

# Replies to referee comments egusphere-2024-196

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Title: CICERO Simple Climate Model (CICERO-SCM v1.1.1) – an improved simple climate model with a parameter calibration tool

Author(s): Marit Sandstad et al.

MS type: Model description paper

Iteration: Revised submission

Below follows our point-by-point responses to the reviewer comments that was also posted on EGU sphere as author comments. However, for easier reference to the detailed list of revisions, we've also given each of the reviewer comments a number and bullet (R1c1, R1c2 etc for the comments from reviewer 1, and R2c1, R2c2 etc for the comments from reviewer 2.). Most revisions are in direct response to reviewer comments, but some are also edits to remove typos or edit the text during the revision, some are also purely due to updates of the citations, formatting and to improve the manuscript. In the bottom of this document, we also provide a detailed list with explanations of the changes made to the document with references to which reviewer comment it was made in response to. In addition to the responses, and detailed list in this document, we enclose separately a copy of the revised manuscript with tracked changes to show all changes to the document made in this revision, all page and line number references in the detailed list of changes here refer to the page numbers and lines in that document. Hopefully with all this it should be clear what has been done and for what purpose.

## Reply to Referee #1:

Dear Anonymous Referee #1,

Thank you for your thorough and comprehensive read and multiple helpful comments on our manuscript! Below we will try to respond to each of your specific comments and we have made amendments to our manuscript according to them. Your comments are added in Italics before each reply.

**R1c1** *L20: missing a space between eg and the citation*

Thank you, we have fixed this!

**R1c2** *Figure 1: use subscripts in the chemical names*

Figure 1: Thank you for pointing out the lack of subscript. We have updated the figure accordingly.

**R1c3** *L96: "dictionary" is this a Python specific term?*

L96: A dictionary is a data structure (in python, but also in other language) of unordered key-value pairs. We have tried to clarify this in the text and used the opportunity to elaborate a bit on what the output dictionary holds.

**R1c4** *Table 1: Sunvolc is this a boolean parameter? If is it set to 1 does that mean that inputs for sun and volcanic radiative forcing are both required? Or could a user provide only one?*

Table 1: The sunvolc parameter is not boolean, but this is mainly to conform with the previous Fortran implementation. There are default datafiles for both solar and volcanic forcing which will be used if the user does not supply data for them. The user can supply their own data for one or both of them, and if one or more of them are missing as inputs, while the sunvolc parameter is 1, whatever the user has not supplied will be taken from defaults. We have tried to elaborate a bit on this in the table.

**R1c5** *L108: what is meant by tracer components here?*

L108: Tracer components is simply a synonym for components, chemical species/components etc. We will change it to chemical components. Hopefully that is easier to understand.

**R1c6** *L120-123 : is a tad confusing, is the model only CO<sub>2</sub>-driven between 1750-1850? If so why? Or are there non-CO<sub>2</sub> emissions during this period that are held constant? More details on which concentrations (the species and the time frame) are needed would be helpful here. Are the required concentrations user-defined?*

L120-123: This might be a bit cryptic indeed. The run is set up so that at nystart, the run start, concentrations are calculated from emissions for CO<sub>2</sub>, but for all other species concentrations are taken from prescribed user input concentrations. At emstart, the start year for emissions, concentrations for all other species will also be calculated from input emissions. We've tried to rewrite a bit to make this clearer.

**R1c7** *L180 - 190: I am having a difficult time understanding equations 6-9 and I think it stems from some confusion related to f<sub>fer</sub> and beta. What is the difference between f<sub>fer</sub> and beta? Are they related in some way? Some more details here would be helpful. Is f<sub>fer</sub> typically negative?*

L180-190: Again, thank you for pointing out a confusing part of the text. We have tried to elaborate a bit so as to show that the f<sub>fer</sub> is the result current fertilization added to time integrated decay of historical fertilization. This is related to the fertilization factor beta in that the current fertilization is calculated from the CO<sub>2</sub> concentration using this fertilization factor according to equation 9. We've rewritten a bit around the equations in this whole sections to make things clearer, hopefully that helps.

**R1c8** *~L220: " This implementation is appropriate for discrete input data only, where the emissions (and concentrations) are assumed constant throughout the year. For a timestep of less than one year..." what is the time step for CICERO-SCM? Can it run on a monthly time step? If it is running in with monthly inputs are all emission inputs needed to be monthly?*

~L220: Currently the model operates with only yearly input data but can handle volcanic forcing data on a monthly resolution. The carbon cycle is integrated using 24 sub yearly timesteps (where you can in principle run with a different number of sub yearly timesteps), and the upwelling diffusion model works with 12 sub yearly integration steps, for which varying monthly varying forcing could be used. However, the current model only takes in yearly data (barring volcanic forcing), and only outputs yearly data. If you wanted

something else, it would need to be rewritten. We've tried to make this a bit clearer in the text now.

**R1c9** L244: *Equation 9, would it be possible to add a subscript to the parameters to indicate which parameters vary with the gas species?*

L244: I assume this comment pertains to equations 10-14. Yes, that sounds like a good idea. We've tried to implement that.

**R1c10** L240: *missing a space between "CH4is"*

L240: Thank you, fixed!

**R1c11** Section started at L220: *Here in 2.1.3 CH4 - emissions to concentrations, the authors describe how CICERO-SCM supports three different methods for calculating tau oh. Which option does CICERO-SCM use by default? What is the motivation for supporting these three different dynamics? Is this feature common in other SCMs? It seems like this is an opportunity for the authors to highlight one of CICERO's unique features.*

Section started at L220: Here in 2.1.3 CH4 - emissions to concentrations. We assume this pertains to section 2.1.3. The default lifetime mode for lifetime is TAR. This is pointed out by putting default in paranthesis, but we can see how that might be missed. The (actually 4) different methods of calculating the OH-lifetime can allow the user who is interested in methane specifically to run with different setup, highlighting this option is a good suggestion which we thank the reviewer for and which we have tried to implement in the updated version of the article.

**R1c12** Figure 3: *where did the uncertainty ribbon/envelop come from? Is it from IPCC AR6 or is it from an ensemble of CICERO runs?*

Figure 3: The uncertainty ribbon is from the IPCC ERF timeseries. We've tried to make this clearer in the caption now.

**R1c13** L476: *"twelve sub-yearly timesteps" like monthly? The discussion here and then also in L220 is confusing me. It would be helpful to have a clear discussion somewhere in the manuscript that addresses CICERO's time step addressing the following*

*If/what inputs can be sub-annual? What happens to the inputs that are not sub-annual?*

*If there are sub-annual inputs, what time step? Monthly? Daily?*

*How does using sub-annual inputs affect outputs?*

L476: Thank you for pointing out the confusion related to various time steps and resolutions. We've now added a few sentences to the introduction to clarify a bit on both temporal and spatial resolution. In general, you can say that the model is yearly and global, though certain parts of the model have sub yearly timesteps to provide a more accurate numerical solution to the differential equations it solves. Only in the upwelling\_diffusion\_model and for forcing does this translate to an option to input monthly data.

**R1c14** L 494: *It would be helpful to have some more details about many new tunable parameters. Are there like or 5 or 10 parameters? Are these parameters listed somewhere?*

L494: We've now added a listing of tunable parameters from the previous version and the current one. We've also added a bit more on the increased flexibility of the new version.

**R1c15** L499: *"automatic tests including regression test to make sure the results from the energy balance model", is a bit unclear, so it is this regression calculating the difference between current model behavior and the previous model behavior? What sort of regression tests are good enough to pass the automatic testing?*

L499 We've now elaborated on this.

**R1c16** L 510: *The change in run time seems minimal to me, yes is unfortunate but adopting Python greatly improves the readability and accessibility!*

L510: We also think this is a price worth paying for readability, however, speed is useful, so we would still like to improve the speed of the code if we can.

**R1c17** Figure 7: *would it be possible to do a more robust comparison between CICERO output? Either plotting a and b on the same figure? Would it be possible to compare CICERO V1.1.1 results with the CICERO results included in AR6 7.SM.4? That could provide more evidence that the results did not change very much.*

Figure 7: We've added a third panel to the plot where results for a single scenario is shown for both versions alongside the observations. Hopefully this makes the comparison easier.

**R1c18** L525: *Where does the parameter distribution set defined in the json-file come from? Is it generated with the calibration tools included in the CICERO repository? Would running the calibration tools result in a new set of parameters? Would the calibration tool work on any tunable parameter?*

L525: You can use the calibration tool to create a json-file defining a parameter ensemble, but you can also generate or have the json file from elsewhere. For instance, we have a json-file of the parameter-ensemble used in the AR6 process which we've used to do the runs shown in figure 7. You can use the calibration tool to generate new parameter set, and yes, you can use the calibration tools to tune whichever tunable parameter you want. We've expanded this a bit to clarify.

**R1c19** L 532: *the phrase "larger the calibration space" is somewhat unclear, does this refer to the uncertainty space of the parameters? The number of parameters being tuned? The number of variables being compared? The length of the time series being used in comparison data?*

L 532: By calibration space we mean both the width and dimensionality of the prior parameter space, i.e. both the number of parameters to fit and the range of their priors. We've added a bit to clarify this.

**R1c20** L 560: *Just a suggestion but I think you could drop the word significantly here...*

L560: We are happy to accept this suggestion.

**R1c21** L 575: *"inclusion of temperature feedbacks into the carbon uptake" is that for the ocean carbon cycle? Or the terrestrial carbon cycle?*

L575: This comment relates to both the oceanic and terrestrial carbon cycle, none of which currently have temperature feedbacks. In practice, it might also be interesting to have feedbacks to just one of the two, but both are valid options to consider for a carbon cycle update of the model.

**R1c22** *Caption of Figure A1: missing a space in "2014and"*

Caption of Figure A1: Thank you for pointing out the missing space. We've fixed this now.

**R1c23** *Figures A1, A3, A6: Why is HCFC-123 constant at 0 over the entire period of the run?*

Figures A1, A3, A6: Good catch. The reason is simply that the input we used didn't have any data for HCFC-123, and hence we ran with zero emissions for this gas throughout. We've added a sentence on this in the captions to clarify any confusion on this point.

**R1c24** *Figures A1-8: what is the plot number for? Is that the code used by the plotter functions to make the plots?*

Figures A1-8: These plots are automatic plots that the code can output if you run with an option for that. The plots are png-files that will be sorted in a folder according to user input, but the naming scheme for each specific plot will have a part according to the topic of the plot like forc, conc, em, ohc etc, For the forcing, concentration and emissions plot, there will be more than one plot, so the number will be the rest of the file name, so forc\_1.png, forc\_2.png and forc\_3.png.

## Reply to Referee #2:

Dear Anonymous Referee #2,

Thank you for reading and commenting on our article. We are sorry that you found our manuscript confusing. We have tried to amend the manuscript to make it more readable. Below we will respond to each of your comments and outline how we have gone about improving the manuscript to solve the issues you point out. This will hopefully improve both the article and your opinion of it. We've added in your comments in italics between the various responses.

**R2c1** *1. This paper is extremely confusing to read. First of all, the completeness of almost all the equation significantly lacks.*

Addressing your first point we have gone through all the equations to try to make sure they are more readable, making sure units and definitions are stated even for equations to which you have made no specific comment. Below we will answer all your specific comments and explain what we have changed in the text to clarify.

**R2c2-** *(Eq1) what is the unit of A<sub>oc</sub>*

Eq1: A<sub>oc</sub> is the the ocean area in m<sup>2</sup>. Thank you for pointing out the lack of units for this variable. We have now added that to the text.

**R2c3-** *(Eq2) what is K<sub>g</sub> here? what is the unit of the partial pressure of the slab ocean?*

Eq2: It's perfectly understandable that you found this confusing, and we apologize for that. We've added the multiplication mark to clarify that  $k_g$  is a coefficient to be multiplied with and not something like a function, we've also added its definition to the text.

**R2c4-** (Eq3) where is  $F$  defined? where is equation 6b?

Eq3: "F is the polynomial approximation given in equation 6b) of (Joos et al., 1996)" means that F is defined in the paper referred to Joos et al., 1996, in equation 6b of that paper. Hopefully this is possible to understand, however we've added the formulation as used in our model, which is the functional form at  $T=18.2$  °C to make this clearer.

**R2c5-** (Eq7)  $\delta f_{npp}(t)$  defines the instantaneous effect of plant productivity. So, what is its unit? How could "an effect" be part of an equation? All equations are supposed to deal with either mass, energy, or momentum conservation.

Eq 7: We've rewritten a bit on the  $\delta f_{npp}(t)$  to make it more readable, and included its unit.

**R2c6** (Eq10) what is the unit of  $t$ ? is it yearly?

Eq 10. Yes, time is measured in years here, we've added that to the text.

**R2c7** (Eq20)  $E_{ref}$  is the function of  $E(t_{ref})$  and  $E(t_0)$  and  $E$  is noted the emission of each aerosol species. Then is  $E_{ref}$  still the function of time ( $t$ )? If so, why the notation of  $E(t)$  is missing in LHS?

Eq 20:  $E(t)$  is a function of time.  $E_{ref}$  is the result of subtracting the value of this function at two specific times ( $t_{ref}$  and  $t_0$ ) and is hence simply a number. We've added a little bit on the function  $E(t)$  in the text that hopefully clarifies this.

More on **R2c1**: *I can point out multiple flaws in each equation, which will make readers extremely frustrated. All the units in equations must be clarified, and the notations also must be consistent if they appear in multiple equations. Moreover, I found that many sentences must be improved for better readability.*

We understand that you have further comments under this point, but they have been mentioned generically and not as an exhaustive list of problems to address. To deal with this, we have gone over all equations to make sure all quantities are defined, and units are stated. We have also tried to make some other clarifications where we have seen the text might benefit. Hopefully this will make the equations and text not explicitly commented on more readable.

**R2c8** *2. the authors compared time series between SCM and other models' outputs. However, the mechanistic explanation of each comparison is absent. For example, the authors might add some exciting explanation about the differences/similarities of the projected surface air temperature/heat content between SCM and others.*

We are not sure exactly what is meant by this comment. While we do make some comparisons with IPCC assessments and observational bounds, these are meant mainly to demonstrate that our model can reproduce such timeseries somewhat reasonably. The main point of an SCM like the CICERO-SCM is that it's very fast, so you can produce results, assess scenarios, and recalibrate to tune to different datasets on a timeframe that is simply not feasible for something like an Earth system model. Also, we would like to emphasize that this is primarily a model description paper, and not a model assessment or comparison paper. Hence, we show results to demonstrate the model's ability to produce

relatively realistic results, and since this is a description of a ported model, to show that its results are consistent with its predecessor model.

**R2c9** 3. *To my eye, a couple of things are not clear. First, the authors said that SCM provides more flexibility than Fortran. The authors need to clarify why their old Fortran SCM is less flexible than Python even though the Fortran should have a namelist to tune the parameters, and restart files especially.*

3. To address the point of flexibility compared to the Fortran model, we have tried to elaborate a bit more on this but want to respond a bit here too. Though one could tune a number of parameters in the Fortran model, the Python version has more tunable parameters, we have tried to make this clearer by explicitly listing which parameters were already tunable and which are now tunable that weren't tunable before. For instance, the carbon cycle model was previously completely fixed. In addition, the old Fortran model required a separate compiled version each to perform a run driven from emissions, compared to one driven from concentrations, compared to one where all non-CO<sub>2</sub> greenhouse gases from concentrations. The porting of the code to Python has also separated more functionally different parts of the code into modules and smaller methods which are easier to further edit and change for new developers. Making the code publicly available, buildable as a module, installable as a library through the widely used library tool pip and equipping it with testing functionality also makes further improvements with continued trust in the results. Whilst elements of this can be done whilst keeping the code FORTRAN based, we do not have that level of FORTRAN competence and we also believe the broader community has a higher level of competence in Python. We wager that the number of people who will easily be able to interact with the Python based code described in this article, is significantly larger than the number that would have been able to do so if we shared an open version of the FORTRAN code.

**R2c10** *Second, this is a case of "calibration for calibration" Suppose, we get a set of parameters that represents well the trend of a targeted variable. Then, do the authors think the parameters are realistic? If not, I think the utility of this kind of simplified CM lies on doing sensitivity analysis. However, this paper does not show the SCM's usability for parameter sensitivity analysis.*

The calibration finds parameter values which faithfully reproduce the output data given the model structure. If the model structure is wrong, and the output is still reduced, then the parameters would implicitly compensate for any structural errors. It is reasonable to argue that the parameter set strictly makes sense for the model structure at hand: eg, the vertical diffusivity may change depending on the numbers of layers in the ocean. However, the model is shown to be able to produce a broad range of outputs for various inputs, for a given calibration, indicating that the model-parameter combinations are realistic. In any case, the model is sufficiently fast, that it is easy to perform sensitivity analysis or different calibrations and assessments of the parameter space. This is in essence the point of developing simple climate models.

To the point of sensitivity analysis, previous work has calibrated the upwelling diffusion model parameters and radiative forcing values to observed temperatures and storage of heat in the ocean (REF Skeie 2014,2018). A main limitation to the simplified calibration outlined in the manuscript and the previous work is the large uncertainties in the temporal development of the aerosol forcing (Skeie et al 2018) that we are not able to capture and

constrain. Future work should address this, and a SCM is a suitable tool for such investigations. In addition, the run speed of a model such as this makes it extremely useful in future projections when large numbers of projections need to be assessed. By calibrating parameter sets to some set of observables or ESM output, we can produce ensembles that spans some distribution, and which produces global results that are consistent with observations or ESM, which in turn can be applied to very large numbers of future projections, such as the AR6 WGIII scenario database. Assessing large numbers of scenarios including ensembles to span a distribution of outcomes using full Earth System Models, or even intermediate complexity models, is unfeasible. Of course this could also be done with a pure emulation approach, but pure emulation does not provide a simplified mechanistic approach that can allow us to assess several variables simultaneously or extrapolate outside of the ensemble space. The reviewer is of course in their full right to see no or dubious value in this, if so, we are unsure whether this paper can remedy this while also fulfilling its own purpose of being a model description paper.

## Detailed list of revision changes

Page 1: Adding a space according to **R1c1**. Additional changes here include an update on an author name and field code changes due to updates of the bibliography. One reference (Sherwood et al. 2020) had also not been added correctly to the bibliography and had to be fixed.

Page 2-3, similarly just updates to do with bibliography style.

Page 4: Made updated version of figure 1 according **R1c2**.

Page 5 around line 100: Clarifying the model time steps and resolution to respond to **R1c13** and **R1c8**.

Page 5 around line 115: Explaining dictionary use to respond to **R1c3**.

Page 5 just before table: Changed "figs" to "Figs.". These types of formatting changes have been made throughout the document for consistency.

Page 5 in table 1: Clarified the description of sunvolc parameter in response to **R1c4**.

Page 6: Changed "subyearly" to "sub yearly". This was done throughout the document for spelling.

Page 7: Took out incorrect bold type set in table, and changed "tracer components" to "chemical components" in response to **R1c5**.

Page 8: Added a bit to explain the default run operations using concentrations for all non-CO2 greenhouse gases in the beginning in response to **R1c6**.

Page 11 table caption: Added a couple of parentheses to show that SARF and ERF are abbreviations of stratospheric adjusted radiative forcing and effective radiative forcing respectively.

Page 11 2.1.1: Took out direct references to decay functions in the first introductory sentence, pure formatting update and changed equation 1 to include the terrestrial carbon uptake  $f_{fer}$  explicitly to make the equations easier to follow and the flow more



readable in response to **R2c1** and hopefully also helping with confusion mentioned in **R1c7**.

Page 12: Added units of  $A_{oc}$  in response to **R2c2**. Changed format of equation 2 and added definition for  $k_g$  to comply with **R2c3**. Added explicit definition of  $F$  as new equation 4, as response to R2c4. Corrected units to models actual use for emissions and  $f_{fer}$ . Tried to write the equations and the text around them more clearly and made sure to explicitly define every quantity and its units in the text in general in accordance with **R2c1**. Updating also equation numbering.

Page 13: Old equation 6 is deleted, as it is now baked into equation 1. The text has also been updated to reflect this, and again we have gone over all equations to make sure all quantities are defined with units and explanations in accordance with **R2c1**. With the addition of a new equation 4 this leaves equation numbering after this point as before. We changed the wording around equation 7 to better explain and address the concerns of **R2c5**. To avoid confusion with other  $\beta$ s as mentioned in **R1c9** we have changed  $\beta$  to  $\beta_f$  in equation 9, which we believe also better matches it to its parameter name (beta\_f) and makes the overall text more readable (**R2c1**).

Page 14: As suggested in **R1c9** we have added a subscript *gas* to both  $\beta$  and  $\tau$  in equation 10 and subsequently for the emissions to concentrations conversions and lifetimes of the various short-lived forcers. Also specified that the time is in years according to **R2c6**.

Page 15: Further changes of  $\beta \rightarrow \beta_{gas}$  and  $\tau \rightarrow \tau_{gas}$  and making equations and text around them more readable, making functional dependence explicit, according to **R1c9** and **R2c1**. Also added a sentence to clarify in accordance with **R1c8**.

Page 16 line 281: One more instance of  $\beta \rightarrow \beta_{gas}$  and  $\tau \rightarrow \tau_{gas}$  and making the expression easier to read.

Page 16 2.1.3: Adding missing space as spotted in **R1c10**. More subscripts for  $\beta$  and  $\tau$  according to **R1c9** here for  $CH_4$  explicitly.

Page 17: Added a bit to highlight the various OH lifetime options as a model specific flexibility according to **R1c11**, and yet another subscript for  $\beta$  according to **R1c9** here for  $N_2O$  explicitly.

Page 19-20: Updated the figure as the title for subpanel c) said  $NO_2$  rather than  $N_2O$ , also augmented the figure caption to clarify according to **R1c12**.

Page 21: Adding a bit of explanatory text on SARF to ERF conversion for general clarification according to **R2c1**.

Page 22: Fixing equations and explanations around them for clarification, units and consistency according to **R2c1**. Also adding a bit to help clear up the concerns brought in **R1c6**.

Page 23: Language detail also trying to solve the confusion voiced in **R2c7**.

Page 26: Fixed incorrect reference.

Page 28: Language fixes, and tiny update to make text clearer.

Page 29 top part: Fixes to make equations and text clearer, adding definitions and units, fixing also equation numbers according to **R2c1**.

Page 29 "Model differences...": Added a bit listing all new and old tunable parameters to respond to **R1c14**.

Page 30: Adding a bit on the nature of added flexibility to respond to **R2c9**. Also describing in more detail the regression testing scheme to respond to **R1c15**.

Page 31: To better showcase the model update consequences as asked for in **R1c17**, we've added a panel to the figure and updated the figure caption accordingly.

Page 32: Added a bit to clarify the role of and creation of parameter ensemble json-files as requested in **R1c18**. Elaborating a bit on what we mean by calibration space size to respond to **R1c19**. Some additional elaboration and clarification that we thought the text would benefit from.

Page 33: Took out "significantly" as suggested by **R1c20**.

Page 35: Added missing space according to **R1c 22**, and a line explaining the reason why HCFC-123 data are zero throughout, as **R1c23** asked about.

Page 38: Added a line explaining the reason why HCFC-123 data are zero throughout, as **R1c23** asked about.

Page 40: Added a line explaining the reason why HCFC-123 data are zero throughout, as **R1c23** asked about.

Page 42: Added a line explaining why forcing from BMB\_AEROS is zero throughout.

Page 44: Added another reference (one on the N<sub>2</sub>O budget).

Pages 46-49: General updates to make text and equations clearer and more readable. For changing constant  $c$  to  $c_p$  to clarify and make consistent with section 2.2 and defining it with units. Updating all equation numbers to begin numbering of supplemental equations from 1. Also making explicit what parameters are tunable and where to find details on them and listing values and units explicitly for constants.

Changes to bibliography are added or fixed references already mentioned where they changed in the text proper.