Response to 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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"Higher-Level" suggestions

1. [Can] 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 be- tween 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?

Response: Given the changes in population, technology, policy, and levels of affluence as the regional level as measured by GDP, the human system component of the iESM (GCAM) 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 updated the discussion of future iESM model extensions to indicate that such model validation exercises are possible within the iESM framework.

2. 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.

Response: *Yes, we are conducting a future coupled simulation with feedbacks on crop productivity and biofuel feedstock production based on potential yield and carbon stores derived from the Community Land Model in the Community Earth System Model built into iESM. However, since these experiments are still underway, we would prefer to subject our provisional results to full peer review rather than exhibit these provisional results here.*

More specific comments:

1. I suggest the authors acknowledge some of the major uncertainties inherent in this modeling approach and point the reader to relevant literature discussing key issues.

These might include:

1. Is human/societal decision making sufficiently "logical" so that it can actually be simulated in some form of deterministic/mathematical manner?

Response: *GCAM represents market forces balancing production and consumption of critical energy, agricultural, and (recently) water resources via interactions between the global economic, energy, agricultural, land use and technology systems. It is a member of the class of dynamic-recursive market equilibrium models that are standard and widely used implementations of deterministic macro-economic laws of supply and demand. Please note that these details are covered in the references cited in the current version of the manuscript.*

2. 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?

Response: *While the equations governing the market dynamics are shared among regions, regional population and labor productivity growth assumptions drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. The scale of human activities is determined by the interaction between labor force, determined by work-aged population, labor participation and unemployment rate assumptions and the price of energy services. These assumptions are introduced via parameters, exogenous data (e.g., regionally-specific population projections), other boundary conditions, and initial conditions supplied as input to the GCAM code. Again, please note that these details are covered in the references cited in the current version of the manuscript.*

(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 modeled 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?

Response: *We concur that the geographic distribution of future climate threats will be highly inhomogeneous. The ESM serving as the foundation of iESM is designed to and has been demonstrated to accurately emulate the current distributions of climate forcings and impacts, and it contains advanced treatments of climate processes needed to forecast the evolution of these distributions as the climate warms further. In particular, the ESM treats the gradients among regions in forcing due to aerosols, land-use and land-cover change, and short-lived greenhouse gases. As discussed in response to "higher level suggestion" 1 above, evaluation of GCAM through hindcast experiments is an active area of research.*

(iv) Can this even be verified in the real world?

Response: *Multi-model projections of climate change were first systematically and comprehensively assessed starting with the First Assessment Report (FAR) of the IPCC released in 1990. Future projections documented starting with the FAR can therefore be evaluated against the actual evolution of the human and natural climate systems over the subsequent 25 years up to the present day. These evaluations are discussed in considerable detail in both the Fourth Assessment Report (AR4) and the AR5 released in 2007 and 2013, respectively, and cover (for example) the changes in surface air temperature with time (AR4) and the relationship between the increases in surface air temperature since preindustrial times and cumulative anthropogenic GHG emissions (AR5). GCAM simulations cover this same time period. The new hindcasting capabilities recently introduced in GCAM (see response to "higher level" suggestion #1 above) will enable more extensive studies of the regionalization of climate forcing, climate response, impacts on human systems, and feedbacks between natural and human systems.*

(v) 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.

Response: *The scenarios for IPCC AR5 included widely divergent projections for land-use and land-cover change (e.g., Lawrence et al, 2012, doi:10.1175/jcli-D-11-00256.1), and the scenarios used in the AR4 and AR5 have completely different scenarios for near-term emissions of anthropogenic aerosols with increasing (decreasing) emissions over the 21st century assumed for model simulations assessed in AR4 (AR5) (Gillett et al, 2013; Rotstayn et al, 2013). The climatic implications of these differences have been exhaustively documented in a series of single-forcing experiments and in the subsequent peer-reviewed literature evaluated in these two assessments, and appropriate citations to the IPCC AR's have been included in the current version of the manuscript.*

3. The paper highlights energy supply/demand. Is this the primary (or only) societal-climate coupling that is presently simulated?

Response: *The version of GCAM employed in this study solves for both the provision of energy and food sufficient to meet demand as described in section 3.2 on GCAM. The coupling in this first version of iESM centers on the land-use and land-cover change attendant on the development of cropped and harvested biofuel feedstock and on the growth of agricultural production to meet future food demands by a globally increasing population.*

(i) The authors mention future work on water availability etc., does this cover things like mass irrigation?

Response: *Yes, irrigation is considered as one of six major demand sectors (along with livestock, domestic, electricity generation, primary energy production, and manufacturing) are modeled by the new Global Water Availability Model (GWAM) in GCAM. Please see Hejazi et al (2014; doi:10.5194/hess-18-2859-2014) for details.*

(ii) Also is agriculture/food production considered?

Response: *Yes, the production of food and forest products sufficient to meet demand is part of the solution for the evolving state of the human system produced by GCAM as described in section 3.2.*

(iii) Likewise possible human responses in terms of land-cover (e.g. mass afforestation)?

Response: *Yes, the human response in the forms of land use and land-cover change in response to competing demands among energy and food supply and demand is part of the solution for the evolving state of the human system produced by GCAM as described in section 3.2.*

4. 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.

Response: *At the moment sea-level rise (SLR) is not included in the interactive climate-society response, but this omission is characteristic of Integrated Assessment Models (IAMs) in general and of the IAMs used to construct the Representative Concentration Pathways (RCPs) for the most recent Coupled Model Intercomparison Project version 5 (CMIP5) in particular. There are several reasons why this impact has been omitted to date stemming from limited modeling capabilities and rapidly evolving scientific understanding, including the omission of interactive land-ice sheets and glaciers from most Earth System Models (to date) and the huge uncertainties associated with the non-steric components of SLR as* *evidenced by the factor of three difference in central SLR estimates between the Fourth and Fifth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). Several ESMs, including the foundational ESM in iESM, will include active land-ice components for CMIP6 (scheduled for the 2017 time frame) and hence could in principle include SLR as an important impact on the human sector, including costs and risks associated with damage, outages, and risks to energy and water infrastructure located close to coasts.*

5. 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?

Response: *Time stepping is discussed explicitly in section 5.9. The only timestep mentioned for GCAM is given as 5 years and is consistently reported as such throughout the manuscript. The annual timestep applies to the updating of land-use/land-cover change information input into the Community Land Model.*

It also leads to a couple of questions:

1. Earth system change may lead to seasonally specific (climatological) responses, e.g. say a warmer and 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?

Response: *The interface between the climate model and the GCAM, which described in section 5.2, has been developed to be quite flexible and extensible with regards to the types of fields it can pass to GCAM and to the temporal sampling, accumulation, or averaging that is applied to each field. The temporal accumulation capability is used, for example, to compute the annual-mean scalars applied to crop yields and ecosystem carbon densities based on the Community Land Model's carbon cycle. These scalars reflect sub-annual interactions among crops and other vegetation with atmospheric and soil processes, typically resolved using a 30-minute timestep. The same interface could, with inputs of instantaneous precipitation and temperature, compute the annual frequency of extreme events including heat waves, long dry spells, downpours, and other hydrometeorological events that can easily stress human infrastructure and resource provision.*

2. 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?

Response: *Please see the answer to question (i) immediately above.*

3. And on a similar note, in the system I guess the regionally specific aspects of socio-economic 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?

Response: *Yes, the simulated climate changes influencing GCAM would be spatially averaged and interpolated to the regions utilized by GCAM as described in section 5.2 concerning the IAC2GCAM interface between the ECM and GCAM. We note that sub-annual and sub-regional processes are reflected in these averaged quantities.*

4. [Is it possible to conduct an] 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.

Response: *Please see our response to "higher-level" suggestion #1 (above).*

5. 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.

Response: *The reduced form climate model is the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), available from http://www.magicc.org. Quoting from this website, "MAGICC was originally developed by Tom Wigley (National Centre for Atmospheric Research, Boulder, US, and University of Adelaide, Australia) and Sarah Raper (Manchester Metropolitan University, UK) in the late 1980s and continuously developed since then. It has been one of the widely used climate models in various IPCC Assessment Reports. The latest version, MAGICC6, is co-developed by Malte Meinshausen (Potsdam Institute for Climate Impact Research, Germany, and the University of Melbourne, Australia). MAGICC has a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model."*

6. What fraction of the total model systems computational time is taken up by the human/societal part of the full model?

Response: *The timing data for the parent Earth System Model (ESM) is available at http://www.cesm.ucar.edu/models/cesm1.2/timing/. For a typical model configuration with 1-degree zonal resolutions for the atmosphere, land, ocean, and sea ice and with an active carbon/nitrogen cycle, the computation time for the non-human-system (i.e., natural Earth system) is 2657 processor hours per simulated year on the NCAR yellowstone supercomputer. The throughput of GCAM is approximately 0.25 processor hours per simulated century, or 0.0025 processor hours per simulated year, so the total time devoted to the human component of iESM is currently a factor of $O(10^{-6})$ times smaller than the natural Earth system component.*

(i) 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.

Response: *We have not yet done so, but the expensive ESM component supports and can be readily configured at lower resolution at will, and the interfaces between the human and ESM components are designed to be accommodate changes in ESM resolution in an automatic and transparent fashion during the configuration and compilation of the whole iESM code. The computational cost of the ESM component scales roughly like the inverse cube of the resolution expressed in degrees, so that the cost of the iESM at 2.5 degrees is approximately $1/(2.5)^3$=0.06 (6%) that of the 1 degree model and hence is much more affordable for ensemble calculations.*

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.