Response to reviewers, “Calibration of key temperature-dependent ocean microbial processes in the cGENIE.muffin Earth system model”

Response to reviewer 1

“Figure 2 highlights a key opportunity that has been overlooked in this study, which is that the fractional assignment of export to the DOM pool could easily be made temperature-dependent, and that would implicitly represent temperature-dependent fast recycling processes in the upper ocean. The authors should discuss why this parameter was not included in their calibration.”

We have added the option to the model of a temperature-dependence to both the production and remineralization of DOM, and assess the consequences of these new processes in the analysis of marine carbon cycling response to historical warming in the revised paper.

As described in a new and extensive subsection in the Discussion (5.2), adding temperature-dependence to the decay of DOM is relatively straight-forward as to a first order, one can start by assuming this takes place analogously to the decay of POM. Hence we adopt the same calibrated activation energy, but re-tune the scaling rate constant, as described in section 5.2.

The production of DOM is more problematic as available empirical equations such of Dunne et al. [2005], requires knowledge of either primary production (integrated across the mixed layer), or Chl*a*, neither of which is explicitly calculated in the standard (non ecosystem) configuration of cGENIE. (The standard configuration of the ocean circulation model also does not calculate a mixed layer depth.) We hence extracted just the temperature sensitivity from the regression model of Dunne et al. [2005] and apply this to the partitioning of POM vs. DOM in the model. And then tune this second parameterization.

While we find that the introduction of temperature-dependent processes in DOM cycling has a much lesser impact on global export than do temperature-dependent processes directly affecting POM, we agree with the reviewer that this makes for a more complete and rounded model development.

“Schmittner et al. 2008, GBC doi:10.1029/2007GB002953 Introduced a temperature dependent remineralization parameterization to the UVic ESCM…”

We have added Kvale et al 2015 and Kvale et al 2019 to those papers discussed in the introduction. And added Loptien and Dietze 2019 and Kvale et al 2019 to the discussion noting that circulation state is important for nutrient and carbon distributions.

“P6, Equation 5: Please either rename A or make it clear on this page that the value is different than the A in Equation 4.”

We have been through all the equations and terms in the entire manuscript, including the equations associated with the new DOM parameterizations, and ensure unique symbol choices for all parameters. (Capital ‘A’ we reserve for fractional sea-ice area only now and indeed, further clarify this by adding the subscript ‘ice’.)

“P7L89: Meyer et al. (2016) prescribed several e-folding depths, which approximates, but is not the same as, temperature dependence in export”

The reviewer is correct in that Meyer et al., (2016) prescribes different e-folding depths to parameterise the potential impacts of changing surface ecosystems in geological time on remineralisation, such as increasing organism size and complexity of trophic interations. Here we are specifically referring to the export production scheme used that is the temperature-dependent scheme described by Monteiro et al., (2012). We have edited this sentence to better clarify and indeed now substituted the Monteiro et al. (2012) reference.

"P9L250: the North Pacific subsurface temperature profile is over-estimated in GENIE according to Fig 4, please correct this sentence"
Corrected in the text.

"P9L256: What are the lowest RMSE for CB and CBRU?"
We considered both the surface and full water column distributions to select the best-fit option for PO4: the (centred) RMSE for surface layer CB is 0.1700, CBRU is 0.1820; for whole ocean CB is 0.2208, CBRU is 0.2043 all in µmol/l. For O2 we use the whole ocean and depth layer 4 (283m to 411m), the (centred) RMSE depth layer 4 CB is 0.8145, CBRU is 0.8443; for whole ocean CB is 0.5476, CBRU is 0.5501 all in µmol/l. These values are represented in figure 5 and have been added to the main text for the STND (formerly CB) and TDEP (formerly CBRU) model and the new $TDEP_{+TDOM}$ configuration as table 4.

"P9L268: My understanding is the models are also tuned to O2 (from P9L253-256)"
Yes, this is correct. Added to the sentence in parentheses for clarity.

"P12L375: what is the Eastern Tropical North Pacific?"
This is a typo and should read "Eastern Tropical Pacific" – now corrected in the text.

"P13L380-381: DOM cycling is also changed"
We now explicitly address and discuss (in Section 5.2) how the DOM cycle is impacted by historical temperature rise, including now also accounting for temperature-dependent processes in DOM cycling. We also add 2 additional figures to the Appendix A (Fig A1 and A2) summarising the cycling of DOM, both in the present-day state, and the response to historical warming (as an anomaly), for all the main permutations of temperature-dependent parameterisations. We have noted that DOM may also be affecting NPP in tropical waters in section 5.1.

"P13 Summary: Please see Kvale et al. 2019 BG /10.5194/bg-16-1019-2019"
Kvale et al 2019 use a transient cold to warm simulation, the warm climate with over 1200ppm atmospheric CO2 and state that in the warm climate more phosphate is stored in the deep ocean due to longer residence time of deep waters. This scenario is entirely different to that used here where the transient simulation follows CO2 trajectory from 1700 CE to the present, with a max ~400ppm. At very high CO2 (such as 1200ppm) the AMOC (Atlantic meridional overturning circulation) is likely very much reduced or collapsed and this greatly reduces the return of deeper waters to the surface compared to a the situation with a strong AMOC at 400ppm (such as the present day). We have added the following to the main text in the discussion of the model response to historical warming:

"We note that circulation states and upwelling/downwelling changes can also have an impact on the distribution of carbon, oxygen and nutrients between the surface and the deep (Kvale et al 2019, Loptien and Dietze 2019), and are also model-dependent. Circulation changes are small between the pre-industrial and the present-day, unlike in the simulations in Kvale et al (2019) where very high CO_2 (up to 1200ppm) and high surface temperature results in large circulation pattern changes; increased nutrient storage in the deep ocean is due to longer residence time of deep ocean water in that study (see Chikamoto et al. 2008 for the effect of Atlantic Overturning Circulation shutdown in cGENIE). In our study we have found that the temperature dependent biological pump offsets some of the effects of physical ocean response to warming (in increase near-surface nutrient recycling, so offsetting to some extent the effect of increased ocean stratification that otherwise reduces surface nutrients in the STND simulation). However, this is not to suggest that a temperature-dependent biological pump could offset the effect of extreme changes in circulation, such as an AMOC shutdown, or for far more extreme warming scenarios than that applied here. We do not test such scenarios here."

"Table 2 can be cut at no detriment to the manuscript. 'CB' and 'CBRU' are defined too late in the manuscript and the naming includes an extra (confusing) reference to BIOGEM. I suggest omitting the Table and renaming the simulations to something more descriptive, like 'Temp' and 'NoTemp', since all models contain 'Remineralization' and 'Uptake'."

We have retained Table 2 because it is now expanded with an additional alternative model configuration, now that we are also addressing DOM-linked temperature-dependent processes. However, we have noted the lack of intuitiveness in the 'CB' and 'CBRU' naming and have replaced these throughout the manuscript with the more intuitive "STND" and "TDEP" references. We have also added these references to the relevant parts in Section 2 that describe the standard and temperature-dependent model formulations.

"Figure 1 can be cut at no detriment to the manuscript"

This figure lays out the basic functioning of the biological pump, and visually summarises the two components of temperature dependence (in both nutrient uptake and remineralisation), as well as the partitioning of organic matter into POM and DOM – we think it is a useful overview of the components discussed in the text.

"Figure 2 caption: is "mixed player plankton" supposed to read "mixed phytoplankton"? Please add a key to clarify what dashed/solid/thick/thin lines, and shading, represent. Why is burial shown if there are no sediments? Should "nutrients" be PO4 (only PO4 in this model)? Why are autotrophic respiration/heterotrophic respiration/ consumers shown if they are not included in the model?"

We have improved the caption to figure 2 based on these comments:

"Figure 2. Schematic of biological pump processes showing where cGENIEs export production operates. In the export production model, no mechanistic consideration of the effects of temperature within the mixed-layer (i.e. GPP vs NPP vs community production) can be considered, but heterotrophic respiration (as remineralisation) vs community production (as export production) can be considered, as well as nutrient recycling. In this study we apply temperature dependency to Organic Matter production and remineralisation that drives the biological carbon pump. We do not model burial in this version of cGENIE (but it is here for completeness). In this cGENIE configuration, the nutrient is phosphate. Dashed line indicates the cycling of nutrient (and re-supply due to circulation). Solid lines indicates the cycling of carbon."

"Figure 8. I see why the figure is normalized (the point made on P9L275), but normalization is misleading (small differences of low concentrations appear to be significant). The figure would be more informative presented without normalization, but the above point can still be made in the text."

Figure 8 is now plotted also as absolute differences, not only as normalised differences, but with the normalised difference plot retained as it is directly referenced in the text and shows that largest proportional changes (where an anomaly alone would tend to reduce the significance of changes in ocean regions that started with low nutrient concentrations that actually see the largest proportional changes). Nutrients limitation is important in the gyres, so any increase in concentration there would likely have a large impact on primary production.

All other technical corrections suggested by reviewer 1 have been applied to the text.

Response to reviewer 2

"At Ea(1) of >54.5 kJ/mol POC export becomes lower compared to the non-temperature dependent model. This could be concerning given that a small variation of the Ea(1) value (0.5 kJ/mol) results in completely opposite patterns compared to the findings of the study, i.e., the temperature-dependent model simulates lower POC export than the non-temperature dependent model. The uncertainty related to this finding does not come across clearly and should be discussed. Also, it does not seem necessary for circles to be color-coded to reflect different rPOM in Figure 11."

We thank the reviewer for highlighting that this is not clear. Partly this may have been due to a missing minus sign in the exponent of Equation 5 which has now been corrected. The relationship in Figure 11 of the manuscript is not immediately obvious as temperature is effectively fixed in the calibration runs. The reviewer is correct in noting a larger activation energy (Ea1) results a greater sensitivity of remineralisation rates to temperature (Figure 1, bottom panel). However, at a constant temperature, the remineralisation rate decreases as Ea1 increases (Figure 1 here, top panel). In our calibration runs (Figure 11 in the manuscript), atmospheric CO_2 is restored to 278 ppm such that climate and SSTs are invariant, i.e., temperature is constant across the calibration runs. Therefore, the increased activation energies tested lead to a decrease in remineralisation rate globally. This leads to deeper remineralisation of organic matter which drives the decrease in export production (e.g., Kwon et al., 2009, Nature Geoscience), but is still related to a greater sensitivity to temperature changes (Figure 1). We have added a brief explanation of this to the text describing Figure 11 in the manuscript as well as added the plates in figure 1 (here) to figure 11 in the manuscript to clarify this point.

The main finding of the study is that warming results in a drop in POC export for STND (-2.9%), but a rather smaller change in POC export for TDEP (at -0.3% for the best-fit setting). Even with Ea(1) at >55kJ/mol this pattern still holds because POC export is stimulated on warming in TDEP due to the increased nutrient recycling, now that remineralisation is temperature-dependent. Figure 11a shows only the global mean POC export at a fixed temperature, not how that export changes on warming. For higher Ea(1) that nutrient recycling increase on warming may be slightly lower, but certainly not such that the findings of the paper are inversed. Even with Ea(1) at 60 kJ/mol (Vmax =1, POC frac = 0.008), the drop in POC export for the historical period simulation is 0.43% (compared to the drop of 0.3% for TDEP best fit). The value of 54kJ/mol was selected as it shows a better fit to PO_4 and O_2 data (fig 5 main text) than other values.

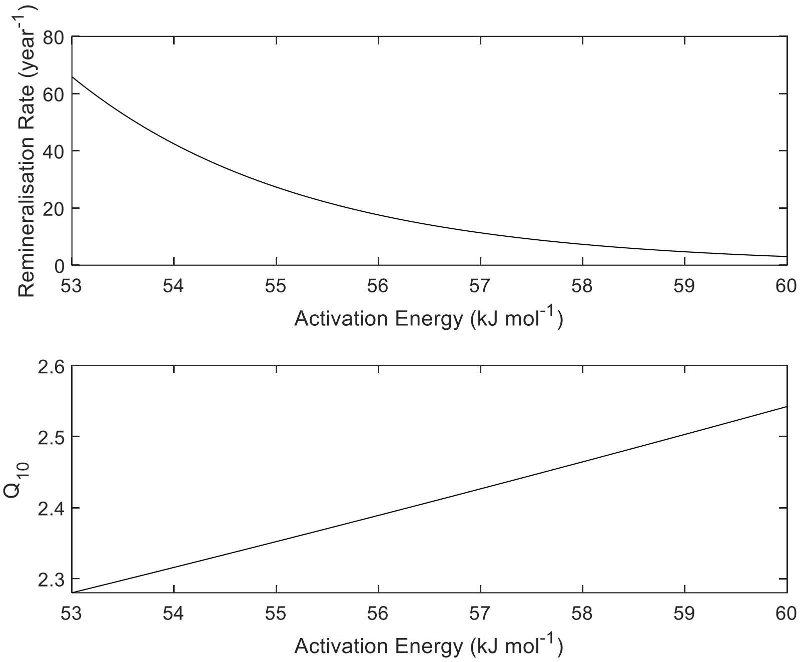

Figure 1. Top panel: The remineralisation rate calculated for with different activation energies for a constant temperature (273 K). Bottom panel: The Q_{10} of the remineralisation rate, i.e., the proportional change in the remineralisation rate for an increase in 10 K.

The colour coding on figure 11 reflects the colours used in figure 5, this has been added to the figure caption.

"In Introduction, in relation to "A deeper mean remineralization depth equates to a more "efficient" biological carbon pump" it would be good to calculate the remineralization depth as an additional measure of the biological pump efficiency from the model simulations. This could be helpful for cross-comparison with other modeling studies focused on the biological pump."

This is a useful suggestion from the reviewer. The key limitation of calculating a mean remineralisation depth here is that we are calibrating the model to observations such that the resulting values for STD and TDEP should be similar. We also note that the absolute mean remineralisation depth has been shown to be strongly dependent on ocean circulation (in particular the deep water formation in the North Atlantic) (Figure 6b in Kriest et al., 2020; Biogeosciences). As such, this is likely to be model dependent.

We note that a global value does not well represent the underlying characteristic identified in this study, where the remineralisation depth is entirely dependent on local conditions. In cold high latitudes the mean remineralisation depth is far deeper than in warm low latitudes. So, the resultant global mean will be somewhere in the middle. What then happens to the carbon in the deeper ocean is a function of ocean circulation and possible burial, so is heavily model-dependent. However, we have added this information to the main text in section 4.4 [627m for the standard model (formerly called CB) and 378m ± 236m for the T dependent model (formerly called CBRU)], and the change in the global mean depth in section 5.1 for the historical period simulation [a shallowing of 16m for T-dependent model (formerly named CBRU)]. We have also added this information in section 5.2 for the additional DOM T-dependent model (the present-day is 399m ± 255m, and a shallowing of 16m since the year 1700).

"In Section 4.1 (line 244-251), it is discussed that cGENIE underestimates surface stratification and overestimates winter-time deep mixing due to an overly-strong AMOC in the physical circulation scheme of the model. The amount of phosphate returned to the surface is a function of deep mixing that increases organic matter production there, and this would not be modeled well if the model underestimated surface stratification. Uncertainties in the warming scenario results should be discussed."

We have added a paragraph in the discussion (in response to reviewer 1), that circulation plays a role in nutrient distribution as well, and that circulation is model dependent. We further note that cGENIEs reduction in export production (driven by an increase in stratification) through the pre-industrial to present warming agrees with the current state of the art in more complex models (CMIP5 models).

The winter time mixing overestimation was only for the North Pacific region (as indicated by the temperature profile there) not for the global ocean, and is not described as "due" to an overly-strong AMOC (which was only suggested as related to the N.Atlantic temperature profile). We do not do an extensive analysis of cGENIEs circulation in this study.

However, as we model a similar pattern of reduced export production in the standard model (due to increased stratification) that is shown in the mean of CMIP5 models, and we can fairly well model PO4 and O2 distributions in the present day we are reasonably confident that we have captured the large scale changes in circulation for the warming scenario. The warming scenario (the historical warming) compares the results from the different model configurations, which are all subject to the same changes in circulation that may be driven by that warming. Therefore we conclude that any differences in carbon cycle parameters are due to the temperature dependent biological processes, not circulation.

In Figure 2, the processes shown are not correct. Microbial (heterotrophic bacterial) respiration is also part of heterotrophic respiration (heterotrophic respiration = zooplankton respiration + bacterial respiration) and also occurs in the euphotic zone. The current schematic makes it look like microbial respiration is a separate process from heterotrophic respiration.

Reviewer 2 is correct. This separation between surface food web (heterotrophic respiration) and sub surface processes (microbial respiration) comes from the way they are often treated in models. Here surface food webs are modelled as being separate from sub surface processes like remineralisation, whereas actually this is not strictly the case in fact. The figure has been changed so that microbial respiration also reads "heterotrophic respiration". The aim of the figure is to demonstrate where cGENIEs export production model "sits" and hopefully makes the comparison to other models' treatments of the biological pump more straight-forward.

"In Figure 13, Please consider putting a global uniform value for POC transport efficiency in CB next to the CBRU plot, instead of presenting the stand-alone CB plot."

This value has been added to the caption for CB, but we keep the figure to really emphasise that including the temperature dependence makes a large difference to ocean carbon cycling.

"In all Figures, increase font size for better legibility as figure quality is currently poor; and use constant symbols in vertical profile figures for data, CB, and CBRU comparison."
Figure quality and legibility has been improved in the revised version for all figures.

All other technical comments from reviewer 2 have been included in the revised version.

Editor comment response

The title has been changed to include the model name and version:

Calibration of key temperature-dependent ocean microbial processes in the cGENIE.muffin (v0.9.13) Earth system model

We thank all reviewers for their comments.

K.A.Crichton on behalf of all authors.