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

Anonymous Referee #1

Received and published: 03 April 2015

This fascinating paper describes the coupling of an integrated assessment model (IAM, GCAM) to the IPCC-class CESM global Earth system model. The idea is not new, other institutions continue to discuss the development of a human dimension in global climate models (MIT, Yale, U Edinburgh). The MIT IGSM is a lower resolution precursor to iESM. GCAM has 5-year temporal resolution and 14 socioeconomic regions, much lower spatiotemporal resolution than the CESM.

In the iESM framework, GCAM is run in serial mode attached to the massively parallel-running CESM, which the authors claim is appropriate. The paper introduces potential future applications of the coupled iESM framework concerning climate change impact on energy demand, supply and production, but the paper primarily focuses on land use land cover change and implementation of the Global Land-Use Model into the CLM component of CESM.

Previously, the community approach has involved applying gridded fixed off-line emissions scenarios (pre-calculated by IAMs) into the global climate models. In this way, uncertainty in human decision-making is accounted for by running a range of IAM trajectories in the global climate models without any feedbacks from the future climate change onto the IAM trajectory.

This approach must be methodologically wrong for the future land use land cover change trajectories that will be sensitive to local, regional and global climate change. However, this standalone paper does not offer any convincing evidence that the massive coding work and computational expense is justified by new "better" information that could not be obtained by running many IAM scenarios and cases in a global climate model?

Response: *We agree with the reviewer that the standard approach of evaluating IAM scenarios within global climate models is "methodologically wrong" with respect to capturing feedbacks from climate to land-use. Certainly it is true that if all one cares about is covering the range of potential climate forcing, then the Representative Concentration Pathway (RCP) method outlined in Moss, et al. (2010), is wholly adequate. And, in fact, even the RCP architecture is excessive if one only cares about the forcing trajectory. In fact, arbitrary forcing trajectories were used in the earliest IPCC assessments. The need for greater consistency arises when one wishes to evaluate the climate implications of specific mitigation targets, match climate projections with socio-economic scenarios for impacts and adaptation research, or to understand the dynamic interplay of climate and human activity for its own sake.*

The reviewer is correct that this paper focuses on the rationale for, design, and implementation of the iESM framework rather than its scientific performance. A rigorous evaluation of the behavior of the coupled system, its performance under historical conditions, and its implications for future climate and land-use trajectories is the subject of several ongoing experiments and papers and is beyond the scope of *this paper. Finally, we note that the added computational cost of the iESM model is negligible in comparison to global climate model simulations forced by static IAM scenarios.*

A further concern is that the short-lived radiatively active species in CAM are not yet fully coupled to the CLM in the default version of the CESM. Worse still, effects of local and regional radiative forcing mechanisms such as short-lived species (aerosols) on local and remote climate response are very poorly understood to date.

Response: *We agree that a priority for future work is coupling non-CO_2 greenhouse gases, short-lived species and aerosols. The present paper focuses on the overall architecture and concept for the iESM, as well as our initial implementation of dynamic land-use interactions with the climate system. The architecture was developed in a flexible manner, to facilitate future integration of non-CO2 emissions and other factors.*

I have a few questions regarding the major science goal of the iESM development: "Will climate change itself affect global human decision making and biogeochemical and biogeophysical processes?

1. Is future global human economic-energy decision making sufficiently logical that it can be predicted to the extent and accuracy that it can be made into a computer program?

Response: *This series of questions from the reviewer has made it clear that we must be more specific in the manuscript as to which aspects of human decision-making are included in integrated assessment models (IAMs), like GCAM, and which aspects are external forcers to the model. The GCAM model takes population, GDP, technology efficiencies and costs, and certain policies as external boundary conditions and determines regional energy, land-use, and emissions distributions as a result. Efforts to evaluate IAMs in the past have largely focused on model intercomparison, but more recent efforts have begun to use hindcast experiments (Chaturvedi et al., 2013; Calvin et al., in prep), which can be used to test predictability. Calvin et al. finds that GCAM can project global and regional trends in crop production and land area, when relevant policies (e.g., renewable fuel standards) are included. A related class of models, Computable General Equilibrium (CGE) Models, have also been evaluated with respect to their predictive capabilities. These models use a similar market-clearing mechanism to that found in IAMs. They have been shown to improve predictability of market outcomes over simple trend extrapolation (e.g., Dixon and Rimmer, 2010).*

There has been a long history of use of IAMs, including GCAM, in providing scenarios of future greenhouse gas emissions, agriculture, land use and land cover to drive climate models. For example, GCAM was used to produce RCP 4.5. The use of IAMs, in preference to an arbitrary emissions trajectory reflects a consensus that the use of IAMs improves the representation of the relationship between underlying human externally specified population, GDP, technology and policy relative to more ad hoc procedures. Similarly, there is strong evidence that climate change has consequences for human systems, particularly those associated with land [IPCC WGII, 2014]. A major contribution of the iESM is the development of an architecture that is capable of producing a consistent representation of the co-evolution of human and physical Earth systems.

GCAM, like all IAMs, is calibrated to a base year (e.g. 2005) to reflect differences in resource endowments, technology history, and consumer tastes across regions. Thus, the model is limited in its temporal range to the decades (certainly no more than a century) surrounding this base year, and its basic function is to model changes from that base year as the above-named boundary conditions change.

The innovation of the iESM system is to explicitly make climate one of those driving conditions and to have the climate and human systems interact dynamically. Even in the iESM system, careful attention must be placed on the selection of reasonable and consistent sets of external conditions that form scenarios for the purposes of exploring the future. The iESM system makes several important aspects of human decision-making endogenous to a climate model, but not all aspects by any means. To correct this lack of clarity, we have updated the description of GCAM found in the current manuscript.

2. Different human cultures make decisions in different ways and with different priorities and value systems. How can all of these possibly be accounted for? Are they even known? Is there any evidence that "global human decision making" exists?

Response: *We did not intend to imply that "global human decision-making" exists, but rather to ask the question whether changes in human decision making has important implications for climate at global scales. To clarify this, we have re-phrased the statement of our scientific goal as follows "*Will climate change itself affect human decision making and its implications for biogeochemical and biogeophysical processes at global scales?" *As discussed in response to point 1, it is not the case that state-of-the-art human system models assume that there is some global human decision maker. Models such as the Global Change Assessment Model (GCAM) employ disaggregated representations of decision-making in terms of sectors and regions (i.e., representative agents).*

3. The coupled human-climate approach in iESM needs to be validated based on historical events. For example, if iESM is run for the 20th century, is it able to simulate the Great Acceleration that started in the 1950s? This simulation represents an important test of the framework.

Response: *This is a very interesting question. As discussed above, the human system component of the iESM (GCAM) does not predict changes in population, technology, policy, or the overall level of affluence in a region as measured by GDP. However, given the changes in these quantities associated with the Great Acceleration, the model should be able to produce a reasonable estimate of the demands for and supplies of energy services and agricultural and forestry products by region and sub-sector. It should also be able to estimate the greenhouse gas emissions associated with this transition. Performing such "hind cast" experiments with integrated assessment models is a data intensive and relatively new area of pursuit (Chaturvedi et al., 2013; Calvin et al., In Prep), but definitely one that we wish to pursue with the iESM framework. Our current plan is to perform such a hindcast with and without climate feedbacks for the period 1970-present. However, this exercise is well beyond the scope of the current paper. We have section of the manuscript text discussing extensions to the current iESM implementation to indicate that such model validation exercises are possible within the iESM framework.*

4. If iESM is run for the past millennium, is it able to simulate the human land use land cover change that occurred across this period (e.g. such as in Pongratz et al., 2008)? If iESM is run on

longer Pleistocene timescales, it is able to simulate the flourishing of human civilization in the Holocene versus the previous InterGlacials?

Response: *See the responses above. iESM would not predict the flourishing of civilization, but it could, in principle, predict the energy and land-use implications of this flourishing given the inclusion of an appropriate set of technology options. This would be pushing the model well beyond the assumptions underlying its calibration, however.*

5. There exists controversy in the social science literature over the human response to water availability and the possibility of subsequent regional conflict. Some studies suggest that water availability may be a driver of violent conflict while other research does not support this phenomenon. How will iESM address such uncertainties in human climate linkages?

Response: *We agree that interactions between energy, water and land are high priorities for future work. The foundations for pursuing such questions exist in newer version of both GCAM and CLM. Furthermore, the extensible nature of the iESM framework could enable bi-directional exchanges of water management and water fluxes between these models in the future. The conclusions section of the current draft paper discusses several potential extensions to the current iESM implementation including extensions related to water resources.*

6. Do users need to hard-wire the system for their own particular research application? For example, if a user wanted to study the economic-energy system response to lower Manhattan and Florida being submerged in seawater, there are of course multiple possible human and society outcomes and responses, but how does GCAM decide the single global human response? And how do we know if it is 'right' and/or realistic?

Response: *As discussed above, the iESM framework does not avoid the need for careful selection of scenarios to support specific scientific experiments using the model. Many of the interesting applications of this framework will involve the specification of particular climate mitigation or adaptation policies. In this vein, the model does not predict how society would respond to the flooding of major metropolitan areas, but one could examine the energy, land-use, and emissions consequences of a particular response to flooding, assuming that the societal response to flooding could be rendered in terms of the scenario parameters used by GCAM, e.g. regional shifts in population, labor, and GDP.*

References

Calvin, KV., MA Wise, LE Clarke, GP Kyle, JA Edmonds (In Prep) "A Preliminary Hindcast Experiment Using the GCAM 3.0 Land-use Module" To be submitted to *Climate Change Economics* in June 2015.

Chaturvedi, V., S. Kim, S. J. Smith, L. Clarke, Z. Yuyu, P. Kyle, and P. Patel (2013), Model evaluation and hindcasting: An experiment with an integrated assessment model, *Energy*, *61*(0), 479-490, doi:http://dx.doi.org/10.1016/j.energy.2013.08.061.

Dixon, PB, MT Rimmer (2010), Validating a Detailed, Dynamic, CGE Model of the USA, The Economic

Record, 86, 22-34, doi: 10.1111/j.1475-4932.2010.00656.x.

Moss, Richard H., Jae A. Edmonds, Kathy A. Hibbard, Martin R. Manning, Steven K. Rose, Detlef P. Van Vuuren, Timothy R. Carter et al. "The next generation of scenarios for climate change research and assessment." Nature 463, no. 7282 (2010): 747-756.