the Southern Hemisphere, but we think that including these comments and figures into the paper would impede the flow of the demonstration without bringing any essential supplementary idea.

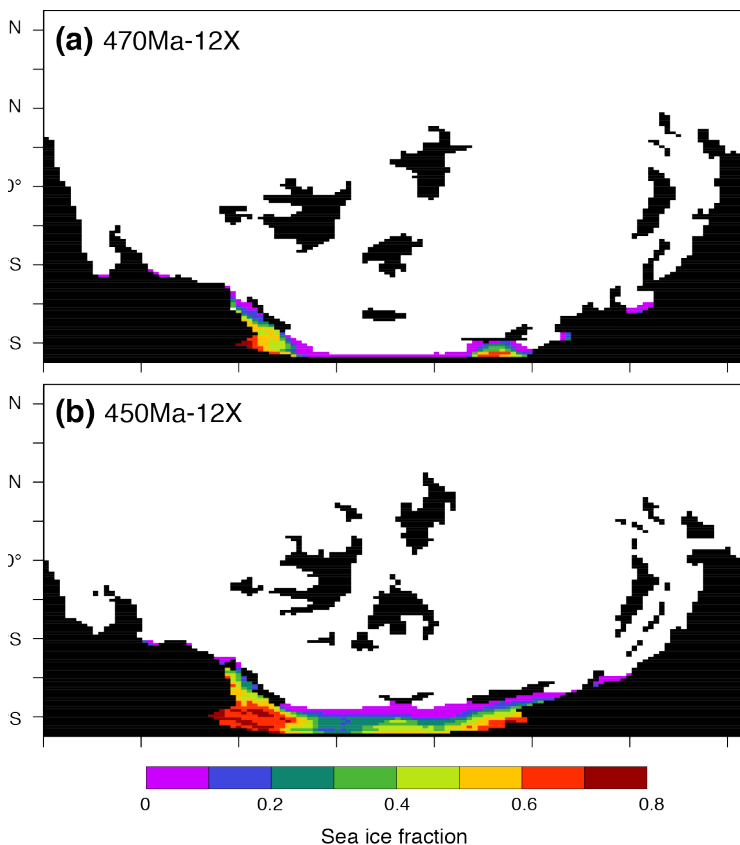


Figure R5. Mean annual sea ice fraction for the experiments conducted with 12 PAL at 470 Ma (a) and at 450 Ma (b) with the fully coupled version of FOAM.

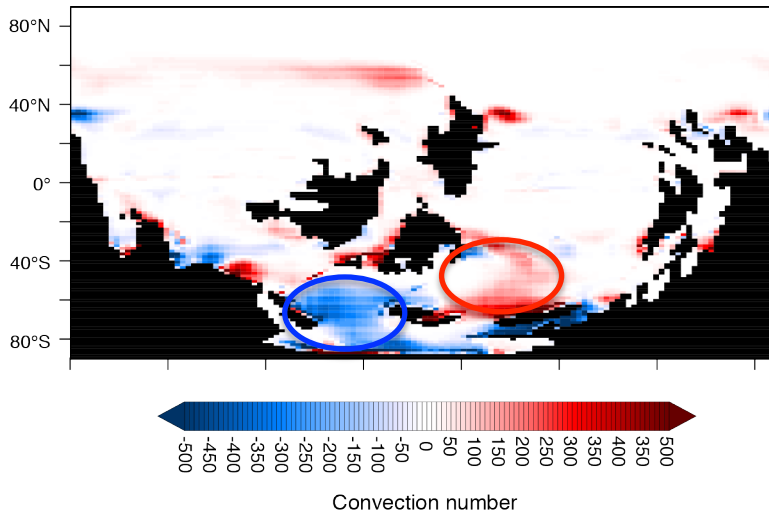


Figure R6. Surface convection difference between the 450Ma-12X and the 470Ma-12X simulations (no unit).

B2. Specific comments:

P2769, Line 26 – not sufficient based on what? A quick calculation of radiative forcing would be useful here.

“Not sufficient” refers here to the fact that the lower solar constant cannot be the sole responsible for the Late Ordovician glacial onset. The solar constant was approximately the same (even weaker actually) during the Early Ordovician whereas climate was much warmer at that time (see for example Trotter et al. (2008)). That is why a supplementary mechanism is required to cool climate and consequently trigger glaciation during the Middle – Late Ordovician.

Figure 1 is not totally clear – e.g what are the blue bars in the timescale?

Thank you, we have added a description of the blue bars in the caption of Fig. 1.

The word “ice” and “ice cap” is used several times without it being clear if sea-ice or land-ice is being discussed – please clarify in all cases.

Actually, we never address the issue of the land ice. Following the referee’s suggestion, we specified the origin of ice in all necessary cases throughout the discussion.

P2773, line 4: “The solar luminosity was set 3.5% below present according to the Faint Young Sun paradox (Gough, 1981)”. This is not according to the FYSP but according to a model of solar physics. OK

Figure 3 – make seaice and land a different colour. Alos, the map projection is not very helpful – why not centre on the pole?.

We changed the colors used in Fig. 3. Concerning the map projection, we did not center on the pole because that kind of oblique projection is useful to see what happens both at the pole and at the equator. Since numerous geological studies focus on the equatorial continental masses (Laurentia, Baltica and Siberia), that choice seemed the most relevant. For comparison, the same figure is given with polar projections in Fig. R7.

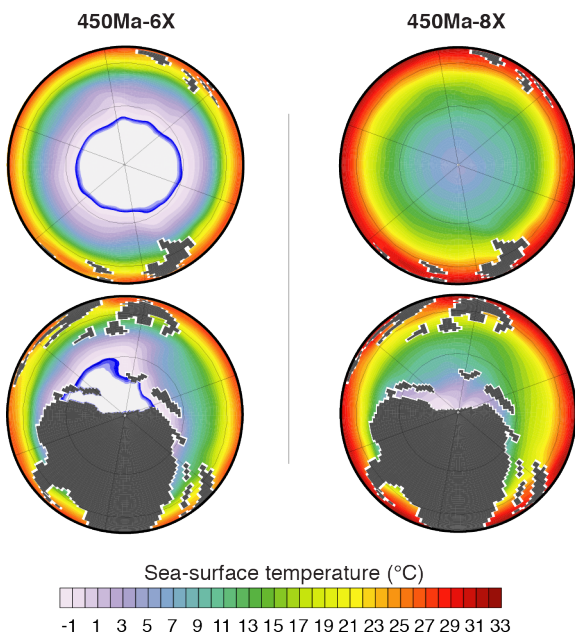


Figure R7. Same as Fig. 3 except that we used here a polar projection.

P2776. line 16 – “more stable” is not clear. ‘has a higher CO2 threshold’ is more accurate. OK

B3. Technical comments:

The paper should be professionally proof-read as there are numerous instances of unusual phraseology and vocabulary.

The numerous corrections made by the first referee – Mark Williams - significantly improved the quality of the manuscript.

Abstract: “quasi-oceanic Northern Hemisphere” does not make sense until the paper is read – please rephrase.

OK. We replaced “quasi-oceanic” by “95 % oceanic”.

Abstract: “The peculiar shape of the oceanic heat transport” is unclear – I am not sure that ocean heat transport can have a ‘shape’.

We reworded the last part of the abstract.

P2769, Line 1: “reflects” is unclear. OK

P2769, Line 1: give dates of Ordovician. OK

P2769, Line 14 “drawdown of icesheets” should be “reduction of icesheets”? OK

P2769, Line 19 “remains yet unusual” should be rephrased. Replaced by “stands out from the crowd”.

P2774, line 1 – “well sensitive” should be “very sensitive”? OK

Figure 4 – state in caption that these are results from the coupled model, not slab model. Also for other figures where appropriate. OK

P2778 occurs later -> occurs at higher co2. “lower” but OK

P2780 line 27 – “slaved”? And 2782 line 1. OK

P2783 – “peculiar” is peculiar! Also elsewhere. OK

P2783 – “till” should be “up to”. OK

P2784 – “brutal”? Replaced by “sudden”.

C. References cited in the response to the reviewers

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