Clim. Past Discuss.,
https://doi.org/10.5194/cp-2018-25-AC1, 2018

Interactive comment on "Deglacial carbon cycle changes observed in a compilation of 117 benthic δ^{13}C time series (20–6 ka)" *by* Carlye Peterson and Lorraine Lisiecki

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Received and published: 13 June 2018

We thank referee #1 for their helpful comments and especially for bringing technical issues to the author's attention. Our responses (AR) are listed after a synopsis of referee #1's comments (R1).

R1 1) Age modelling strategy. It is not entirely clear to me, how age models have been created for the individual cores. It seems though, that the age models are all based on a graphic correlation or automated alignment (?) to the stacks provided by Stern and Lisiecki (2014). If so, it is not clear to me why the authors deliberately used a graphic correlation stratigraphy with an error of 1-2 ka, when radiocarbon dates are available,

at least for some of the cores. Radiocarbon ages should provide better constraints on the posterior calendar age distributions. It seems that, at least in the tropics, the uncertainties in the reservoir ages are small enough to provide better constraints on age than ages derived from alignment of benthic oxygen isotopes. I recommend that the authors better explain, how they have obtained the age models why they have not (if not) used the individual calendar age distributions of radiocarbon ages that may exist.

AR 1) Thank you for bringing up this important point of discussion. We will clarify these issues during revision of the manuscript text.

Yes, the age models used here are those developed by Stern and Lisiecki (2014, Paleoceanography; hereafter SL14). The SL14 regional age models have 95% confidence intervals of 0.5-2.0 kyr. (A 2-kyr 95% CI width is approximately equivalent to a standard deviation of 0.5 kyr). We did not perform any new δ18O alignments or other age model development for this study.

One of the main goals of this paper is to evaluate whether the SL14 age models are accurate enough to reconstruct the timing of global carbon cycle change. In fact, our results demonstrate that the SL14 age models agree well with ice core CO2 changes which have very well-constrained age models (Monnin et al., 2004; Marcott et al., 2014; Kohler et al., 2017). Research is currently underway to further improve the sediment core age models and their uncertainty estimates, but this work will take 1-2 years and is clearly beyond the scope of the current paper.

Because the reviewer's questions/concerns about our method will likely be shared by many readers, we will add more explanation of how the SL14 age models were created and why we expect them to have similar or better precision than most 14C age models (i.e., except for a handful of low-latitude cores with the most 14C dates). For example, recent work by Khider et al. (2017, Paleoceanography) demonstrates that, for 17 tropical Pacific cores, the uncertainties between radiocarbon ages and δ18O alignments are very similar.

Here is the proposed text to add:

Stern and Lisiecki (2014) created seven regional age models based on all available 14C planktonic dates from each region. Each of the seven regions has an age model based on planktonic 14C measurements from multiple cores; 14C dates are combined across cores by assuming that benthic δ18O is synchronous within each region (but not necessarily between regions). The first step of this process was generating an initial radiocarbon age model for each of 61 cores by using that core's radiocarbon dates, the Bayesian age modeling software Bacon (Blaauw and Christen, 2011), the Marine13 calibration (Reimer et al., 2013), and constant 405 14C-yr reservoir ages. Bacon was used to estimate 14C-based ages at specified depths throughout each core, including Monte Carlo uncertainty estimates that increase with distance from the 14C measurements. To identify the core-specific depths for which 14C-based ages would be combined, each core's benthic δ18O record was aligned to an Atlantic or Pacific target core using the alignment software Match (Lisiecki and Lisiecki, 2002). Creating regional age models maximizes the total number of 14C dates which contribute to each age model. For example, the intermediate Pacific age model is derived from 14 sediment cores that include a total of 160 radiocarbon dates. The δ13C records analyzed here use the age models produced by Stern & Lisiecki (2014), which were created by converting each core's Match-based δ18O alignment to its region's radiocarbon age model.

Additionally, Stern and Lisiecki (2014) estimate 95% confidence intervals for each regional age model using 10,000 Monte Carlo age samples for each core from Bacon. Age uncertainty estimates for each region include the effects of any errors in benthic δ18O alignment because alignment errors would increase scatter in the compiled radiocarbon dates (by aligning portions of cores with different ages) and, thus, increase the observed spread in age estimates. For the time range of 0-20 kyr used in our δ13C compilation, the 95% confidence interval widths of the regional age models range from 0.5-2.0 kyr. Although Match does not quantify alignment uncertainty, alignment uncertainties have been estimated using a similar algorithm, called HMM-Match (Lin et

al., 2014). For age models generated either by δ18O -alignments or radiocarbon, the amount of age uncertainty depends on the time resolution of the δ18O or 14C data, respectively. A comparison of 15 low-latitude Pacific cores found that 14C-based age uncertainty is comparable to, if not greater than, the uncertainty associated with δ18O alignments by HMM-Match (Khider et al., 2017, Paleoceanography).

R1 2) ... It is not clear, whether age uncertainty has also been considered when producing the stacks (i.e. through time series ensembles), and (if so) what assumption has been made regarding the distribution of age uncertainty (i.e. normally or uniformly distributed). The authors might argue that the age uncertainty is already included through the averaging of several time-uncertain time series to produce the stacks, but on the other hand the number of time series is small for some of the stacks and perhaps not representative for the error.

AR 2) The contribution of age uncertainty is important to consider. In the manuscript text, we intend to clarify the descriptions of our methods and the sources of uncertainty, including our bootstrapped Monte Carlo uncertainty estimates. Specifically, estimates of 0.1-0.25‰ in foraminiferal δ13C estimates implicitly include the effects of age model uncertainty. For example, Marchal and Curry (2008) report a standard deviation of 0.1‰ which "includes errors in sediment core chronology and oceanic representativity of benthic δ13C, which alone appears better than this value on average". Additional discussion of the most appropriate δ13C uncertainty is presented in response to Q7 of reviewer 2. We have decided to increase the δ13C uncertainty to 0.2‰ which will slightly increase our reported uncertainties.

Additionally, we address age model uncertainty by calculating the correlations between our δ13C results and ice core CO2 for a range of time lags. Because age model errors would be expected to weaken the correlation between these two archives, the comparison we present is conservative, and improved age models would likely strengthen the observed correlations. During revision, we will add more discussion throughout the manuscript of the potential impact of age uncertainty.

R1 3) Variations in sea level affect the water depth of the core location by more than 100 m over the considered time period. If core locations are close to the boundary between the intermediate box and the deep box, a core might fall into the shallow box during the LGM and into the deep box at 6 ka. The authors should clearly describe whether water depth always refers to the modern water depth. This is particularly important for figure 2, where apparently LGM and 6 ka symbols have been plotted at the same water depth. Sea level changes should also be taken into account in the animation provided in the supplement.

AR 3) This is a good point to bring up that will be clarified in the manuscript text. Sea level changes are not included in our volume weighting – modern sea level and volumes (calculations based on GEBCO 2014, https://doi.org/10.1002/2015EA000107) are used throughout the deglaciation because incorporating sea level changes in our calculations would likely introduce undesirable data artifacts in the regional stacks. The depth-boundary between intermediate and deep boxes would need to shift every 1 kyr, and some sites near the boundary would move from an intermediate to deep box across the deglaciation. Because core coverage is relatively sparse, only a few cores would be affected. If we allowed cores to jump between regions as sea level rises, we would alter the spatial representation of cores in the regions, potentially creating artificial jumps in the regional δ13C stack when these cores switched regions.

R1 4) Data base documentation: how have the data been aligned to the stacks. Has this just been done by graphic correlation or has some automatic alignment been involved? If the age models are based on an automatic alignment the methods should be clearly stated. If it is just based on individual age markers and interpolation, these markers should also be included into the data set in the supplement.

AR 4) As described in the response to question 1, the age models used here are those developed by Stern and Lisiecki (2014, Paleoceanography; hereafter SL14). We will revise the manuscript to clarify that we did not perform any new δ18O alignments or other age model development for this study. Therefore, aside from a summary of

the methods of SL14, no additional age model documentation should be required. The supplemental materials include both core depth and estimated age for each δ13C measurement in each core.

R1 5) Real depth vs. composite depth?

AR 5) Details such as composite depth vs. real depth are not always clearly documented when data are downloaded from a repository, but we have done our best to preserve the integrity of the original data. We plan to include a doi identifier or URL for each core's record so that readers will have the ability to find the original documentation for each δ13C record used (see next question/reply). Additionally, the distinction between real depth versus composite depth is usually quite small in the top 20-kyr of the record. Regardless of whether real or composite depth is used, our age estimates will be accurate as long as we use the same depth scale that SL14 used when producing their age models. Another indication that the depth scale for each core has been processed in a consistent manner is the observed similarity of δ13C records among all cores in each region.

R1 6) I also recommend to document not only the references in table A1, but also the actual source (i.e., PANGAEA, NOAA, personal communication) of the data, if possible with doi. This allows to resolve possible inconsistencies later (see 7/8).

AR 6) Although the reviewer brings up a good point, and outlines what will hopefully become part of the best-practices in our field, we did not keep track of the download location or doi for every site. However, we will try to gather this information for as many of the sites as possible within the time constraints of the manuscript revision. When we finish gathering this meta-data, we will add it to the data compilation that will be uploaded to NOAA and Pangaea.

R1 7-8) Site labels, location info.

AR 7-8) We thank the reviewer for finding inconsistencies in the supplemental files. It is challenging to find every mistake in such a large database without concerted effort. Before submitting the revised manuscript, we will track down and correct any errors in the coordinate information or records from the core sites in this compilation.

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