Review "Southern Ocean bottom water cooling and ice sheet expansion during the middle Miocene climate transition" by Leutert et al.

Response to Referee #3

Please find below the referee's comments in blue font and the authors' response in black font.

In their study Leutert and colleagues present a record of bottom water changes from ODP Site 747 spanning 16.0-12.2 Ma. The data and the integration of the records to existing geological data reveals fascinating insights into the transition between the Middle and Late Miocene (MMCT). However, in the present manuscript version the authors are retentive in the presentation and discussion of their results. Therefore, it is strongly recommended to further exploit the potential of the study.

Reply: We thank Referee #3 for the constructive comments on our manuscript. We will substantially revise Results and Discussion to be separate and expanded, including more details on all parts of our new bottom water proxy record (e.g., the interval at ~14.4–13.6 Ma) and on possible underlying mechanisms (e.g., changes in ocean gateway configurations, water mass changes).

Comments:

- Focus of the study is the MMCT. Leutert et al. define this interval as ~14.5-13.0 Ma, as it contains key changes in the presented records. Given the relatively long definition of this interval it is recommended to define a nomenclature and time intervals for different sub-phases along the key bottom water temperature (BWT) and bottom water d18O (BWd18O) changes. Once introduced they should be used consistently throughout the paper. For instance, statements like 'Our dataset demonstrates that BWTs at Site 747 decreased by ~3–5°C across the MMCT.' don't do justice to the complexity of the recorded changes, since the full cooling magnitude can be already reached between ~14.5-14.3 Ma, i.e. even before the phase of major ice growth.

Reply: We will modify the sentence pointed out by Referee #3 to clarify in the abstract that the main cooling preceded the stepped main increase in benthic $\delta^{18}O$ as well as to describe the BWT record from Site 747 in more detail and thus do justice to the complexity of the reconstructed changes. A similar sentence in the conclusion of the previously submitted manuscript version will also be adjusted to more adequately describe the complex structure of our BWT record.

In Fig. 3, we will highlight the two main sub-phases along the key BWT and bottom water $\delta^{18}O$ changes recorded at Site 747 with coloured bars (1. Phase: bottom water cooling during the early MMCT, 2. Phase: bottom water warming during the later MMCT). In the following Results and Discussion, we will then consistently refer to these two sub-phases. However, we prefer to not go further into detail here and label these phases even more specifically (e.g., for use in future studies), not only due to potential hiatuses (Site 747 record is based on only one drill hole), uneven sampling and age model uncertainties, but also because we do not know the spatial extent of the changes reconstructed at Site 747 (as pointed out in our Discussion and Conclusions).

In addition, we will expand the description of our results. Amongst other things, we will include temperature confidence intervals and link the Δ_{47}-BWT series more directly to benthic $\delta^{18}O$ for temporal orientation (benthic $\delta^{18}O$ values from Site 747 and 761 will be added to Fig. 3). Furthermore, we will generally use the nomenclature for time intervals more consistently, as suggested by the referee. For example, we will replace "middle Miocene greenhouse" in the abstract by "middle Miocene climatic optimum" to use the same term for this period as later on in the text. We will also discuss bottom water $\delta^{18}O$ in a manner that is more in line with the two main MMCT phases seen at Site 747. We further note that we will decrease the x-axis tick mark spacing to 0.2 Myr in the relevant figures, making it easier for the reader to follow the description and discussion of our results.

- The sub-intervals might be chosen to cover the divergence of BWT and BWd18O, including a rapid cooling and abrupt warming into and out-off the phase of minimum BWT (between ~14.3-13.7 Ma). This phase is accompanied by a pronounced decrease (increase) in BWd18O at the beginning (end) of this interval. So far, the focus is towards the end of this interval.

Reply: See previous answer.

- In the current manuscript version, the timing between BWT/ BWd18O changes to upper ocean temperature changes is touched only marginally. However, the timing of these changes can be a key to better differentiate between various forcing mechanisms.

Reply: We will better recapitulate the previously observed coupling of upper ocean temperature and benthic $\delta^{18}O$ at Site 1171 located at high southern latitudes (Leutert et al., 2020), and relate it to our contrasting observation (and interpretation) of decoupled BWT and benthic $\delta^{18}O$ at Site 747 in a substantially revised version of our discussion on regional and global implications.

- Although this paper is a data study, it would be helpful to relate a growing body of relevant model studies to their findings. Interesting aspects might include e.g. the impact of CO2 or ice sheet changes on upper-ocean and BWT changes across the MMCT. Both factors are expected to have different impacts that can support a mechanistic interpretation, since ice sheet changes might have a more heterogenous impact on these temperature records. In this context Section 11.3.5 (Impact of Ice on Miocene Climate) in the recent review of Steinthorsdottir et al. (2020) (doi.org/10.1029/2020PA004037) might be a helpful starting point.

Reply: As pointed out previously, we will substantially expand the discussion of potential mechanisms, relating our observations at Site 747 for example to potential ocean gateway and/or Antarctic ice volume changes. A precise correlation of our new Site 747 proxy record to existing CO_2 records is considered to be difficult, as all of these data sets are of rather low resolution and fragmentary. In addition, the CO_2 records are partly (in some details) contradictory. Therefore, we prefer to only mention the robust overall decrease in atmospheric pCO_2 across the MMCT (~14.5–13.0 Ma; Foster et al., 2012; Sosdian et al., 2018; Super et al., 2018), but then rather focus on oceanographic changes. For the sake of completeness, we will point out overall decreasing pCO_2 in the interval of this study also in the Discussion.

According the Steinthorsdottir et al. (2020), only two studies (Hamon et al., 2012; Knorr and Lohmann, 2014) have simulated the impact of Miocene ice sheet changes, whereas the bulk of existing paleomodelling studies (e.g., most of those cited in Section 11.3.5 (Impact of Ice on Miocene Climate) of Steinthorsdottir et al. (2020)) focus on older time intervals (e.g., Eocene and Oligocene) characterized by very different boundary conditions (e.g., paleogeography and ocean gateway configurations, global mean temperature and ice volume) than the middle Miocene. Therefore, in our opinion, these latter modelling studies (e.g., Kennedy et al., 2015; Goldner et al., 2014; Ladant et al., 2014; Kennedy-Asser et al., 2019; 2020) are only of limited use to explain our reconstructed middle Miocene bottom water conditions at Site 747. Furthermore, we note that, although modelling Miocene ice sheet changes, Hamon et al. (2012) focus on testing the impact of varying pCO_2 and Antarctic albedo on European vegetation during the middle Miocene climatic optimum but not on assessing Southern Ocean mechanisms in detail.

We will therefore include the relevant modelling studies (Hamon et al., 2013; Knorr and Lohmann, 2014) referenced by Steinthorsdottir et al. (2020) in our discussion of the observed changes. The study of Hamon et al. (2013) will be referenced in the context of a potentially closing eastern Tethys gateway inducing circulation changes and thus influencing bottom water conditions at Site 747. We will also add a sentence relating our findings to the interpretation of Knorr and Lohmann (2014), suggesting a complex interplay between winds, ocean circulation and sea ice that may have led to spatially heterogeneous temperature changes in large parts of the Southern Ocean during the MMCT.

In addition, we will relate the results of our study to the recent modelling-based studies of Burls et al. (2021) and Bradshaw et al. (2021). In their synthesis of Miocene climate modelling efforts, Burls et al. (2021) indicate that intermediate to deep waters in the Southern Hemisphere may have been warmer than modern due to differences in ocean currents related to the open Central American Seaway throughout the middle to late Miocene, whereas Bradshaw et al. (2021) point out the importance of the spatial extent of the Antarctic ice sheet affecting the hydrological cycle and deep-water production regions.