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Interactive comment on "Climate and marine biogeochemistry during the Holocene from transient model simulations" *by* Joachim Segschneider et al.

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Response to Rev#1

We wish to thank Rev#1 for his many thoughtful comments and in particular for pointing us to the work of Liu et al. (2014) on the Holocene climate conundrum. We performed additional analyses to address the reviewer's comments where possible and also extended the control experiments KCM-CTL and BGC-CTL further. Comments are adressed point-by-point in the following. In addition we plan to divide the Discussion into subsections for better readability as it was already fairly lengthy and will now have

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to further increase in length.

1) Role of model drift

In deed the control run of 'only' 2000 years turned out to be non-satisfactory for the non-accelerated experiments, and Rev#1 is right in that we could not exclude that at least part of the signals we discuss are remaining model drift or internal model variability. 2000 years seemed quite long with regard to the accelerated 950 year-long experiments. It was then unexpected that there was still some model drift (and/or internal variability) that amounted, for some parameters, to variability of similar magnitude as the variations of the non-accelerated transient experiments.

The basis for the KCM experiments is a 1,000 year KCM experiment with 0k orbital parameters, 286.6 ppm CO_2, and 805 ppbv CH_4 concentration (with a final global average SST of 15.8C), followed by a spin up for a further 1,000 years with 9.5kyr BP orbital and GHG forcing. From this state the KCM-CTL and KCM-HOL experiments were started. Apparantly the 2x 1,000 year spinup time was still not long enough, and a model drift remained in KCM-CTL that was significant given the small temperature changes that occured during the Holocene. We have become aware of this problem during the analyses of experiment KCM-HOL, and extended the control runs (KCM-CTL and BGC-CTL) since, but they are not finished yet and will still need up to 6 more month to do so (currently at 6200 years, 3.2 kyr BP).

From the current state, this has an impact of the interpretation of the SST (revised Fig. 2a, see also response to FC 7), but not on the finding about the EEP OMZ (revised Fig. 13). For the deep North Pacific, also in the control run the ideal age increases, but not as strong as in BGC-HOL (100 years younger at 3.2 kyr BP). For the Eastern Equatorial Pacific OMZ, however, the extended control run does not show the increase in volume as simulated by BGC-HOL, so that we are now more sure that the results are not caused by model drift.

We also note that for all the paleo experiments in the literature, there are no(!) control experiments to be found for transient and time-slice experiments (Fischer and Jungclaus, 2011; Varma et al., 2016; Liu et al., 2014; Bopp et al., 2017). So this is a more general problem in the paleo climate modelling community, probably based on an underestimation of model drift and internal model variability compared to the relatively weak forced Holocene variability on long time scales.

We will include the extended control run in our revised manuscript and revise the text were necessary.

2) Off-line biogeochemistry

Convection and diffusion are simulated as in the online version, based on the stored mixing parameters from OPA9 as part of KCM. So there might be some differences from the monthly time-averaging of the online output and the non-linearity of mixing, but we have not investigated this systematically for our model configuration as there is no online version of KCM-PISCES available.

For the same reason, we can not make a statement about potential differences of water mass ages in the on- and off-line versions of PISCES.

3) Vertical resolution of the ocean

There are 20 layers below 100m depth, and layer thickness near the bottom is about 500m. We have no indication that this causes problems for the simulation of deep

Pacific O_2 within the general limitations due to the coarse model resolution.

We will describe the vertical resolution of the ocean model in the model description.

4) Missing processes, potential impact on results should be discussed

- sediment is not included in model setup

- no changes in weathering

- no coral reefs (Vecsei and Berger, 2004)

In setting up our experiments, we followed the standard PMIP protocol. So while the above processes are not included in the model setup, their combined effects on GHG climate forcing must be represented by the reconstructed PMIP GHG forcing from ice cores. With regard to the evolution of atmospheric CO_2, we plan to point to the study of Brovkin et al. (2016), were all these processes are described in fair detail and nicely summarized in their Fig. 8.

- how is freshwater pulse of 8.2 kyr BP reprented in the forcing?

The freshwater pulse at 8.2 kyr BP is not included in the forcing, and hence we can not expect to find changes in AMOC related to it. This will be picked up in the discussion of AMOC (Sec. 3.1.2 and Discussion).

- role of changes in the land biopshere carbon inventory

The land biosphere is not included in the model, but we use reconstructed pCO_2, which should include any contribution of the land biosphere to atmospheric pCO_2. So what remains neglected is albedo changes from changes in vegetation, but we can not quantify the potential impact this would have on the simulated climate.

- potential influence from volcanic eruptions?

Including volcanic aerosol forcing would likely have a cooling effect during the first 1-2 years following the volcanic eruptions, but this is difficult to quantify for KCM without performing the experiment. For the same reason, also any integrated effect of volcanic eruptions on long term evolution of temperature is difficult to establish, but would likely to be small based on the coupled climate model experiments for the last millennium (Brovkin et al., 2010) that indicate a -0.8cooling for the 1258 eruption (the largest eruption during the simulated period), but within a decade surface air temperature fluctuations are within the background range (their Fig. 1). Any effect on atmospheric pCO_2 related to post-glacial increased volcanic activity and additional outgassing of 1,000-5,000 $GtCO_2$ between 12 kyr and 7 kyr BP (Huybers and Langmuir, 2009) will be included in the prescribed PMIP GHG-forcing (which shows decreasing pCO_2 during the early Holocene).

In summary, while these are all interesting points, we do not want to hypothesize about the potential effects of the omitted forcings and model components.

Also in response to Rev#2, we will now describe our model experiments as sensitivity experiments to the PMIP orbital and GHG forcings with likely deviations from the

Holocene climate variations that are caused by other forcings and biogeochemical processes that are not included in our model setup. We will explicitly mention the neglected components and forcings, and indicate where this might have a direct impact on our results.

5) Interpretation of CO_2 fluxes in the light of prescribed pCO_2

We think that we were quite careful in our wording as to how much the diagnosed CO_2-fluxes can be meaningful for a quantification of a potential contribution of the ocean to atmospheric pCO_2, however, seemingly not careful enough.

We will delete Fig. 7 and include the time-integrated ocean-atmosphere carbon flux in a revised Fig. 6a as suggested. We will revise the description of the time-integrated carbon flux along the following lines:

Early Holocene: The integrated carbon flux is constant (revised Fig. 6), despite a decrease in atmospheric CO_2 (revised Fig.1a): During this initial phase, the global mean SST in KCM-HOL is decreasing by about 0.3C (orig. Fig. 2a), and the alkalinity in BGC-HOL is increasing by 10 μmol/l (orig. Fig. 8a), while export production is slightly decreasing by 0.2 GtC/a (orig. Fig. 11a). In summary, these effects balance out during the early Holocene, and the time-integrated ocean-atmosphere carbon flux remains about zero until 7 kyr BP (revised Fig. 6a, blue curve).

In the mid-Holocene, from 7 kyr BP to 4 kyr BP, the time-integrated carbon flux is slowly increasing to a total ocean uptake of 10 GtC. This occurs during a period of atmospheric pCO_2 increase that would drive such a flux, and also SST is rising slowly, while EP is further decreasing and alkalinity is increasing by a further 10 μmol/l.

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In the late Holocene, after 4 kyr BP, the ocean is outgassing a total of 50 GtC, potentially driven by the simulated increase in SST and damped by the increasing prescribed atmospheric pCO_2.

In summary, the contribution of oceanic processes to air-sea carbon fluxes is in line with the prescribed pCO_2 in the mid-Holocene, while reversing the flux expected from the atmospheric forcing in the early and late Holocene.

6) Attribution of changes of O_2 and other tracers to underlying processes

- stratification changes and impact on O_2

In contrast to studies based on global warming and O_2 (Cocco et al., 2013; Bopp et al., 2013) and marine biological production (Steinacher et al., 2010), that showed an impact of stratification changes on O_2 fields and marine biological production, here we simulate much smaller temperature variations. Global and annual mean of the MLD in KCM-HOL reveal little temporal variability: MLD is around 48m at 9.5kyr BP, and starts to decrease after 5.5 kyr BP to around 47m at 0 kyr BP. We, therefore, state that stratification changes play only a minor role for O_2 changes during the Holocene. We will include this in the Discussion.

-O_2 saturation and AOU

We computed also the fields of O_2-saturation and AOU for experiment BGC-HOL. While O_2-saturation has a similar evolution as SST, AOU reflects the slow-down in circulation in the Pacific (see Fig**??**,left). Meridional sections reveal a different Holocene-trend of O_2-saturation in the upper and lower part of the OMZ: decrease in the upper part, increase below 400m, reflecting the evolution of temperature. AOU is stronger in the late Holocene at all depths save from a small decrease in the upper 100m off the equator. The long term changes show a decoupling of O2sat and AOU, the former driven by temperature changes, the latter by a slower circulation (increase in water mass age).

This differs from the shorter time-scale fluctuations that show compensating effects as in Bopp et al. (2017), where a decrease in O_2-saturation has a signature in lower AOU and vice versa.

We will mention the above explicitly in the revised ms and will add a new figure similar to the above. We further refer to the already existing attribution of the changes in the EEP OMZ to changes in circulation as represented by the ideal age tracer, and the fairly constant export production in the EEP OMZ region (Section 3.2.5).

7) export production wrong metric to judge efficiency of the biological pump

With due respect, on this point we disagree with Rev#1. A large number of studies describe the biological carbon pump, also called soft tissue pump as driven by the export production (e.g. Six and Maier-Reimer, 1996; Sigman and Hain, 2012; Ducklow et al., 2001), and the whole JGOFS project was based on this principle. See also https://www.us-ocb.org/biological-pump/ for a very condensed description. Evidently the export production is related to the uptake of nutrients in the euphotic zone, but as not all of the nutrients that are taken up in the euphotic zone are exported to depth because of remineralization and grazing in the euphotic layer itself, we emphasize that export production is a correct metric for the strength of the biological carbon pump.

We do not intend to change the section in question, but will include a reference to the biological pump.

Response to further Comments (FC)

FC 1) Other transient simulations not mentioned (p4, 2. para)

We referenced some exemplary transient simulations rather than trying to give a complete overview (again, our focus being more on the marine biogeochemistry), but to address this point we will include references to Brovkin et al. (2016) as an example of EMIC experiments, and to Liu et al. (2014) as an example for the 21ka experiment, and to Fischer and Jungclaus (2011) as a further non-accelerated coupled model experiment from mid-to-late Holocene (looking at changes in the seasonal SST cycle).

FC 2) Are changes in ice albedo taken into account? (p9)

Changes in sea ice cover are simulated by LIM, the sea ice component of NEMO, but that is probably not meant here. We will mention explicitly in Section 2.2 that we do not take into account solar TSI and volcanic forcing, nor changes in the continental ice sheets (neither topography nor albedo) and also no fresh water pulses.

FC 3) Forcing data GHG

We admit somewhat shamefacedly that due to a misunderstanding we stated that we force KCM-HOL with only CO_2 as green house gas. However, the experiments were

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also forced with transient CH_4 and N_2O from the PMIP data base. This mistake in the description of the forcing, however, does not change the findings of our study.

We will rewrite section 2.2.1 accordingly and revise Fig. 1a to include the time series of CH_4 and N_2O (see above). We will also provide the internet address from where we obtained the data, and add the reference to Augustin et al. (2004) decribing the EPICA data.

https://www.paleo.bristol.ac.uk/ ggdjl/pmip/pmip_hol_lig_gases.txt

FC 4) 1st para would better fit in methods sections (p12, ln 2)

Since this para describes the common features of the following figures, we feel that this para is well-placed at the beginning of the Results section, in particular having in mind that readers might skip the Methods and go straight to the Results section.

However, it could be moved to a new section 2.5 Common features of figures in results section in the Methods section but we would prefer to leave it at its current position.

FC 5) delete 'again' p12, ln 21

will be deleted

FC 6) drift is not 'modest', please delete modest (p12, ln 25)
we will delete 'modest'

FC 7) It seems the whole [SST] signal may be explained by drift? (p13, ln1-2)

See also response to main comment **1)**. As we have extended experiment KCM-CTL in the meantime by a further 4800 years (leading up to 3.2 kyr BP) we are in a position to state that parts of the initial SST decrease in KCM-HOL can indeed be explained by the drift (the decrease is stronger in KCM-HOL), while the following SST increase is damped by the model drift (which becomes smaller after 6 kyr BP). As a result, the initial SST decrease would be weaker in a drift-free setup, while the following SST increase would be stronger. It would of course be ideal to run the extended control experiment until 0k, but that would potentially delay publication by several months (a minimum of 2.5 months, from past experience more likely 4-6 months).

We will revise Section 3.1.1 accordingly, and ammend Fig. 2a to include the extended control run as far as possible.

FC 8) Indo Pacific overturning should be discussed also (p13, sec. 3.1.2)

In response to FC8 we also analysed the Indo Pacifc overturning. We found that the deep inflow into the Pacific decreases, e.g. at 3000m depth, 10S zonal mean MSF from 5 to 2 Sv around 7.5 kyr BP and remains about constant thereafter (based on 4th order polynomial fit to monthly data). In the upper ocean there are only minor variations. Also in the Indian Ocean the overturning is rather constant.

We will mention this in the revised ms., but do not intend to show an additional figure.

FC 11) Authors should say sth. on SST evolution at different seasons (p20, Discussion)

While we feel that this goes a bit beyond the scope of our manuscript (and possibly the focus of Biogeosciences), we analysed the summer (JJA) and winter (DJF) SST separately. Only when looking at the northern hemisphere poleward of 30N, we find some separation of the evolution of the annual mean and the JJA SST, with a later and longer lasting minimum (around 6 kyr BP and a major increase only after 3 kyr BP), with similar SST in early and late Holocene, and an amplitude of around 0.5 K. For the global mean SST, the JJA mean evolves similar as the annual mean SST. Also using the yearly maximum temperature, indicating local summer, does not change the temporal behaviour, it only shifts the SST curve upward by roughly 2 K.

With regard to the work of Samartin et al., 2017, that focusses on the Mediteranean, we find only very locally in the Adriatic (close to the data point 3 in Samartin et al) and in the orbitally only forced experiment a warmer mid-Holocene than late Holocene SST.

SST and land surface temperature might develop differently, and this might be investigated further using a 'site-stacked' approach as in Liu et al. (2014) in a future study aiming at KCM-proxy comparisons. As a first step, we computed the global and annual mean land surface temperature, and found a principally similar temporal evolution as for SST. We will work on the topic, also in the follow up of the study of Schneider et al. (2010).

With regard to the focus of our present study, however, and the limited relevance of the additional analysis for the investigated biogeochemistry, we would prefer not to include details of the above in the revised ms. but merely plan to add that the simulated SST evolution in KCM-HOL is seemingly not very sensitive to the choice of season. We further plan to point to the study of Liu et al., 2014 for a more detailed analysis of the general proxy-model mismatch for MH temperatures and its seasonal dependency.

FC 12) How was BGC-CTL extendend (Fig. 5)

BGC-CTL was extended by forcing PISCES for another cycle of the 2000 yrs available from KCM-CTL. Admittedly not an ideal approach, and this will be replaced by the extended BGC-CTL, based on the extended KCM-CTL in a revised Figure 5.

Further errors found by the authors

OMZ-volume was erroneously divided by 100, now correct volumes are given

Typo in Ref of (Leduc et al., 2010): Ma/Ca was corrected to Mg/Ca

E.g. misplaced p23 ln 3

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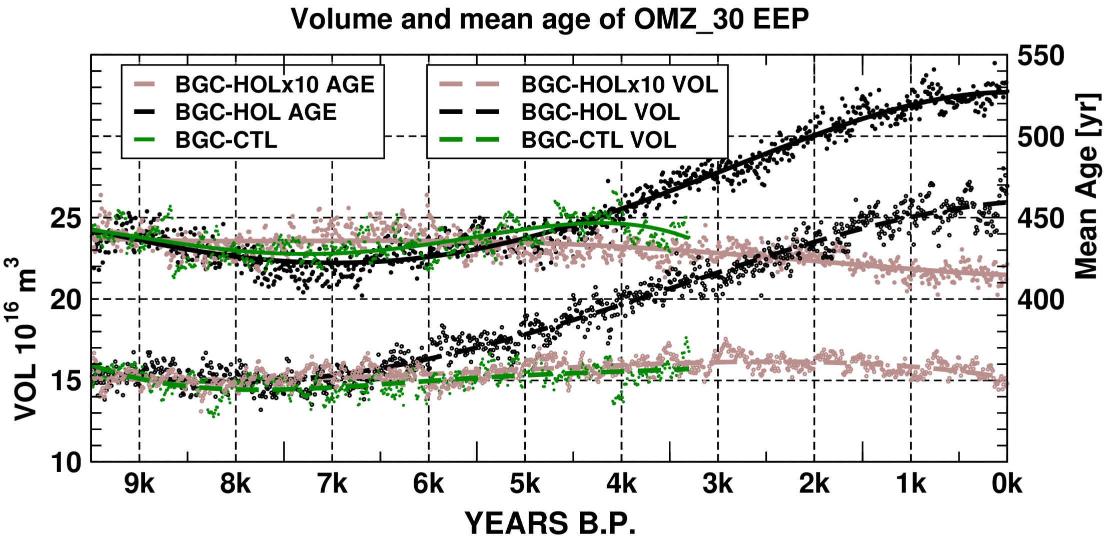

Fig. 1. Revised Fig. 13

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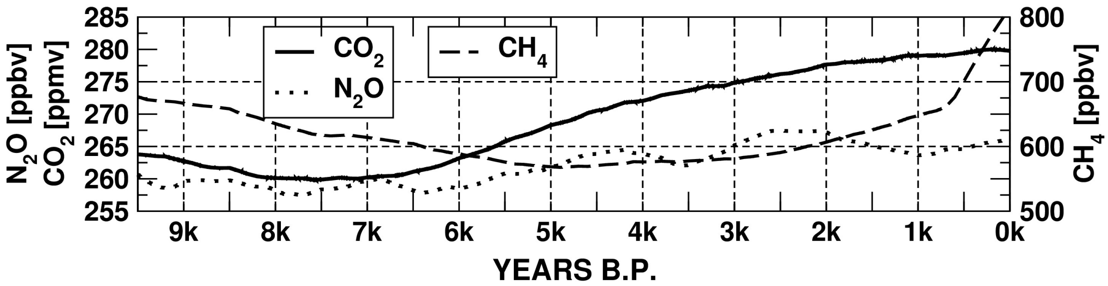

Fig. 2. Revised Fig. 1a

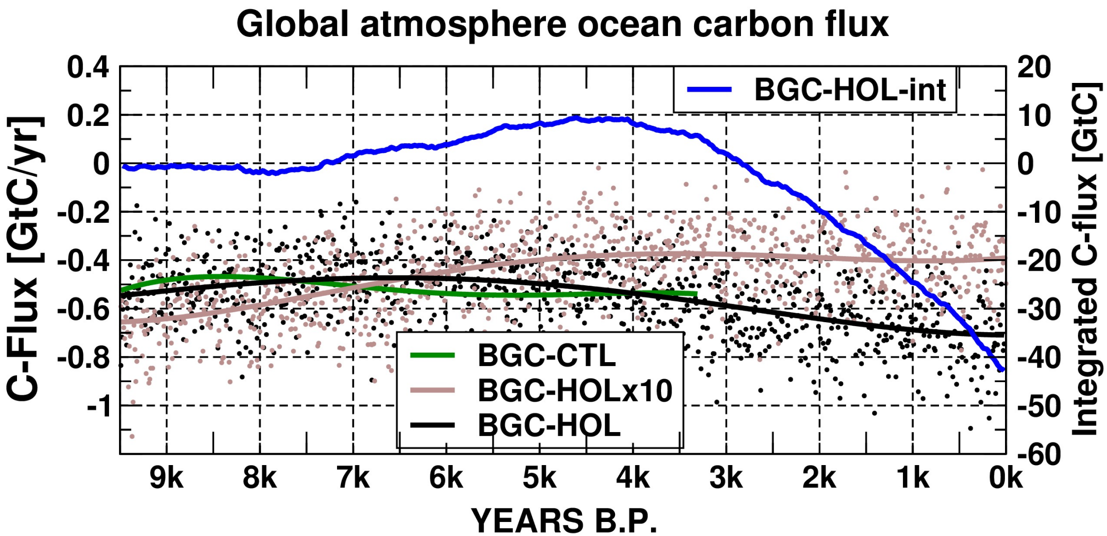

Fig. 3. Revised Fig. 6a

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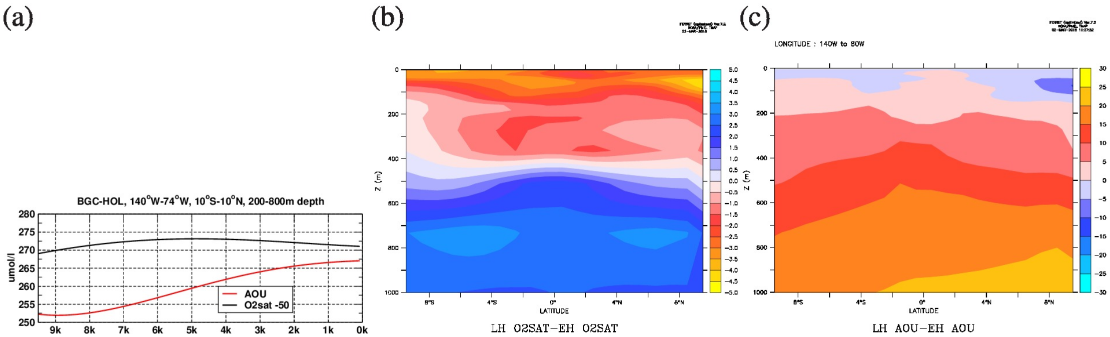

Fig. 4. New Fig. (a) AOU and O2sat in EEP. b) O2sat Late Holocene minus Early Holocene zonal means EEP, c) as b) but for AOU

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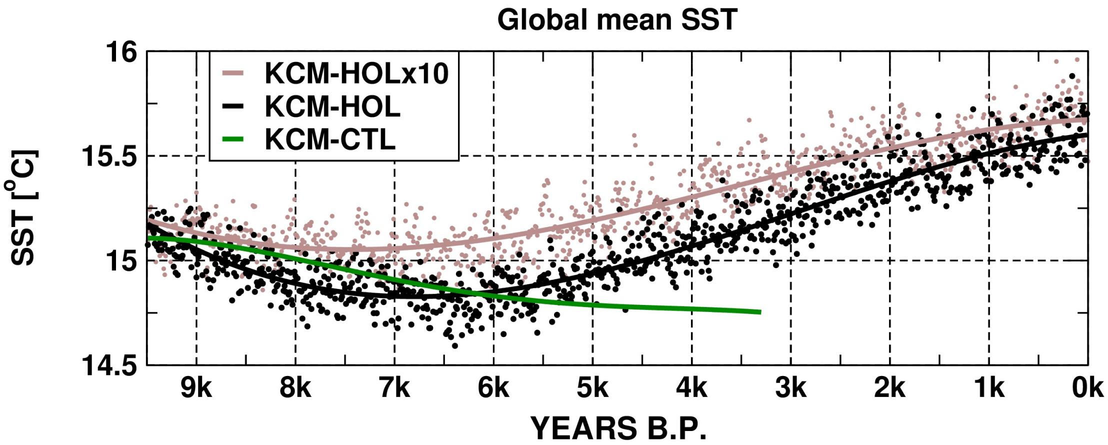

Fig. 5. Revised Fig. 2a

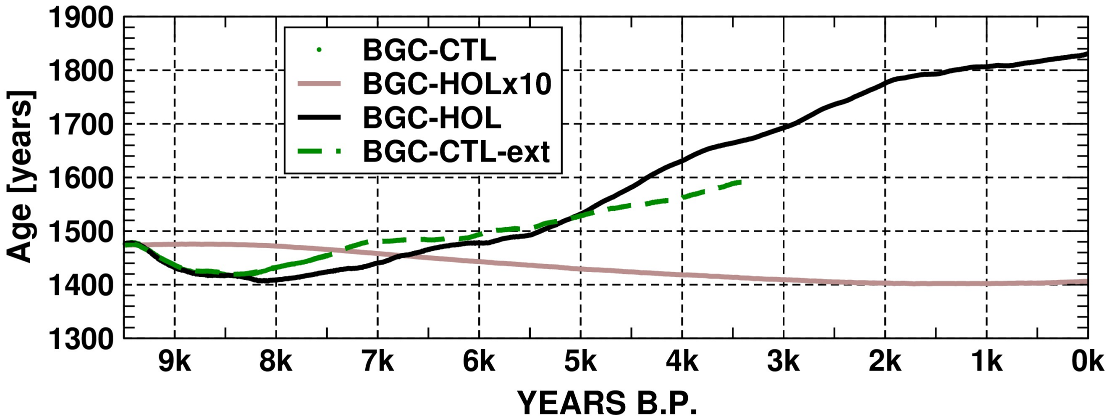

Fig. 6. Revised Fig. 5