Response to comments from Referee #2

This paper presents a set of simulations of the Cenomanian and Maastrichtian, together with selected gateway perturbations, to investigate the intermediate and deep circulation pathways of these time periods and compare with available proxy evidence. There is a substantial amount of work presented here and a thorough examination of all different circulation pathways and possible mechanisms. The text is generally well written and the figures are well composed. This paper is likely suitable for publication in Climate of the Past, subject to revisions.

Thank you for this comment.

My main criticism of the manuscript is that it is very long in describing all details and some of these descriptive parts are less interesting than others. I think the authors ought to prioritise better to focus the manuscript on the most compelling results and conclusions. The text itself is 39 pages, not including references and figures, making it heavy work to read. I have made some suggestions for shortening below; however I encourage the authors to look for their own ways of making it shorter. As a guiding principle, the authors may consider prioritising the two main experiments (Cenomanian vs Maastrichtian), and reducing the discussion of the gateway perturbation experiments.

We acknowledge that the paper is quite long. However, we instead believe that this length is necessary and a strength of the paper because the details of water mass pathways and reorganizations will probably be particularly useful to non-modelers and researchers working with Late Cretaceous ε_{Nd} records. We also note that reviewer #1 requested additional information that we provided. Averaging reviewer comments does not guarantee successful revisions but the comments from reviewer #1 suggest that our manuscript was not generally considered to be too long.
This said, in the course of the revisions, we have tried to keep your comment in mind by improving readability throughout. We have also tried to establish a clean and intuitive organization with topics divided into clear subsections. Readers with specific interests can read relevant sections and skip portions that are of less interest to them. For instance, as you mention, readers that are not interested in gateway sensitivity experiments can conveniently skip over sections 2. (Paleogeographic considerations), 4.3 (Sensitivity of the Maastrichtian circulation to ocean gateways and atmospheric CO_2) as well as parts of section 5. (Discussion).

One of the main findings of this paper is that Southwest Pacific sinking dominates the deep circulation in all cases. The authors have given some explanation as to why this region always produces sinking (generally low river runoff), but perhaps it is worth mentioning that the Pacific Ocean is the only major basin in these paleogeographies that spans from one polar region to the other (unlike a modern geography where there are two). It is thus virtually guaranteed that equator-to-pole heat transport will drive at least one mode of Pacific sinking that dominates the deep ocean.

You are correct that the Pacific Ocean is the basin that spans from one polar region to the other because the Cenomanian and Maastrichtian North Atlantic Oceans are located at lower latitudes than modern. The Pacific also contains most of the high latitude open ocean area and the majority of the deep ocean area in the Late Cretaceous. Although these considerations render more probable the formation of deep waters in either the North or South Pacific Oceans, there is no requirement for deep water formation on the basis of continental configuration alone. For instance, the 2x CO_2 (560 ppmv) Maastrichtian simulation described in Farnsworth et al. (2019) predicts formation of deep waters in the South Atlantic and Indian Oceans rather than in the North/South Pacific, although Farnsworth et al. (2019) employ the same Maastrichtian paleogeography as we do.

Models and Spinups section

The color scheme used in Figure 1 suffers when in print form: It becomes hard to distinguish between land and shelf – this can easily be fixed by making the land grey. Also, it might be better to use a "cell fill" mode rather than contours, so that the topographic resolution is visible.

Done.

In Figure 2, I'm confused that the model extension runs are only plotted for roughly 300 years each. The methods state (Line 304) that each of these runs has been extended for 950 years. Where is that data?

The first ~ 650 years of the gateway sensitivity experiments have unfortunately not been archived on long-term storage disks and are now lost. However, we would like to point out that this information was and is explicitly stated in the caption of Figure 2 (we have clarified the names of the simulations): "Only the ends of the sensitivity simulations (Deep Labrador Seaway, Deep Drake Passage, Deep Caribbean Seaway and Deep Neotethys Seaway) are shown because the full history of the evolution of these simulations was not conserved."

Results section
I suggest removing Figure 5 and Figure 6, or move them to supplementary, because these figures are visually difficult to digest, require cross-referral back to the captions in Figure 5 and Table 1 to understand properly, and I'm not sure what the story is and why it is interesting. Each of the gateways tends to increase its transport when it is deepened or widened. That is what one would expect. Table 1 already covers all the net transports – to me that is enough.

We agree with you that Table 1 and Figures 5 and 6 are probably redundant. However, we believe that these figures are easier to read in order to get a rapid view of how the intermediate and deep circulations are modified by the opening of specific gateways. It is indeed expected that the deepening of a gateway will lead to an increase in water transport across it. But whether the global pathway of water masses will change in response to the deepening of a gateway is not easily read from Table 1 whereas it is easy to see from Figures 5 and 6. We have thus opted to move Table 1 to the Supplementary Information and to keep Figures 5 and 6 in the main text.

The discussion of the individual gateway perturbation experiments could be substantially shortened. Accordingly, I think parts 3.1 to 3.4 of the Results section could be either reduced or shifted to the supplementary material. Figures 4 and 12 nicely capture the major changes that are seen by altering these gateways. One can see that there is a robust mode of South Pacific sinking in all cases, and there are some modest inter-basin temperature changes resulting from changing certain gateways.

Please refer to your first main comment above.

Discussion section
Section 1 of the Discussion gives a very detailed account of how these simulations agree / do not agree with Donnadieu et al (2016). I find this section unnecessarily long and suggest cutting or shortening it.

The detailed comparison with the results of Donnadieu et al. (2016) was warranted, in our opinion, because this is the only other study (to our knowledge) that actually provides a detailed explanation of deep ocean circulation changes during the Late Cretaceous. Other Late Cretaceous modeling studies mostly focus on surface ocean/climate (Tabor et al. 2016, Lunt et al. 2016, Hunter et al. 2013, Poulsen and Zhou 2013, Niezgodzki et al. 2017, 2019) or skim over deep ocean changes without providing details (Farnsworth et al. 2019). We agree, however, that this section was probably too long and we have therefore shortened it.

The Neodymium discussion is genuinely important, i.e. Sections 2.1 to 2.3 present the available Nd data, and how their earlier and later Cretaceous simulations line up with these data. I would still

suggest that some tightening of the text could be made by prioritising the two main experiments (the Cenomanian and Maastrichtian paleogeographies) and reducing the discussion of the individual gateway perturbations.

Please refer to your first main comment above.

Section 2.4 seems like a bit of an afterthought and could be greatly reduced (not nearly as informative as the Nd data comparison). Lines 1014-1016 state, "In summary, the comparison of simulated temperature changes and foraminiferal d18O between the Cenomanian and Maastrichtian does not provide strong evidence for or against proposed changes in ocean circulation patterns or the nature of ocean gateways." That sentiment ought to inspire some reductions to Section 2.4.

Section 2.4 (now section 5.2.4) has been revised following comments from referee #1. We now describe an additional Maastrichtian simulation with prescribed CO_2 levels of 560 ppmv and its comparison with our Cenomanian simulation gives results that fit better with temperature changes inferred from foraminiferal $\delta^{18}O$ between the Cenomanian and the Maastrichtian.

Line / Technical Comments
-L148-149: This sentences changes from past to present tense halfway through, which makes it difficult to read.

Corrected.

-L150-154: Again, the tense changes from past to present in this sentence.

Corrected.

-L192: Antarctica Peninsula: should be Antarctic Peninsula

Corrected.

- L188-213: This paragraph provides a lengthy discussion of past evidence of Drake Passage, without having much bearing on the experimental design. I suggest cutting this. The following paragraph L214-225 explains what changes were made and why and that is much more important.
-L228-250: As above, this paragraph on the Caribbean Seaway doesn't serve a great deal of purpose. The actual experimental design is laid out clearly in the following paragraph.

We thank the reviewer for these suggestions but we believe that the reviews on the tectonic history of the gateways that we modify in the simulations are an important part of the paper. These reviews give insights, albeit sometimes not as constrained as desirable, on the current understanding of the Late Cretaceous configuration of these gateways and provide a complimentary (to proxy records of ε_{Nd}) framework to interpret our results.

-L251: "consistent with these interpretations": This statement is a bit vague. There is a lot of detail in the preceding paragraph, and it's hard to tell which "interpretations" are being referred to here.

Corrected to:
"Our Cenomanian and Maastrichtian paleogeographies are consistent with a shallow Caribbean Seaway."

-L508: "It is also interesting to note that: : :": this is unnecessary word padding.

Removed.

-L543: "decrease supply": grammar.

Corrected.

-L548-550: The words 'slight' or 'slightly' are used 3 times in this sentence, giving the impression that the authors are not convinced about what they are saying here. I suggest removing these.

Thank you. The sentence now reads:
"The water fluxes are generally slightly higher, which is probably linked to the deepening of the North Atlantic and western Neotethyan Oceans winter MLD and associated increase in the vigor of ocean circulation (Fig. S12)."

-L678-679: "each change in gateway profoundly alters the Maastrichtian deep circulation". I'm not convinced by this statement. Some of the key features of the circulation (e.g. MOC) are not greatly affected by these gateway changes.

You are correct that some global features of the ocean circulation, such as the MOC, are only slightly affected. However, the water mass pathways change greatly in most of the gateway sensitivity simulations performed. We have modified the sentence, which now reads:
"With the exception of the Deep Labrador Seaway and the 2x CO_2 experiments, each gateway change profoundly alters Maastrichtian deep ocean water mass pathways."

-L828-835: This sentence is far too long.

The sentence has been cut in two.

-L950: "It is noteworthy that": this is unnecessary word padding.

Removed.

-L958: "concur": I think concur is the wrong word here.

Changed to (l. 1027-1028 of the revised manuscript):
"Thus, we concur with the suggestion that…"

-L1055-1057: Climate of the Past requires authors to provide an online data supplement (unless a compelling reason is given not to). This should be made available to the reviewers before publication.

Done. We have uploaded an online data supplement of model variables on Zenodo:
https://doi.org/10.5281/zenodo.3741722

It is strange that the authors do not use numbered sections for their Level 1 Headings, but from Level 2 and downwards they number the subsections (but without a top-level section number). This leaves the reader somewhat disoriented, since there are multiple instances of Section 1, Section 2, etc throughout the manuscript. I suggest numbering the top-level headings, re-numbering the lower level sections, and thus complying with the style of Climate of the Past.

Done.

References

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