Geosci. Model Dev. Discuss., 7, C3425–C3437, 2015
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Geoscientific Model Development Discussions
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7, C3425–C3437, 2015

Interactive Comment

Interactive comment on "A simple object-oriented and open source model for scientific and policy analyses of the global carbon cycle – Hector v0.1" *by* C. A. Hartin et al.

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Received and published: 26 February 2015

General comments

I have two major concerns with the manuscript: 1) experiments to validate Hector are not well described, and 2) Hector appear to have issues at longer timescales that are not well described or acknowledged. I recommend the authors include additional material on the performed experiments and fidelity of Hector at different timescales. The manuscript also need significant cleanup of typos and grammatical errors, and could benefit from improvement of figures.

The authors have since restructured the results section to better describe the experimental design. All experiments are run under prescribed emissions scenarios from the Representative Concentration Pathways (RCP 2.6, 4.5, 6.0, and 8.5). However, the CMIP5 data used to compare with Hector are from prescribed concentration scenarios, with the exception of atmospheric [CO2]. We acknowledge that this may not be a perfect comparison, but the CMIP5 archive is limited in the number of models that ran scenarios with prescribed emissions.

As noted in the title, Hector is concerned with policy relevant timescales, notably the next 100-300 years. We agree with the reviewer that a more detailed explanation of the timescales is needed in the manuscript and have since updated this. "Hector's strengths lie within policy relevant time scales of decades to centuries. Studies suggest that 80% of the anthropogenic CO2 emissions have an average atmospheric lifetime of 300-450 years (Archer et al., 1997; Rogner, 1997; Archer, 2005). Hector has all the necessary components to model the climate system from present day through the next approximately 300 years."

Lastly, grammatical errors, and figures have been improved in the updated manuscript.

Specific comments

Title: The title of the paper does not appropriately describe the contents of this manuscript. The title suggests that this manuscript describes a global carbon cycle model, but Hector is a full climate model and the paper describes all the components of Hector. A better title might be something like, A simple object-oriented and open source model for scientific and policy analyses of the global climate system – Hector v0.1. I recommend that the authors revise the title to better reflect the overall contents of the paper.

The authors agree with the reviewer and have edited the title as suggested: "A simple object-oriented and open source model for scientific and policy analyses of the global climate system–Hector v1.0"

Introduction: The introduction is lacking a description of previous work in the field and needs to add citations and discuss the novelty of Hector. The authors properly describe the purpose of simple climate models, their general structure and implementation. But, the authors should cite previous simple climate models and explicitly explain why the design of Hector is novel. Relevant citations include but are not limited to Meinshausen et al. (2011), Joos et al. (2013), Glotter et al. (2014), and models described in van Vuuren et al. (2009) and Hof et al. (2011).

The authors have added significant changes to the introduction to better reflect the current state of simple climate modeling within Integrated Assessment Models.

“Depending on the purpose of the IAMs (economics, cost-benefit analysis, or more physical based processes), the corresponding climate and carbon component varies in complexity and resolution. For example, models like DICE, FUND, and MERGE have a highly simplified carbon/climate system (Nordhaus, 2008; Anthoff and Tol, 2014; Manne and Richels, 2005). IAMs focusing more on the physical processes of the natural system and the economy employ more complex representations of the climate/carbon system. Models like GCAM (Global Change Assessment Model) and MESSAGE use MAGICC as their SCM (Meinshausen et al., 2011a; Riahi et al., 2007; Calvin et al., 2011). Increasing in complexity, some IAMs include the climate/carbon system at gridded scales (e.g., IMAGE), and can be coupled to earth system models of intermediate complexity (e.g., MIT IGSM), or more recently coupled to a full earth system model (the iESM project) (Bouwman et al., 2006; Sokolov et al., 2005; Bond-Lamberty et al., 2014; Di Vittorio et al., 2014; Collins et al., 2015).”

Results: The experimental design for the tests performed in this manuscript are not well described. There remain several ambiguities in Section 5 that must be clarified so results can be properly assessed. In general, figure captions should be expanded to explain the experimental design used to make that display. The authors may find it beneficial to add a table that describes all experiments performed, including Hector’s configuration for each experiment, input data used to drive Hector, and the model out-

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put (or data) that Hector is compared to. Specific examples of ambiguities related to experimental design include:

For most figures, it remains unclear precisely when Hector is driven by an emissions scenario and when atmospheric carbon is prescribed. For example, is Figure 8 made using fixed exogenous CO2 concentrations or with emissions scenarios that reproduce RCPs? The authors should clarify when RCPs are used and when esmRCPs are used. An experimental design table (as described above) would help clarify here.

The authors have clarified this information in the text as well as in the figure caption. “All CMIP5 variables used in this study are from model runs with prescribed atmospheric concentrations, except for comparisons involving atmospheric [CO2] which are from the emissions driven scenario (esmHistorical and esmRCP8.5) (Figures 3 and 5). We acknowledge that this comparison, between an emissions-forced model (Hector) and concentration-forced models (CMIP5), is not perfect. However, few CMIP5 models were run under prescribed emissions scenarios.”

The paragraph on page 7081 (lines 4-16) that describes how atmospheric concentrations are prescribed needs to be re-written. If the model simply inverts concentrations to find emissions, it is not clear why the assumption in lines 14-15 is necessary. I am also not sure this statement would hold true for large perturbation scenarios, such as an instantaneous doubling (or more) of CO2. If this is how the authors perform the prescribed-CO2 experiments, it is vital that it be described carefully else results are not interpretable.

The paragraph on page 7081 explains some of the capabilities built into Hector to force its output to match a user-supplied time series. This is very helpful with testing and debugging the carbon cycle system within Hector. We do not invert concentrations to find emissions; instead for example, atmospheric CO2 concentrations are read into Hector and over write any calculated [CO2] values. The user-supplied time series can be started and stopped at any point. When the model exits the constrained time

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period, [CO2], in this case, becomes fully prognostic. We have updated the manuscript to better reflect this.

“Hector can be forced to match its output to a user-supplied time series. This is helpful to isolate and test different components. Available constraints currently include atmospheric CO2, global temperature anomaly, total ocean-atmosphere carbon exchange, total land-atmosphere carbon exchange, and total radiative forcing.”

Which “historical conditions” are used to run Hector (page 7089, lines 17-18)?

The text containing ‘historical conditions’ has been rewritten to better reflect the inputs use to run Hector in this study.

“Within this study, Hector is run with prescribed emissions from 1850 to 2300 under all four Representative Concentration Pathways (RCPs), freely available at http://tntcat.iiasa.ac.at/RcpDb/”

Which models run esmRCP8.5 (page 7090, lines 11-12)? Are these different than the 11 CMIP5 models?

The authors have updated table 3 within the manuscript to reflect the models that ran esmHistorical and esmrcp85 (emissions prescribed scenarios).

RCPs (by definition) are CO2 concentration pathways. What does it mean for atmospheric CO2 in Hector to be highly correlated with MAGICC for the four RCPs (Page 7091, lines 23-27)? Shouldn’t the definition of an RCP necessitate identical concentration pathways? This confusion also applies to figures 5-6, and is likely related to the confusion described in the second bullet. Please clarify.

The authors apologize for the confusion on the wording of RCPs and how they relate to the Hector output. We have clarified this issue in section 5.0 below: “RCPs by definition are concentration pathways; however, for all experiments within this manuscript we use the corresponding emissions trajectories from each RCP as input for Hector.”

I disagree with the statements at the beginning of section 6.2. It is incorrect that models that accurately estimate historical climate are simply "assumed" to be reliable for future scenarios. The credibility of Hector in making future projections of the climate should not be based solely on the fact that it can reproduce historical trends. In fact, we see that Hector has problems at long timescales (where short timescales are more accurate– Figures 8 and 10), and even some errors appear in the historical record itself (Figure 4). The authors must re-write this paragraph, but more importantly, must be explicit about issues with the use of Hector over long timescales. There are issues with the fidelity of Hector at different timescales that are not acknowledged or described. Hector does not include the dissolution of calcium carbonate in its representation of the carbon cycle (to my knowledge) and therefore will not be dependable past _2000 years. But I do not know whether Hector is dependable up to 2000 years. Potential users of Hector would benefit greatly from a dedicated discussion of its usefulness at different timescales. Specific concerns with the fidelity of Hector include:

The authors fully agree with the reviewer that accurately simulating historical conditions does not thereby make them reliable for future scenarios. We also agree with the reviewer that a discussion of the timescales in which Hector is useful over is needed within the manuscript (section 6.2). "We compare Hector to MAGICC and CMIP5 under differing future climate projections. Hector's strengths lie within policy relevant time scales of decades to centuries. Studies suggest that 80% of the anthropogenic CO2 emissions have an average atmospheric lifetime of 300-450 years (Archer et al., 1997; Rogner, 1997; Archer, 2005). Hector has all the necessary components to model the climate system from present day through the next approximately 300 years."

Hector is unable to reproduce 1970-2010 temperatures (Fig 4). These errors should be described in the text, including possible explanations linked to underlying physics.

We have addressed and fixed the high temperature sensitivity after 1960 by including a variable ocean heat flux, as well as lagging the temperature effects from atmospheric [CO2]. There are numerous processes that are not simulated in Hector that buffer the temperature effects of increasing GHGs. Therefore, we take a simple approach in this current version and lag our temperature. We have addressed this in the manuscript section 4.1, “As global temperatures rise, the uptake capacity of the ocean thus diminishes, simulating both a saturation of heat in the surface and a slowdown in ocean circulation with increased temperatures. Finally, the temperature effects from atmospheric [CO2] are lagged in time, as there are numerous real-world processes not simulated in Hector buffering the temperature effects of increasing atmospheric [CO2].” See figures 4 and 8 for updated global temperature change.

Atmospheric CO2 concentrations in figure 5 are only shown from 1850-2100. Is there a reason why this plot isn't extended to 2300 like figures 6-11? If model errors are prevalent from 2100-2300, it is essential that this plot show the entire time range.

The CMIP5 archive of models that ran esmrcp85, do not run out to 2300. Therefore, we can only compare out to 2100. The caption for Figure 5 has been updated: “Figure 5: Atmospheric [CO2] from 1850 to 2100 under RCP 8.5 for Hector (blue), MAGICC6 (green), Mauna Loa (purple), Law Dome (brown) and esmRCP 8.5 (prescribed emissions scenario) CMIP5 median, one standard deviation and model range (pink, n=4 (1850-2000) and n=5 (2001-2100)). Note that the CMIP5 models run under esmrcp85 do not extend to 2300.”

Hector also appears unable to reproduce temperatures in CMIP5 models past year 2100 (Fig 8). This misrepresentation is downplayed in the text (page 7092, lines 11-20). It is not sufficient to simple state that errors are negligible because correlations are high. It is unclear whether this is an error in the temperature or the carbon cycle model of Hector because the experiment is not well described. Please clarify.

Since fixing the temperature problem post 1960s, Hector is now closer to the CMIP5 median post 2100, than MAGICC6 is. Post 2100, Hector remains within the standard deviation of the CMIP5 models. We have included in the figure captions, the numbers of models for each scenario, for each time period. Post 2100, the number of model

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run out to 2300 drops off dramatically, which could be responsible for some of the differences between the CMIP5 median and Hector.

The authors do a nice job highlighting deviations in the atmosphere-ocean flux in Hector from CMIP5 models after _2100 (Fig 10). However, these deviations do not seem trivial, and may impact long-term projections. If Hector cannot be trusted after _2100, this should be stated. Until a later version of Hector is released with an updated modeling approach, the authors should acknowledge these issues and should add discussion on the physical causes that may produce deviations from observations (or more complex models). The authors do include some discussion of the underlying physics at the end of section 6, but more should be included throughout the manuscript.

The authors agree with the reviewer and have since updated section 6.2 with more detail: "Hector's calculation of air-sea fluxes is within the large CMIP5 model range up to 2100. However, after that Hector peaks close to 2150, while the CMIP5 models are beginning to decline. One potential reason for this discrepancy after 2100 is that in this version of Hector, we do not simulate changes in ocean circulation, potentially biasing fluxes too high after 2100. Most ESMs in CMIP5 show a weakening of the Atlantic meridional overturning circulation by 2100 between 15% and 60% under RCP 8.5 (Cheng et al., 2013). A slowdown in ocean circulation may result in less carbon uptake by the oceans, as seen in Figure 9. Another potential reason for this bias is Hector's constant pole to equator ocean temperature gradient. Studies show that the Artic is warming faster than the rest of the globe (e.g., Bintanja and van der Linden, 2013; Holland and Bitz, 2003; Bekryaev et al., 2010). A warmer high latitude surface ocean in Hector would suppress the uptake of carbon, potentially contributing to higher air-sea fluxes after 2100."

Technical corrections - figures and tables All figures: Figure text is too small.

Figure fonts and line size have been enlarged for all figures.

Figure 2: Describe (in caption or key) the definitions of variables TT , EIL, EID, etc. A

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reference to Table 2 has been included in the figure caption.

Figures 3-5, and 8: use consistent colors for models across figures. It is very hard to compare across figures when Hector output is shown as yellow in one plot and green in another.

The authors agree with the reviewer and have updated all figures to have the same color scheme.

Figure 8: Label panels a, b, c, and d.

Figure 8 has been updated.

Tables 1 and 2: Include references for initial condition values where applicable. For example, the recent IPCC estimates a pre-industrial total oceanic carbon content of _38,000 GtC. Numbers here are closer to 35,000 GtC. This difference is not likely significant for Hector, but my confidence in the model would be higher with references to justify these numbers.

The authors agree with the reviewer and have added references for initial values where applicable in Table 1 & 2.

Technical corrections - text (Note that I did not provide comments for sections 4.2.1-4.2.6, and suggest a different reader with expertise in this area to review this material.) Page 7077, line 5: #4 (modeling the carbon cycle) seems a subset of #1 (calculating future concentrations of greenhouse gases). Either remove #4 or move it up as an explicit subset of #1 (or explain what is meant, if I am missing something). The order should reflect the general order of operations in an SCM.

Sentence edited as suggested: "Most SCMs have a few key features: 1) calculating future concentrations of greenhouse gases (GHGs) from given emissions while modeling the global carbon cycle; 2) calculating global mean radiative forcing from greenhouse gas concentrations; and 3) converting the radiative forcing to global mean temperature (e.g., Wigley, 1991; Meinshausen et al., 2011a; Tanaka et al., 2007b; Lenton, 2000)."

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Page 7077, line 7: Recommend changing the word "policy" to "decision making".

Sentence edited as suggested: "With these capabilities, SCMs play an integral role in decision making and scientific research."

Page 7077, lines 12-13: Recommend changing "have a simple representation" to "rely on simple representations".

Sentence edited as suggested: "Therefore, all IAMs rely on a simple representation of the global climate system."

Page 7077, lines 24-27: Consider re-writing the first sentence of this paragraph. There is also a grammatical error in this sentence: "therefore are used for run multiple simulations of future climate change. . ."

Sentence edited as suggested: "Lastly, SCMs are computationally efficient and inexpensive to run. Therefore, they are used to run multiple simulations of future climate change emissions scenarios, parameter sensitivity experiments, perturbed physics experiments, large ensemble runs, and uncertainty analyses (Senior and Mitchell, 2000; Hoffert et al., 1980; Harvey and Schneider, 1985; Ricciuto et al., 2008; Sriver et al., 2012; Irvine et al., 2012)."

Page 7077, line 29: Please be more specific with wording choice for "fast enough".

Sentence edited as suggested: "Lastly, SCMs are computationally efficient and inexpensive to run."

Page 7078, line 5: "This study introduces Hector v0.1, an object-oriented, simple. . ."

Sentence edited as suggested: "This study introduces Hector v1.0, an object-oriented, simple. . ."

Page 7078, line 11: Consider changing the word "basic" to "fundamental".

Sentence edited as suggested: "One of the fundamental questions faced in developing a SCM is how much detail should be represented in the climate system."

Page 7082, line 19: typo– "-political" Formatting issues with a '-' have been corrected.

Page 7083, line 6: typo– "NPP is modified by a the use-specified. . ." Formatting issues with a '-' have been corrected.

Page 7083, line 7: Does (or can) beta change with time or temperature? If parameter is fixed, state that explicitly.

No, beta (the shape of the NPP response to CO2 fertilization) doesn't change with time. It does, optionally, change spatially: users can define separate beta values for different biomes, for example. "These are commonly used formulations: NPP is modified by a user-specified carbon fertilization parameter, β (Piao et al., 2013), that is constant in time but not necessarily in space. For example, users can define separate β values for different biomes."

Page 7083, line 14: Do you mean Eqs. (7)-(9)? Correct if this is a typo.

The authors corrected this typo.

Page 7083, eqs 7-9: Explicitly define all terms and/or refer to Table 1. Terms do not match those in Table 1 (e.g. FLC).

The authors have corrected this.

Page 7084, lines 10-12: This assumption is essentially a statement of fixed equator-pole temperature gradient. But when the Earth warms, the poles tend to warm more than the equator. This assumption should be discussed explicitly, including under what conditions it would affect the performance of Hector

Within Hector it is assumed a fixed equator-pole temperature gradient in sea surface temperature. While this may not hold under future warming scenarios, v1.0 of Hector is a simple representation of the climate system and this change in temperature gradient is a major future improvement to the model. A warmer high latitude ocean will poten-

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tially result in less CO_2 uptake in the high latitude ocean. “We assume a constant pole to equator temperature gradient, but acknowledge that this assumption may not hold true if the poles warm faster than the equator.”

Page 7084, lines 21-23: Carbon cycle description (section 3 up to 3.1) is incomplete. Presumably the model includes the non-linear effects in oceanic carbon uptake from changing ocean acidity as atmospheric carbon is transferred to the upper ocean, but these are not described. The relevant equations should be included here. Some discussion comes later on page 7093, but the pH dependence is not well described.

This has been addressed under section 3.0: “We model the nonlinearity of the inorganic carbon cycle, calculating pCO_2, pH, and carbonate saturations based on equations from Zeebe and Wolf-Gladrow, (2001). The flux of CO_2 for each box i is calculated by: $F_i(t) = k\,\alpha\,\Delta pCO_2$ (11) where k is the CO_2 gas-transfer velocity, α is the solubility of CO_2 in water based on salinity, temperature, and pressure, and ΔpCO_2 is the atmosphere-ocean gradient of pCO_2 (Takahashi et al., 2009). The calculation of pCO_2 in each surface box is based on the concentration of CO_2 in the ocean and its solubility (a function of temperature, salinity, and pressure).”

Page 7089, line 17: Please be more specific with “other models”. Do the authors mean more complex models? Or widely used models? Or both? Sentence edited as suggested: “A critical test of Hector’s performance is to compare the major climatic variables calculated in Hector, e.g., atmospheric [CO_2], radiative forcing, and atmospheric temperature, to observational records and both simple and complex climate models. ”

Page 7090, line 8: Spell out “SD”.

Sentence edited as suggested: “standard deviation”

Page 7090, line 24: Remove words “a few”.

Sentence edited as suggested: removed “a few”

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Page 7090, line 25-26: Consider re-wording sentence.

Sentence edited as suggested: "After spinup is complete in Hector, atmospheric [CO2] in 1850 is 286.0 ppmv, which compares well with observations from Law Dome of 285.2 ppmv."

Page 7091, line 19: Is Hector actually perfectly correlated here, or is R=1.0 from rounding? Please double check.

The authors have since removed the correlation values from the manuscript. We have replaced them with absolute changes over given time periods. We feel that this is a better comparison between all the models, than correlation. 2 models can be well correlated, but that does not necessarily suggest that they are in agreement.

Page 7092, line 23: Grammatical error – "the higher the correlation and low RMSE between CMIP5 and : : :". Presumably what is intended is "the lower the RMSE".

The authors have since removed figure 9 from the manuscript as well.

Page 7093, line 23: Change "see" to "estimate".

Sentence edited as suggested: "We estimate a significant drop in pH from present day through 2100."

Interactive comment on Geosci. Model Dev. Discuss., 7, 7075, 2014.