Response to referee #5. S. Motesharrei

Referee #5:
Review of the manuscript "Improving the representation of anthropogenic CO_2 emissions in climate models: a new parameterization for the Community Earth System Model (CESM)" by Andrés Navarro, Raúl Moreno, and Francisco J. Tapiador, submitted to the Journal Earth System Dynamics, European Geosciences Union (EGU).
Decision:
Because of the importance of the topic, I would recommend the publication of this manuscript after major revisions in the presentation of the work as described below.

Reply: Many thanks for your positive feedback. Please, see following comments for a detailed revision of the updates.

Referee #5:
General comments:
The authors acknowledge (but not completely clearly) a major shortcoming of the Earth System Models (ESMs) and Integrated Assessment Models (IAMs).
Even though the Human System has become the dominant driver of most components of the Earth System since about 1750, and especially since about 1950, IAMs use independent, exogenous projections of the Human System (HS) variables in order to drive ESMs to create future projections. Not including essential bidirectional feedbacks between ES and HS can lead to missing important dynamics that is critical to the sustainably of our planet and people. This problem is discussed in detail in the "Modeling Sustainability" paper by Motesharrei et al. [2016]:

Motesharrei, Safa, Jorge Rivas, Eugenia Kalnay, Ghassem R. Asrar, Antonio J. Busalacchi, Robert F. Cahalan, Mark A. Cane, et al. "Modeling Sustainability: Population, Inequality, Consumption, and Bidirectional Coupling of the Earth and Human Systems." National Science Review 3, no. 4 (December 11, 2016): 470–494. https://doi.org/10.1093/nsr/nww081.

Reply: Many thanks for giving us the opportunity to expand this point in the paper. Also, thanks for the reference, which reinforce our point. We have used it to expand the issue in the revised version of the manuscript.

We extended the third paragraph of the introduction section to explain the point in details. The text now reads:

> *One of the fields most in need of development is the inclusion in global models of co-evolutionary dynamical interactions of the socioeconomic dimension into global models with other Earth system components (Nobre et al., 2010; Robinson et al., 2017; Sarofim and Reilly, 2011). Human activity was a major driver of change in the Earth System in the recent past (Alter et al., 2017; Barnett et al., 2008; Crutzen, 2002), and it now dominates the natural system (Ruth, et al.*

2011). However, most global models use basic socioeconomic assumptions about the behavior of societies and are only unidirectionally linked to the biogeophysical part of the Earth system (Müller-Hansen et al., 2017; Smith et al., 2014). The standard way of introducing anthropogenic climate change into ESMs is through Representative Concentration Pathways (RCPs). These are consistent sets of projections involving only radiative forcing components (van Vuuren et al., 2011), but which represent a step forward from the scenario approach of the last decade (Moss et al., 2010; van Vuuren et al., 2014; van Vuuren and Carter, 2014). However, RCPs are not fully-integrated socioeconomic parameterizations but rather estimates for describing plausible trajectories of human climate change drivers (Moss et al., 2010; Vuuren et al., 2012). They provide simplified accounts of human activities and processes from one-way coupled Integrated Assessment Models (IAMs, Müller-Hansen et al., 2017).

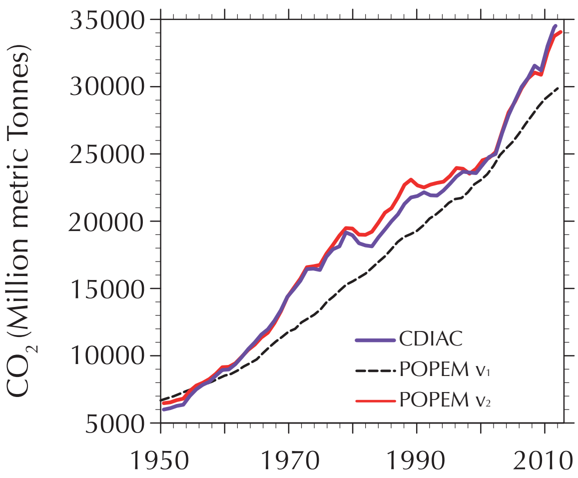
The use of RCPs is advantageous because they provide a set of pathways that serve to initialize climate models. However, two major problems remain within this approach. Firstly, human activities are not intrinsically embedded into the ESM, impeding sensitivity studies. Secondly, because of the weak coupling of IAMs, they cannot capture the sometimes counterintuitive bidirectional feedback and nonlinearity between the socioeconomic and natural subsystems (Motesharrei et al. 2016; Ruth et al. 2011). Good examples that illustrate the importance of including such bidirectional feedbacks feature in the HANDY model (Motesharrei et al. 2014) which has been used to analyze the key mechanisms behind societal collapses using the predator-prey model.

The RCP approach has been used in climate models because of its low computational cost. However, advances in computational resources now allow to parameterize human-Earth processes in a more detailed way, including the inclusion of population dynamics into the modeling, as in the POPEM (POpulation Parameterization for Earth Models) module (Navarro et al., 2017).

Referee #5: *The manuscript is closely related to a recently published paper by the same team of authors (and, unfortunately, there is much overlap with that already published work):*
Navarro, Andrés, Raúl Moreno, Alfonso Jiménez-Alcázar, and Francisco J. Tapiador. "Coupling Population Dynamics with Earth System Models: The POPEM Model." Environmental Science and Pollution Research, September 16, 2017, 1–12. https://doi.org/10.1007/s11356-017-0127-7.

Reply: Actually, there are major differences with that paper. Navarro et al. (2017) described in detail the **demographic** part of POPEM. In that paper, we were focused on the explanation and validation of the demographic and emission parts at global scale. In contrast, the current paper deals with the coupling of that demographic model with an **Earth System Model**, and compare the model outputs with observational data. That is a completely different history.

Also, the original emissions modeling module has been improved. We included a new figure (EXT1) in the supplementary material to show that. It looks:



EXT1: Comparison of the historical global CO_2 emission estimates for the years 1950–2012. The black line shows the estimates given using POPEM v1, red indicates POPEM v2, and purple indicates CDIAC estimates. Values are given in million of metric tonnes.

We have now limited the potential overlaps to the minimum required for the paper to be self-contained. We have rewritten parts of that section and added a new paragraph in the *2.2.1 POPEM parameterization model overview* subsection to clarify the novelties between successive POPEM versions and how the changes affect the emission estimates and the coupling with the model.

The new paragraph reads:

> *The demographic/emissions module presented here is an updated version of the demographic module explained in Navarro et. al (2017). The differences between the versions are minimal. They involve better approximation of emissions in highly polluting regions with poor population data, such as China; a better estimate for coastal zones and country limits; and a change in the model time step for more efficient coupling with CESM. The inclusion of these changes results in more accurate emissions estimates when compared with inventories than the previous version did. However, the model is not immune to bias. The most important limit is the degradation of the model outputs when there is increased spatial resolution –resolution of 0.25^o and higher–.*

Referee #5: *These two papers take a step toward including at least parts of the Human System (human population and emissions) explicitly in the ESMs, however, the somewhat in- accurate presentation of the work (and occasional over-statements) may lead to readers' confusion about the extent and novelty of this work. During my initial* *reading of the manuscript, I was very impressed by the model and thought that it is a bidirectionally coupled Human System + Earth System Model. (It seems Anonymous Referee 3 has this same impression.) But upon further reading of the manuscript as well as Navarro et al. [2017], I realized that POPEM is essentially a demographic projection model (although it uses dynamic variables for age cohorts) that is used to drive CESM.*

Reply: Sorry if the description of POPEM in the first version of the manuscript was unclear. We have now amended the explanation to avoid the confusion [cf. reply to section (A)].

Referee #5: *By contrast, I believe the use of local population projections to project emissions at each grid point is novel, and is advantageous to the current practice of using global emissions projections to drive ESMs.*

Reply: Thank you for noting this. We believe that this is the central idea of the paper.

Referee #5:
Suggested Revisions:
The other three referees already provide many helpful, important suggestions to improve the manuscript. Here, I outline some additional suggestions to help accurately present the model, its value for the Earth System modeling community, and possible future steps that needs to be taken by the modeling community to make the projections of the "Earth–Human System Models" more realistic.

Reply: Many thanks for your valuable comments to improve the model.

Referee #5: *I do not ask for any changes to model, since such changes would require major effort and could be implemented in future versions.*

Reply: Thanks for your understanding and consideration; really appreciate it.

Referee #5: *(A) Clarify that POPEM is, after all, a demographic projection model. It is true that its 18 age cohorts are dynamic variables, however, they still change based on exogenous fertility and mortality rates*

Reply: Sorry if that was not clear in the first version of the manuscript. We have now extended the first paragraph of *2.2.1 POPEM parameterization model overview* to make it clear. We also redesigned Figure 1 highlighting now the external parameters.

The paragraph now reads:

> *The POPEM module is a demographic projection model coded in FORTRAN that is intended to estimate monthly fossil fuel CO_2 emissions at model grid point scale using population as the input. Due to a lack of actual GHG measurements at*

appropriate spatial and temporal scales, it is necessary to use a proxy. For this, POPEM employs population, the evolution of which is modeled using external parameters that feed the module.

Referee #5: *(POPEM does not model Migration, which has become a major driver of population change, especially recently.)*

Reply: Modeling migration flows is an important point that we have taken into account since the very beginning of this project because it is a key element of population change –present and future-. However, there are several restrictions to accuracy estimate migration flows for historical populations at grid cell scale. Firstly, there are two different types of fluxes –short and long distance migrations- that have to be modeled in different ways (Lenormand et al. 2016). Secondly, we must quantify the entering and the exiting population for each cell using a probability rate of migration that is difficult to estimate with the limited migration data (Navarro et al. 2017). Thirdly, it is difficult – but not impossible- to validate a highly-detailed migration model with limited availability of migration data. Fourthly, the computational cost rises dramatically (e.g. *4 types of migration fluxes* x *number of cells* x *age-group* x *number of timesteps*).
Consequently, these sources of uncertainties are greater than the benefits for the period of time and the spatial resolution used in this work.

Referee #5: *These rates are projected into the future using statistical methods such as in the UN Population Projections. Therefore, the projections using POPEM could not be much different from traditional demographic projections, as can be seen from comparisons of POPEM to UN projections in Navarro et al. [2017]. I believe indeed POPEM cannot properly capture demographic change details for some regions and for certain age cohorts. Therefore, the value-added from this 'dynamic' population model is limited, at least from a demographic perspective.*

Reply: We assume that there is room for improvement in the demographic part of the model and it is an important point that we have to develop in the future versions of POPEM. However, the time period that we used here (1950-2000) and the actual spatial resolution offered by POPEM (1^{o} x 1^{o}) make model outputs less sensible to the referred biases. We have nonetheless clarified the limitations of the approach in the revised version. [see above the reworked text]

Referee #5: *(B) Because ES and other components of the HS do not feedback onto the demographic variables in POPEM, POPEM will not be able to capture non-trivial dynamics that can arise due to such bidirectional feedbacks [Motesharrei et al., 2016]. For basic examples of how these bidirectional feedbacks (in a minimal model) can lead to surprising behavior, see:*
Motesharrei, Safa, Jorge Rivas, and Eugenia Kalnay. "Human and Nature Dynamics (HANDY): Modeling Inequality and Use of Resources in the Collapse or Sustainability of

Societies." Ecological Economics 101 (May 2014): 90–102. https://doi.org/10.1016/j.ecolecon.2014.02.014.

Reply: Firstly, thank you for this crucial reference. We considered that the citation of this work in the first part of the manuscript clarifies how important are the Human-Earth interactions and their feedbacks for models.

Secondly, we agree with you that bidirectional feedbacks between ES and HS are essential to make ESMs more accurate and realistic. The work presented here is just the first step in that direction.

[See the second comment in the discussion to check how we have expanded this point in the revised version of the manuscript.]

Referee #5: *(C) I strongly recommend adding a schematic diagram at the begging of the paper to show how POPEM interacts with CESM (e.g., variables, parameters, input/output, couplings).*

Reply: Thanks. We have reworked Figure 1 following your recommendations.

Figure 1 now looks:

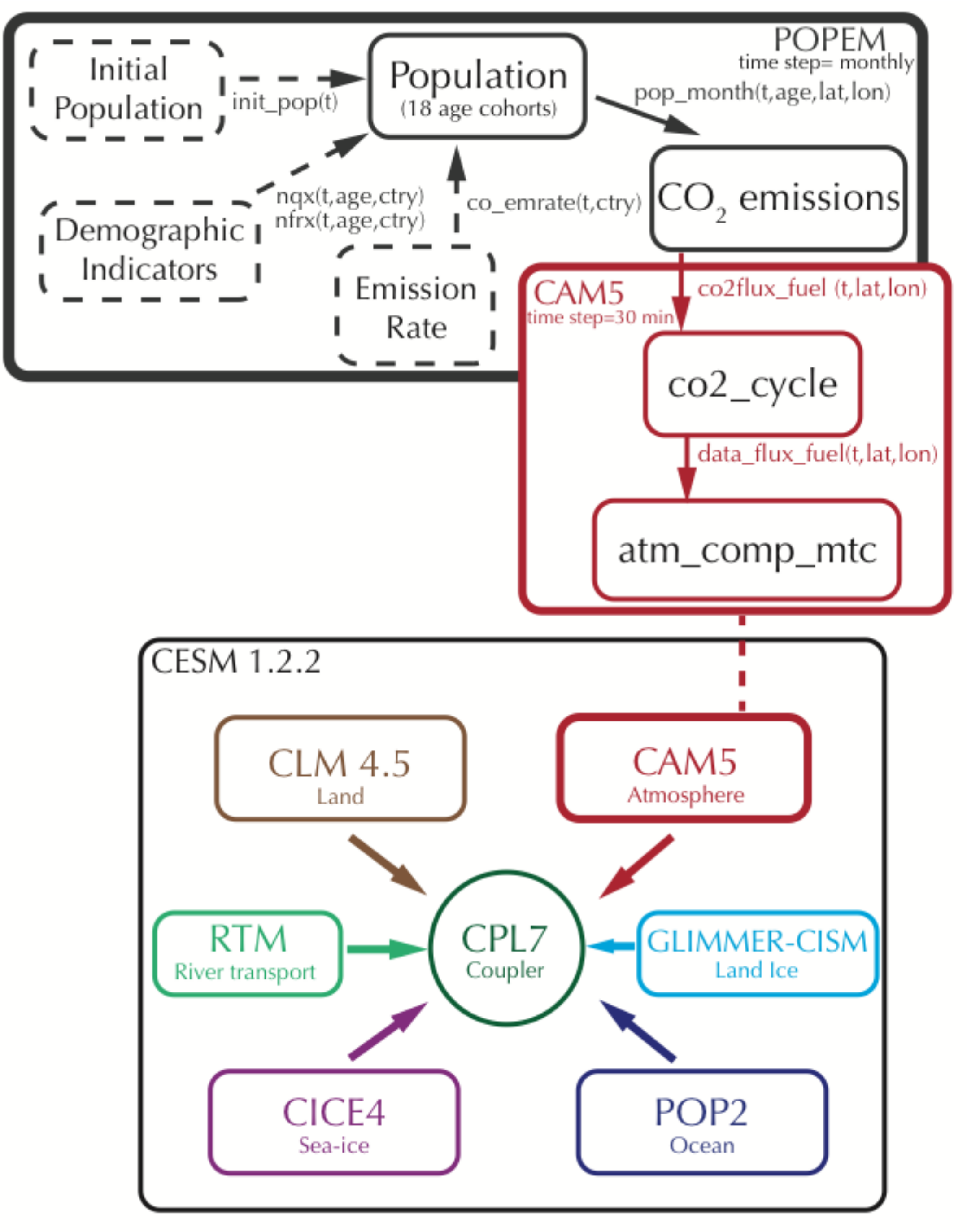


Figure 1: Conceptual schema of the POPEM module coupled with the CAM5 atmosphere module. POPEM requires three input data sets to compute emissions (black dashed rectangles): initial population distribution; demographic parameters (age structure, death, and birth rates); and per capita emission rates by country. POPEM provides a 3D array (time, latitude, longitude) with emissions that are read by the *CO2_cycle* module and passed to the *atm_comp_mct* module which computes the total amount of CO_2 in the atmosphere.

Referee #5: *(D) If POPEM + CESM is indeed the* first *model that calculates emissions at a local scale, as opposed to using global emissions projections, please emphasize that as the novel accomplishment of this research*

Reply: Thanks for the suggestion. We added two sentences in the las part of the first paragraph (section 2.2.1).

The extended version now reads:

> *[...]The idea of using population as proxy is not new, and population density has previously been used to downscale national CO_2 emissions (Andres et al., 1996, 2016). However, these inventories were not dynamical, but instead tied to historical data so it is not possible to use them either to estimate future changes in emissions, or coupled with other components of the model. This change represents an important advance in the way emissions are computed. Thus, POPEM uses a bottom-up approach, where emissions are calculated at cell level on the basis of population dynamics, while global inventories use a top-down approach, which is less flexible when coupled with other components of the ESM.*

Referee #5: *(E) Remove any parts of the manuscript that overlaps with Navarro et al. [2017], and instead refer to specific parts of that publication.*

Reply: We have removed some overlapping text and referred to Navarro et al. 2017. However, there are some elements that it is important to keep in the manuscript for the reasons mentioned at the beginning of this discussion (see reply to third comment). Hope you find the reasons compelling enough to justify our choice.

Referee #5: *(F) Be more careful with the definitions of, and distinctions between, ESMs and IAMs. Navarro et al. [2017] write, for example: "[RCPs] provide simplified versions of human activities and processes, such as population density and economic development, from non-coupled Integrated Assessment Models (IAMs)." It is not true that IAMs are 'non- coupled'; they are indeed one-way coupled.*

Reply: Sorry about that. What we wanted to say here was 'one-way coupled'.

Referee #5: *Then the authors write "researchers in the iESM Project (Collins et al. 2015) developed a global integrated assessment model, the GCAM, to address human impact on climate dynamics, with special emphasis on the representation of the human earth system." GCAM was not developed in the iESM project, but has been in development since 1990s and is one of the leading IAMs. The rest of the description of the sentence is also incorrect. iESM couples land use and agriculture to ES via bidirectional feedbacks.*

Reply: Sorry about that. Perhaps we should have described more precisely that GCAM is the IAM used by the iESM model in that paper. We take note of that for the future.

Referee #5: *(G) In the last section of the manuscript (4), emphasize that dynamic models of various Human System components need to be developed and coupled to ESMs via* *bidirectional feedbacks in order to produce realistic projections and to capture counterintuitive and unexpected dynamics.*

Reply: Thanks for the suggestion. We added a concluding paragraph in the manuscript.

The new paragraph reads:

> *Although the version of POPEM presented here is already functional, this work is intended to be just the first step in fully coupling socioeconomic dynamics with ESMs. This will include bidirectional feedback between Human and Earth systems and the simulation of societal processes based on the internal dynamics of the model instead of using external sources to make the projections. Only within a coupled global Human-Earth system framework can we produce more realistic representations of the Earth system capturing much of the counterintuitive feedback that is missing from current models (Motesharrei et al. 2016). The success of this approach will depend on the ability of scientists from different research fields to work in an interdisciplinary framework of continuous collaboration.*

Referee #5: *(H) Please go over your citations carefully and make sure that they appear at proper places. Also, the manuscript can benefit from additional important, relevant references. (The bibliography of Motesharrei et al. [2016] could be helpful for this manuscript.)*

Reply: Thank you for the advice and the reference. That excellent review helped us to find new relevant references, such as the previous work done by Matthias Ruth, Eugenia Kalnay and Jorge Rivas. We revised and extended the introduction section and added new citations from the bibliography of Motesharrei et al. (2016). (see the second comment for details on changes in the introduction section).

REFERENCES

Lenormand, M., Bassolas, A. and Ramasco, J. J.: Systematic comparison of trip distribution laws and models, J. Transp. Geogr., 51, 158–169, doi:10.1016/J.JTRANGEO.2015.12.008, 2016.

Navarro, A., Moreno, R., Jiménez-Alcázar, A. and Tapiador, F. J.: Coupling population dynamics with earth system models: the POPEM model, Environ. Sci. Pollut. Res., in press, doi:10.1007/s11356-017-0127-7, 2017.