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Discussions

Interactive comment on "A regional ocean circulation model for the mid-Cretaceous North Atlantic Basin: implications for black shale formation" *by* R. P. M. Topper et al.

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Response to reviewer comments "A regional ocean circulation model for the mid-Cretaceous North Atlantic Basin: implications for black shale formation"

We are grateful to both reviewers, W.W. Hay (Referee #1) and the anonymous referee (Referee #2), for being appreciative of our methodology and results, and for providing us with constructive comments that helped to improve and clarify our manuscript. In the following we will answer the questions raised in the reviewer comments and explain how we implemented these in our manuscript. Each reviewer is addressed individu-

ally following the order in which their comments were published, with the reviewer's comments in italic font, our answers in normal font.

Response to comments of reviewer #1 (W.W. Hay)

The term 'sponge' is used to designate some sort of special characteristic of the model at the gateways, but it is never described. As far as I know, computational 'sponges' were originally developed to act as absorbent baffles along coastlines or regional models to prevent the reflection of waves back into the main computational domain. I tried to find some description of how 'sponges' might be used with reference to conditions in gateways, but was unable to do so. Since the gateways involve at least two-way flow I cannot figure out how the 'sponges' work. If this computational device has gotten very far from the original 'absorbent gridcell' concept it might be useful to give it a new name. In any case it needs to be described: what is it? How does it work? The authors should be aware that their audience is geologists who do not have extensive background in numerical modeling, much less in the peculiarities of regional models driven by global models. I was unable to find any definition of 'sponge' in any dictionary or technical glossary (ie. Glossary of Geology) that would be helpful.

Our model has closed boundaries on all sides and the sponges are strictly speaking not boundary conditions since they are positioned within the main computational domain. In the boxes attached to the North Atlantic Basin temperature and salinity are restored at all depth levels to the initial conditions, which are the interpolated steady state temperature and salinity fields from the CCSM3 run. The restoration timescale, implemented by means of a Newtonian damping term in the tracer equations, is 1 day in those parts of the sponges more than 5 gridcells away from the gateway and decreases to zero towards the gateways.

For example, salinity and temperature of water flowing from the North Atlantic into the Pacific sponge are (partly) restored to the salinity and temperature of the Pacific (as found in the CCSM3 run) before the water flows back into the North Atlantic Basin with these characteristics. The decreasing restoration timescale towards the gateways gradually reduces the density contrast between sponge and basin which otherwise could have limited exchange and induced non-physical flow at the gateways.

The first use of this type of sponge with the MOMA is from Roussenov et al. (1995), who justified it as a way "[...] to control areas of the model which are not well resolved.". It had been used before in other regional ocean models (e.g. Philander et al., 1987) and has since been widely used for Mediterranean ocean circulation research (e.g. Haines and Wu, 1998; Meijer et al., 2004).

To remedy the confusion about the 'sponges' we will add a more detailed description, similar to the one above, in section 2.4 of the revised manuscript.

Also the term 'tracers' is used, I assume, in the old physcial oceanographic sense of temperature and salinity. Most geologists will associate tracers with chemical properties such and O2 content, PO4 content, etc., as discussed in Broecker and Peng's book Tracers in the Sea. It would avoid confusion to simply refer to salinity and temperature by those terms.

The term 'tracers' is indeed used for temperature and salinity as mentioned on line 26 on p.2376. To avoid confusion we will state it explicitly at first use in both the results and discussion sections in the revised manuscript.

Some of the illustrations are so small that features such as the current arrows are difficult to read.

This problem is inherent to the format of Climate of the Past Discussion papers and will be automatically solved when the figures are put on A4 sized pages in the CP format.

p. 2380 in the discussion of water fluxes, the P - E values are such that they would produce topography on the sea surface. Does the model use a 'rigid lid' or does it include the topographic effects?

MOMA includes the explicit free-surface model from Killworth et al. (1991) and thus includes topography on the sea surface.

The other editorial suggestions listed by the referee concern minor textual issues and will be accomodated in a revised manuscript.

Response to comments of reviewer #2 (Anonymous reviewer)

1) The authors could discuss in a little more detail what some of the potential pitfalls of the regional modelling being driven by conditions from CCSM3 at the interface could be. How good was this simulation in predicting global and regional climates for the Cretaceous and what biases could be introduced within the regional model?

It is very hard, if not impossible, to validate the boundary conditions provided by CCSM3 as used by the regional model. The main reasons are the lack of other model simulations for a similar Cretaceous period (i.e. $\sim$93 Ma) and the lack of proxies for the required boundary conditions (e.g. Sewall et al., 2007).

There are only a few proxies available for the sea surface temperature (SST). Although they only give a very limited insight how good CCSM3 simulates the Cretaceous climate, a compilation is shown in Fig. 1. The large-scale pattern is captured by CCSM3 atlhough it simulates too high SSTs at high latitudes and too low SSTs at low latitudes. The relatively low SST at 40^o N inferred from oxygen isotopes is remarkable because it is generally believed that the Cretaceous thermal meridional gradient was less steep than the one at present. If the proxy data are not contaminated by, for instance, diagenesis, the low SST must be explained by local processes that are not captured by CCSM3. For example, most of the records are located near the northwestern European epicontinental sea (not shown). From intrusions of boreal marine fauna (Voigt et al., 2006) it is known that cold water from the Arctic has flowed into this epicontinental sea likely leading to relatively low SST. Due to the small depth and width of the epicontinental sea strait together with the limited resolution CCSM3 is not able to simulate a realistic throughflow.

However, as already stated, SST alone does not give an adequate validation for the Cretaceous simulation of CCSM3. In order to give a validation, we can only strongly speculate. For that reason we decided not to describe the performance of CCSM3. Another important reason is that we focus on sensitivity experiments. The boundary conditions as taken from CCSM3 are the same for these experiments and, consequently, will not influence the qualitative results from the regional model.

2) The brief description of the Muller et al. (2008) reconstructions is interesting although it's intriguing how a 0.1 degrees resolution product can be produced for a time period so far back as this. Some discussion of discrepancies between the CCSM3 bathymetry and the Muller reconstructions is provided as well as the challenges of blending the two products in the regional model. Ultimately not much can be done about this other than performing more sensitivity experiments but it would be nice to know how much of the reconstruction can really be supported by the geology and how much is a product of the processing or interpolation to the high resolution.

The 0.1 degree resolution for palaeobathymetry reconstructions back to the Early Cretaceous (Müller et al., 2008) indeed calls for an explanation. However, the data used for the reconstructions makes this possible; marine magnetic anomaly data, palaeomagnetic data and rotation poles together with information on mid-oceanic ridge subduction events and the rules of plate tectonics are either available at this resolution or known good enough to support this resolution. Detailed information about the reconstruction from Müller et al. (2008) is beyond the scope of our paper, but can be found in the supplementary information from Müller et al. (2008) and on www.earthbyte.org/Resources/palaeoagegrid2008.html.

The CCSM3 bathymetry from Sewall et al. (2007), used to add continental shelves to the Müller et al. (2008) oceanic lithosphere, is supported by geology where possible.

Both parts of our reconstruction, deep water bathymetry from Müller et al. (2008) and shelves from Sewall et al. (2007), are therefore as good as possible constrained by geological/geophysical data/principles. Processing and interpolation (only applied on the CCSM3 bathymetry) have left the reconstructions largely unchanged; in order to make the bathymetry suitable for MOMA only removal of large topographic gradients and deepening of the shelves were neccesary.

3) I agree with reviewer 1 that a more detailed description and discussion of what the sponges are and represent would be useful. It is not a term that I am particularly familiar with.

We have taken this point into account by changes to the 'Model setup' section as described in the answer to reviewer #1.

4) Could more information be provided on the spin up of the model in each case? It would be good to have a figure showing that the oceanographic properties are in equilibrium in the regional model.

Because each experiment starts with initial (CCSM3) salinity and temperature fields and the water fluxes between sponges and basin are large, the spin up of the model is short ($<$ 200 years). Figure 2 shows layer averages of temperature and salinity at 0, 100, 300, 1000 and 3500 m and kinetic energy in the North Atlantic Basin for the REF experiment. Figures for all other experiments presented in our article are similar.

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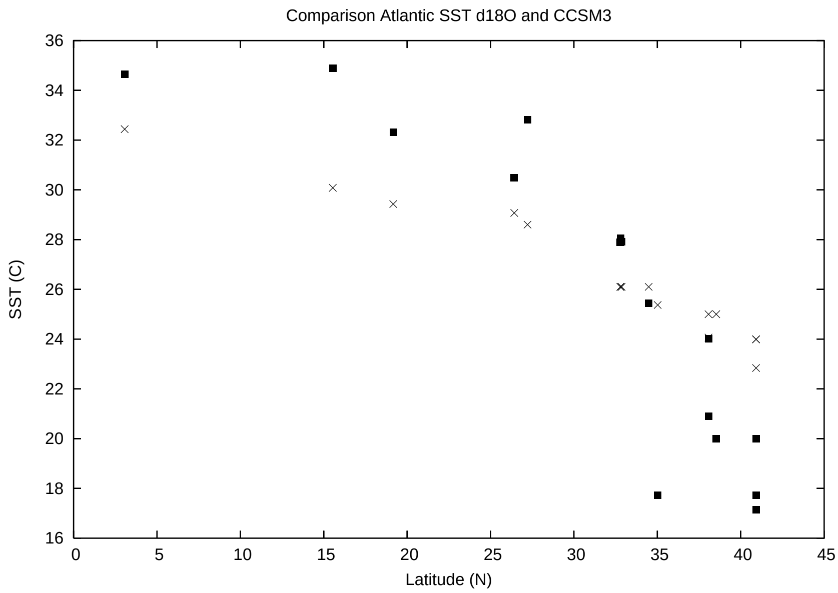

Fig. 1. Annual sea surface temperature for 94Ma inferred from oxygen isotopes (boxes) and as simulated by CCSM3 (crosses) for locations within the model domain of the regional model (5S-50N; 75W-10E).

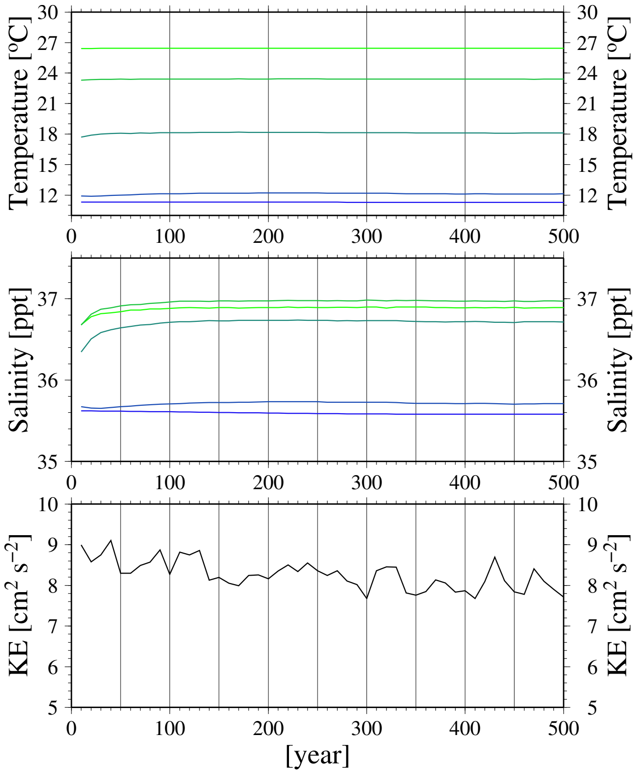

Fig. 2. Layer averaged temperature and salinity at 0 (light green), 100, 300, 1000 and 3500 m (dark blue) and kinetic energy in the North Atlantic Basin for the REF experiment.