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Interactive comment on "The integrated Earth System Model (iESM): formulation and functionality" *by* W. D. Collins et al.

Anonymous Referee #2

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This paper describes the coupling of models generally referred to as Integrated Assessment models, IAMs (here GCAM and GLM) with physically-based Earth system models (here CESM and CLM) so the 2 can run interactively influencing each others evolution during runtime. Traditionally this coupling has been unidirectional, in that IAMs are (first) run to generate a range of future socio-economic development pathways which result in a range of associated future emissions of greenhouse gases, aerosols, pollutants and land use/land cover. These emission/land-use time series are then prescribed as inputs to physical Earth system models and the future response of the Earth system/climate to the different emission and land scenarios are assessed. In this procedure there is no mechanism by which a changing (simulated) future climate (arising from the applied emission trajectory) can influence human behaviour and thus feedback onto and modify the evolving emissions/land use scenarios interactively with

the evolving climate. This of course is a quite conceivable in reality, e.g. one or more major future climate shocks might stimulate a response by society that radically alters future emission and/or land use trajectories directly in response to this climate shock so that the emission pathways, post-shock, are radically different to those in the original IAM estimates that did not include the "climate-shock". Such mitigation responses may be of sufficient magnitude that the resulting climate response is then radically different to if the climate-shock induced response had not occurred (as in the prescribed IAM trajectories).

The coupling described in this paper, in principle, allows such societal-climate interactions to be investigated and is therefore an important direction for the IAM and ESM communities to move towards. This is particularly true with respect to investigating possible future response options open to society/government as climate change unfolds and whether such responses can actually mitigate climate changes (i.e. will they do what we hope they might do, at least in a model world) and, more basically, what type of mitigation responses would actually have an impact on the desired time and space scales. To some extent these investigations could occur in an offline, iterative sense, e.g. emission scenario X (from an IAM) generates a major climate shock considered sufficiently large that society would be expected to respond in some manner. The ESM simulated "climate shock" time series could be used as a new input to an IAM model and a new set of socio-economic future pathways generated and these also prescribed in the ESM. Comparison of the 2 ESM climate states would indicate whether the IAM simulated response to the "climate-shock" was sufficient to mitigate the state of the climate post-shock. In a similar manner the iESM modelling system allows more gradual responses of society/technology to a changing future climate to feedback onto and modify the co-evolving emission and land-use scenarios and thereby the simulated climate as well.

The major advance in this study is the development of a modelling system that allows such interactions (co-evolution and mutual modification of both society and climate to each other) to occur "on the fly" as part of a standard model integration. As the authors state: "The goal is to create a first-generation integrated system to improve climate simulations and enhance understanding of climate impacts on human activities and feedbacks from human activities to the climate system" This goal is well achieved with the described modelling system.

While there are numerous uncertainties and difficulties with the approach, these should not detract from the ground-breaking nature of this effort. i.e. If we wait until all the modelling uncertainties are sorted out before developing such a modelling system, future climate change will have come and long gone before we have any useful responses. This is the main motivation for my accepting the paper with only minor changes. The paper is clearly written as a documentation of the approach and models/coupling procedures involved and from this perspective the authors do a pretty good job in clearly describing the actual formulation of iESM. Some details could be explained a bit more clearly these are mentioned in my specific points below. The rather "high-level" suggestions I make next, may not be possible. If some of them are, then I do think they would increase the interest level of the paper. Some of the suggestions may require major research effort and may already be planned by the group. They should not therefore be considered as a requirement for publication, rather suggestions. The items under "specific points" can be considered as necessary to address.

"Higher-Level" suggestions

It would be helpful to get an idea of whether such a coupled model system (as iESM) can be evaluated in the traditional sense of climate models. e.g. can it reproduce the observed response of society to some know (past) climate drivers and the reverse, could the system reproduce (in some statistical sense) known past interactions between human activities and regional to global climate responses (if there is sufficient documentation of these). Basically, can the coupled system be evaluated against "observations" (climate and socio-economic) in the way a standard climate model is evaluated? I have no feeling if this is actually possible, but if it is then it would give the

reader some assurance that the system had a certain degree of reliability.

Similarly, an example of the system being used "in anger" (for a future scenario) would increase the interest level of the paper e.g. have the authors carried out a future coupled simulation where the system generates a distinct human/societal response (behaviour/emission change) to future climate evolution that was unexpected and had clear impacts back on the physical climate, with the simulated societal responses and climate feedbacks understood and picked apart? If yes such an example would be nice to include.

More specific comments:

1. I suggest the authors acknowledge some of the major uncertainties inherent in this modelling approach and point the reader to relevant literature discussing key issues. These might include: (i) Is human/societal decision making sufficiently "logical" so that it can actually be simulated in some form of deterministic/mathematical manner (I assume there is considerable literature on this subject demonstrating at what level this is possible) and if so (ii) Will different societies across the globe respond in similar or contrasting manners that support/counteract such responses at the global scale (e.g. are human responses describable by a single set of rules, or are they regionally and temporally distinct and dependent on earlier decisions? (iii) Presumably society will respond to future climate threats in a spatially (or temporally) heterogeneous manner, can these responses and their impacts on climate be modelled with sufficient fidelity that we are in anyway confident the simulated climate response to a regionally-specific (emission/land-use) change is accurate and reproducible (i.e. are our climate models up to the job yet?). Can this even be verified in the real world? In a similar vain it would be helpful to discuss previous studies that have looked at climate responses to different (model) land use/cover changes and inclusion of emission reductions for certain short-lived species. This review would help set the frame for what the magnitude of such responses might be in a future interactive system.

2. The paper highlights energy supply/demand. Is this the primary (or only) societal-climate coupling that is presently simulated? The authors mention future work on water availability etc, does this cover things like mass irrigation? Also is agriculture/food production considered? Likewise possible human responses in terms of land-cover (e.g. mass afforestation) I assume these are possible in the system. This does not come out too clearly in the paper which can be read as only considering energy systems.

3. The authors mention GLIMMER. I assume this is for simulating Antarctic and Greenland ice sheets? One of the, low-probability but high-risk, future climate shocks could be an unexpected melting of one of these ice sheets and its impact of sea-level. In general how does sea-level rise get factored into the interactive climate-society response? This seems like one of the stronger driving impacts of Earth system change on future human responses.

4. It is not 100% clear to me what the coupling timescale is between CESM/CLM and GCAM/GLM. A 5-year time scale is mentioned, then later an annual time scale. Can this be explained more clearly? It also leads to a couple of questions: (i) Earth system change may lead to seasonally specific (climatological) responses, e.g. say a warmer moister winter, that is not so clearly seen in annual mean changes, or even balanced by systematic changes in other seasons. How are such sub-annual climate changes communicated to GCAM/GLM? (ii) In a similar sense, I imagine it is likely that some climate changes that induce a major societal response (in the future) will be associated with changes in weather variability within the climate umbrella e.g. major changes in regional storm statistics/intensities, changes in regional drought statistics etc. How is such information translated to influence the societal response simulated in GCAM/GLM if this is operating on an annual time step? And on a similar note, in the system I guess the regionally specific aspects of socio-econmoic development is at the spatial scale of the GCAM socio-economic regions. Does this mean that simulated climate changes (land-use/cover aside) influencing GCAM are averaged onto these spatial scales? i.e. Overall the degree by which the spatial and temporal scales of the evolving climate in

CESM are averaged before impacting GCAM (humans) is not clear.

5. The authors mention verification of the fully coupled system against offline simulations. This lends confidence that the coupled system (iESM) can reproduce the uncoupled suite of models when linked in the more traditional manner, but (as I mention higher up in the review) there is no overall evaluation of iESM in terms of simulated societal and climate statistics against actual occurrences that might be considered an observational evaluation of the system. Some references are given in section 6. It is not clear to me if these are evaluating the full iESM system. I admit I am not even sure if one can "evaluate" this system in the manner one would like to in terms of evaluating climate responses to societal changes or vice versa. If this is possible it would certainly increase the overall interest level of the paper, although I recognise the paper is primarily a documentation of the basic system

6. In the description of the GCAM model (section 3.2). The authors refer to "a reduced-form climate model". Please explain a little more what this is.

7. What fraction of the total model systems computational time is taken up by the human/societal part of the full model? and if there is a need to have large ensembles to develop statistically robust estimates of future society-climate response interactions, it may prove necessary to reduce the resolution of the CESM component. Have the authors investigated what the sensitivity is to having a lower resolution CESM (say 2.5x2.5 deg) in this system. It seems to me that the ability to generate large ensembles may prove very important.

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