Authors response to interactive comments on "Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement efficacy of low-carbon technologies" *by* K. B. Z. Ogutu et al.

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We thank the Referee #2 for her/his comments and respond to them herewith. In the following, the referee's comments are in italics, our responses are in Roman, and the changes to be made in the manuscript are in bold. Unless otherwise stated, sections, equations, figures, page numbers, and line numbers referred to are those of the original manuscript.

Overall assessment

CoCEB model is an Integrated Assessment Model (IAM) focusing on interactions between economic growth and climate. It is a simplified (less variables and parameters) and highly transparent version of the DICE model, using an endogenous growth model with physical and human capital accumulation. CoCEB model is applied to evaluate investments in emission abatement.

CoCEB-model provides a simplified and innovative perspective on the DICE model especially by examining the growth effects. In contrast to other IAMs – mainly DICE -, CoCEB-model does not perceive abatement only as costs, but acknowledges its contribution to increasing energy efficiency. In CoCEB savings rate is kept constant and so the model's predictions are of a limited explanatory power. Because the overall outcomes of the model are highly sensitive to the choice of the parameter values, it is essential to provide full intuition of the choice of parameter values. The major contribution, however, is to emphasize growth effects due to the endogenous growth model.

We thank the referee for the encouraging assessment. As s/he correctly points out, because the overall outcomes of the model are highly sensitive to the choice of the parameter values, we do hopefully provide, in the responses below, further intuitive insight into the choice of parameter values. However, we would like to add that the sensitivity to the choice of parameters is in fact a key result of the paper, as stated in section 4 and in the conclusions. The point is that, in more complicated and less transparent IAMs, no such sensitivity analyses have been carried out, because of the greater computational cost involved or because of the generalized-equilibrium, cost-benefit outlook.

Our choices of parameters are reasonable and justified, but we also analyze which of these parameters are critical, and point to the uncertainties that need to be addressed. Moreover, this work tries to go beyond the choice of parameter values — about some of which there is currently very little relevant empirical evidence — to consider a simplified and innovative perspective on the DICE model, especially by examining the growth effects. Nevertheless, we do not pretend to improve the DICE model in this respect, just to simplify it. Such simplifications allow us: (i) to carry out an extensive sensitivity analysis in this paper; and (ii) to include further processes in Part 2.

Major comments

1. The focus on the impacts of climate change on growth is important. The chosen model is, however, basically an AK endogenous growth model (see Barro and Salai-Martin 2004, Chapter 4). The authors should emphasize this and link their model stronger to other works that aim to include endogenous growth effects besides Moyer et al, e.g. the recent paper by Dietz & Stern 2015.

Thank you for the comment. In the answer below, we emphasize the fact that the economic component of CoCEB is basically an *AK* endogenous growth model. We also link our model stronger to other works that aim to include endogenous growth effects. To do this, we add the following in Sect. 2.4, after line 5, page 8.

Moreover, recent studies argue that the DICE framework supports strong controls on emissions if its restrictive assumptions about growth, damage and climate risk are relaxed. These assumptions arguably lead to gross underestimation of the overall scale of the risks from unmanaged climate change in DICE and other IAMs (Stern, 2013); see also the further discussion in Sect. 5.2 below. This paper basically considers a so-called *AK* model (Aghion and Howitt, 1999, Ch. 1), with *K* being "broad capital": privately held machines, human capital, public infrastructure, and possibly energy use. It is an endogenous growth model, in which the damage from climate change affects the long-run growth, not just current output; see also Barro and Salai-Martin (2004, Ch. 4), and Dietz and Stern (2015). In fact, the study relaxes the assumption that the underlying drivers of economic growth — notably human capital — are exogenous or implicit and unaffected by climate change; see also Greiner and Semmler (2008).

We have also added the following references to the paper's bibliography:

Aghion, P. and Howitt, P.: Endogenous Growth Theory, MIT Press, Cambridge, Massachusetts, London, England, UK, 694 pp., 1999.

Barro, R. J. and Sala-i-Martin, X.: Economic Growth, 2nd Edn., MIT Press, Cambridge, Massachusetts, London, England, UK, 673 pp., 2004.

Burke, M., Hsiang, S., and Miguel, E.: Global non-linear effect of temperature on economic production, Nature, 527, 235–239, 2015.

Dietz, S. and Stern, N.: Endogenous growth, convexity of damage and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions, Econ. J., 125, 574–620, 2015.

2. The chosen model framework assumes a constant savings rate rather than an endogenous savings rate based on intertemporal welfare optimization. The authors should provide a justification for this because the savings rate is an important determinant of the long-run economic growth (and so carbon emissions). Fankhauser & Tol (2005) and Edenhofer & Kalkuhl (2016) discuss the role of endogenous savings rate for assessing climate damages.

The referee is quite correct. The growth model presented in this study is not an optimizing model in the generalized-equilibrium sense: the consumption, and hence savings, is fixed and is not determined by a decision of the consumers or the firms — i.e. we neglect effects resulting from different preferences (see lines 1–4, p. 5). Therefore, we note that the size and growth of GDP change as a result of changing the abatement share τ_b. The consequences of neglecting effects resulting from different preferences may partly be addressed by models with overlapping generations of individuals, each of whom lives a finite number of years (e.g., McCandless, 2008, and references therein). Including such savings decisions, however, is beyond the scope of this study and will be the object of future work.

To clarify matters further, we rewrite the pertinent paragraph on page 5 as follows:

Note, furthermore, that the growth model presented in this study is not an optimizing model in the generalized-equilibrium sense and we take, as a starting point, the Solow–Swan approach (Solow, 1956; Swan, 1956; Greiner and Semmler, 2008), in which the shares of consumption and savings are given. We do this because we want to focus on effects resulting from climate change, which affect production as modeled in Eqs. (3)–(10) and, therefore, neglect effects that result from different preferences. The consequences of this assumption may be addressed by models with

overlapping generations of individuals, each of which lives a finite number of years (e.g., McCandless, 2008, and references therein). Including such savings decisions, however, is beyond the scope of this study and is left as a worthwhile line of future work; see also Fankhauser and Tol (2005) and Kalkuhl and Edenhofer (2016), who discuss the role of an endogenous savings rate for assessing climate damages. Our model's macroeconomic production function only considers per capita […]

We have also added the following references to the paper's bibliography:

Fankhauser, S., and Tol, S. J. R.: On climate change and economic growth, Resour. Energy Econ., 27, 1–17, 2005.

Kalkuhl, M., & Edenhofer, O.: Knowing the damages is not enough: The general equilibrium impacts of climate change, CESifo Working Paper No. 5862, 2016.

McCandless, G.: The ABCs of RBCs: An Introduction to Dynamic Macroeconomic Models, Harvard University Press, Cambridge, UK, 448 pp., 2008.

3. Provide intuition for value of the coefficient $nchi=2.43$ used in the damage function. Why should the outcomes micmic RCP8.5 (as stated on the p.8)?

It is an *ad hoc* value deliberately chosen in order to produce a BAU output. The value of the damage function exponent is not known. In fact, the choice of the parameter $\chi > 0$ in the literature is ad hoc and based on "informed guesses" (Peck and Teisberg, 1994). In our case, we estimate — by trial and error — an *ad hoc* value, so that our model's BAU emissions of CO_2 yr^{-1} and concentrations by 2100 mimic the Representative Concentration Pathway (RCP) 8.5. Our approach is motivated by Burke et al.'s (2015, Fig. 5a and Extended Data Table 3) study, in which unmitigated warming is expected to reshape the global economy by reducing average global per capita incomes roughly 26 % — or more — by 2100.

To clarify matters further, we have rewritten the sentence starting on line 36, page 7, as:

On the other hand, we calibrated the exponent $\chi = 2.43$ so that our model's BAU emissions of CO_2 yr^{-1} and concentrations by 2100 mimic the Representative Concentration Pathway (RCP) 8.5 (…); see Sect. 4.1 for details on calibrating χ. Our approach is motivated by Burke et al.'s (2015, Fig. 5a and Extended Data Table 3) study, in which unmitigated warming is expected to reshape the global

economy by reducing average global per capita incomes roughly 26 %, or even more, by 2100. In fact, our projected climate change damages before and after abatement…

We have also added the following reference to the paper's bibliography:

Burke, M., Hsiang, S., and Miguel, E.: Global non-linear effect of temperature on economic production, Nature, 527, 235–239, 2015.

4. Provide a better explanation and justification for the choice of the abatement efficiency parameter $nalpha_ntau=1.8$. On page 8, it is chosen to achieve a certain emission path it should, however, depend only on actual abatement costs (while the choice of $ntau_b$ depends on the achievement of a specific abatement path.

To remove any ambiguity, we have rewritten the sentence on line 35, page 8, as:

Next, we choose the abatement efficiency parameter $\alpha_\tau = 1.8$ such that a reduction of 50 % in carbon emissions from BAU — for the scenario corresponding to $\tau_b = 0.075$ — costs 1.5 % of GDP by 2050. This abatement cost is in the range used by recent IAMs in the literature; see, for instance, Tol (2010) and Den Bergh (2015).

Minor comments
5. An important innovation of the CoCEB model is the examination of the feedback effects between economic growth and climate. This, as well as the strong relation to the DICE model should be stressed in the abstract.

This is a good suggestion, thank you. Now the abstract reads as follows:

In the present Part 1 of a two-part paper, we formulate and study a simple Coupled Climate–Economy Biosphere (CoCEB) model. This highly idealized model constitutes the basis of our integrated assessment approach to understanding the various feedbacks involved in the system. **CoCEB relies on recent versions of the Dynamic Integrated model of Climate and the Economy (DICE) model but innovates by taking into account the mutual feedback effects between climate and economic growth.** CoCEB is composed of a physical climate module, […]

6. Since the model is expressed in per capita terms (e. g. equation (3), (4) etc.), do not use capitals.

We just adopted the notation as used in Greiner and Semmler (2008): aggregate variables are indicated as capitals with a bar on top, while per capita variables are denoted by capitals; see, for instance, our Eq. (11). We think it is more understandable this way. Furthermore, using a lower case *k* for per capita physical capital will confuse the reader because *k* is also used to denote the per capita ratio (physical capital)/(human capital). We prefer keeping this notation, but if the editor insists we are willing to change it.

7. When explaining a formula, explain single variables in sequence (e. g. equation (1)).

Thank you. Done.

8. When describing the results provided in the tables and figures, always refer to the figure/ table, the values are taken from.

Done

9. It is several times referred to the outcomes of RCP2.6. For better overview, provide the values of outcomes in table 4.

Done

10. On p.9 outcomes presented in table 2 are compared to the outcomes from RCP6.0 RCP4.5, RCP2.6. For better overview, include a table with outcomes of the RCP scenarios.

Done

11. There are several other integrated assessment models that aim to better represent mitigation options and the benefits of increased energy efficiency or the use of backstop technologies. Examples include Edenhofer et al. (2005), Grimaud et al. (2011), Kalkuhl et al. (2012;2015), Kverndokk & Rosendahl (2007), Popp (2004; 2006)

We include this suggestion in Section 2.5 and the mentioned references in the paper's bibliography. Thus the following is added after line 11, page 8:

In fact, there are several IAMs that aim to better represent mitigation options and the benefits of increased energy efficiency or the use of backstop technologies. Examples include Edenhofer et al. (2005), Grimaud et al. (2011), Kalkuhl et al. (2012; 2015), Kverndokk and Rosendahl (2007), and Popp (2004; 2006).

We have also added the following references to the paper's bibliography:

Edenhofer, O., Bauer, N., and Kriegler, E.: The impact of technological change on climate protection and welfare: Insights from the model MIND, Ecol. Econ., 54, 277–292, 2005.

Grimaud, A., Lafforgue, G., and Magné, B.: Climate change mitigation options and directed technical change: A decentralized equilibrium analysis, Resour. Energy Econ., 33, 938–962, 2011.

Kalkuhl, M., Edenhofer, O., and Lessmann, K.: Learning or lock-in: Optimal technology policies to support mitigation, Resour. Energy Econ., 34, 1–23, 2012.

Kalkuhl, M., Edenhofer, O., and Lessmann, K.: The role of carbon capture and sequestration policies for climate change mitigation, Environmental and Resource Economics, 60, 55–80, 2015.

Kverndokk, S. and Rosendahl, K. E.: Climate policies and learning by doing: Impacts and timing of technology subsidies, Resour. Energy Econ., 29, 58–82, 2007.

Popp, D.: ENTICE: Endogenous technological change in the dice model of global warming, J. Environ. Econ. Manag., 48, 742–768, 2004.

Popp, D.: ENTICE-BR: The effects of backstop technology R&D on climate policy models, Energ. Econ., 28, 188–222, 2006.

We have furthermore added the following references to the Bibliography:

Aghion, P. and Howitt, P.: Endogenous Growth Theory, MIT Press, Cambridge, Massachusetts, London, England, UK, 694 pp., 1999.

Barro, R. J. and Sala-i-Martin, X.: Economic Growth, 2nd Edn., MIT Press, Cambridge, Massachusetts, London, England, UK, 673 pp., 2004.

Burke, M., Hsiang, S., and Miguel, E.: Global non-linear effect of temperature on economic production, Nature, 527, 235–239, 2015.

Dietz, S. and Stern, N.: Endogenous growth, convexity of damage and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions, Econ. J., 125, 574–620, 2015.

Edenhofer, O., Bauer, N., and Kriegler, E.: The impact of technological change on climate protection and welfare: Insights from the model MIND, Ecol. Econ., 54, 277–292, 2005.

Fankhauser, S., and Tol, S. J. R.: On climate change and economic growth, Resour. Energy Econ., 27, 1–17, 2005.

Greiner, A. and Semmler, W.: The Global Environment, Natural Resources and Economic Growth, Oxford University Press, New York, NY, USA, 219 pp., 2008.

Grimaud, A., Lafforgue, G., and Magné, B.: Climate change mitigation options and directed technical change: A decentralized equilibrium analysis, Resour. Energy Econ., 33, 938–962, 2011.

Kalkuhl, M., Edenhofer, O., and Lessmann, K.: Learning or lock-in: Optimal technology policies to support mitigation, Resour. Energy Econ., 34, 1–23, 2012.

Kalkuhl, M., Edenhofer, O., and Lessmann, K.: The role of carbon capture and sequestration policies for climate change mitigation, Environmental and Resource Economics, 60, 55–80, 2015.

Kalkuhl, M., and Edenhofer, O.: Knowing the damages is not enough: The general equilibrium impacts of climate change, CESifo Working Paper No. 5862, 2016.

Kverndokk, S. and Rosendahl, K. E.: Climate policies and learning by doing: Impacts and timing of technology subsidies, Resour. Energy Econ., 29, 58–82, 2007.

McCandless, G.: The ABCs of RBCs: An Introduction to Dynamic Macroeconomic Models, Harvard University Press, Cambridge, UK, 448 pp., 2008.

Peck, S. C. and Teisberg, T. J.: Optimal carbon emissions trajectories when damages depend on the rate or level of global warming, Climatic Change, 28, 289–314, 1994.

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Popp, D.: ENTICE-BR: The effects of backstop technology R&D on climate policy models, Energ. Econ., 28, 188–222, 2006.

Stern, N. H.: The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models, J. Econ. Lit., 51, 838–859, 2013.

Tol, S. J. R.: Carbon dioxide mitigation, in: Smart Solutions to Climate Change – Comparing Costs and Benefits, edited by: Lomborg, B., Cambridge University Press, New York, NY, USA, pp. 74–105, 2010.

Van Den Bergh, J. C. J. M.: Safe climate policy is affordable: 12 reasons, in: Climate Change Mitigation: Greenhouse Gas Reduction and Biochemicals, edited by: Albanese, J. A. F. and Ruiz, M. P., Apple Academic Press, Oakville, Canada, pp. 299–357, 2015.