Professor Hermann Held
Editor, *Earth System Dynamics*
Copernicus Publications

Resubmitted manuscript: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement efficacy of low-carbon technologies, Earth Syst. Dynam. Discuss., doi:10.5194/esd-2016-64, in review, 2017

Authors: Ogutu et al.

Dear Professor Held,

Subject: Changes made in the re-revised manuscript

Thank you for your comments to the authors dated 09/01/2017. We are happy that our resubmitted manuscript has been accepted for publication in *Earth System Dynamics Discussions* and hope that it will finally be accepted in *Earth System Dynamics.*

In your comments, you requested we supply you with a PDF that would explicate any changes we undertook as against the comments raised by the reviewers and you, as well as our response, to a previous manuscript with id: esdd-6-819-2015, titled: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement share and investment in low-carbon technologies.

Based on the instructions, find enclosed the changes as made in the re-revised manuscript: **Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement efficacy of low-carbon technologies.**

Hoping that we will not be repeating ourselves, we will also attach our reply to the reviewers of ms. esdd-6-819-2015 as Appendix A; and the originally submitted ms. esdd-6-819-2015 as Appendix B.

We would like to take this opportunity to once more express our sincere thanks and acknowledge the reviewers' thoughtful and constructive comments and suggestions, together with your own; they have contributed immensely to the improvement of the current manuscript.

Sincerely Yours,

Keroboto B.Z. Ogutu

Cc: F. D'Andrea, M. Ghil & C. Nyandwi

Changes as made in the re-revised manuscript: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement efficacy of low-carbon technologies.

In the following, each referee's and editor's comments are in *italics*, our responses are in Roman, and the changes made in the current re-submitted manuscript (hereafter ms. doi:10.5194/esd-2016-64) are in **bold — and as reflected by the red marked parts of our new ms. doi:10.5194/esd-2016-64**. Unless otherwise stated, sections, equations, figures, page numbers, and line numbers referred to are those of the original previous manuscript with id: esdd-6-819-2015, titled: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement share and investment in low-carbon technologies (hereafter ms. esdd-6-819-2015).

Referee #1:

1. *The paper is unclear about the main innovation and the main new findings. The paper states: "Figure 1e is the key result" (p. 838. L. 4). However, this is a well published and also seems to be an intuitively obvious effect. Abatement in a DICE type setup causes near-term costs and long-term benefits.*

To remove any ambiguity, the abstract of our new ms. doi:10.5194/esd-2016-64 is rewritten as:

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 is composed of a physical climate module, based on Earth's energy balance, and an economy module that uses endogenous economic growth with physical and human capital accumulation. We concentrate on the interactions between the two subsystems: the effect of climate on the economy, via damage functions, and the effect of the economy on climate, via control of greenhouse gas emissions. Simple functional forms of the relation between the two subsystems permit simple interpretations of the coupled effects. The CoCEB model is used to evaluate hypotheses on the long-term effect of investment in emission abatement, and on the comparative efficacy of different approaches to abatement. In this paper, we consider investments in low-carbon technologies. Carbon capture and storage (CCS), along with deforestation reduction, will be dealt with in Part 2. The CoCEB model is highly flexible and transparent; as such, it allows one to easily formulate and compare different functional representations of climate change mitigation policies. Using different mitigation measures and their cost estimates, as found in the literature, one is able to compare these measures in a coherent way. While many studies in the climate–economic literature treat abatement costs merely as an unproductive loss of income, this paper shows that mitigation costs do slow down economic growth over the next few decades, but only up to the mid-21st century or even earlier; growth reduction is compensated later on by having avoided negative impacts of climate change on the economy.

Also we rewrite the paragraph in lines 23-29 on page 824 of (the originally submitted) ms. esdd-6-819-2015 as:

Various climate change mitigation measures have been considered heretofore. **Still, many IAMs in the contribution of Working Group 3 to the Fifth Assessment Report of the IPCC (Clarke et al., 2014)** treat abatement costs merely as an unproductive loss of income **(Edenhofer et al., 2015; Stoknes, 2015, p. 59) and conclude that limiting total human-induced warming to less than 2 °C can be achieved by carbon emissions reductions and establishment of a low-carbon economy on their own; see also Edmonds et al. (2013), Wasdell (2015), DDPP (2015), and Rogelj et al. (2015, Table 1).** Our CoCEB model innovates in (i) making emissions depend on economic growth; and (ii) treating investment in abatement not as a pure loss but as a way to increase the overall energy efficiency of the economy and decrease the overall carbon intensity of the energy system.

Our study will also point to the fact that investment in low- and zero-carbon technologies alone is a necessary (Kriegler et al., 2014, and references therein) but not sufficient step towards global climate stabilization: no matter how fast CO_2 emissions are reduced, the 2 °C target will still be violated; see also Held et al. (2009), Pielke (2010), Scott (2014, p. 21), Akaev (2015) and Wasdell (2015). The inability of low- and zero-carbon technologies alone to produce effective climate change mitigation may partly be attributed to the warming from the carbon stock already in the atmosphere (e.g., Held et al., 2009; Steffen, 2012; Wasdell, 2015) and the "rebound effect" (Jevon's paradox) whereby gains in efficiency are offset by increased consumption or new uses for energy (Garrett, 2012; Palmer, 2012).

Also line 4, p. 838 is rewritten as: **Figure 1e is a key result of our study: …. This result agrees with those of many other analyses in the literature, in which economic growth in the long run is higher with mitigation than without it; see, for instance, Guest (2010, Fig. 1), Richardson et al. (2011, p. 320), and Bréchet et al. (2015, Figs. 6.1 and 6.2).**

In the sensitivity analysis Section 4.1, p. 840, the following paragraph is inserted:

Considering the damage function of Eq. (20), the choice of the parameters $m_1 > 0$ and $\chi > 0$ in the literature is ad hoc and based on "informed guesses" (Peck and Teisberg, 1994). Clearly, the exponent χ is more important than the coefficient m_1, as the shape of the damage function varies from linear to cubic, $1 \le \chi \le 3$ (Ackerman et al., 2009), while $0.0022 \le m_1 \le 0.0231$, cf. Roughgarden and Schneider (1999) and Labriet and Loulou (2003).

We modify the values of the parameters m_1 and χ by +50 and −50 % from their respective values of $m_1 = 0.0067$ and $\chi = 2.43$ in Tables 1–4 above, **so as to get their ranges into fair agreement with the ones in the literature**, and examine how that affects model results for year 2100. In Table 5 are listed the per annum CO_2

emissions, CO_2 concentrations, SAT, damages, and growth rate of per capita GDP. All parameter values are as in Table 1, including $\alpha_\tau = 1.8$.

Furthermore, the following is added on page 841, after line 4 (But now to be found under the newly added Section: "Comparison to previous studies," in our new ms. doi:10.5194/esd-2016-64):

CoCEB's year 2100 climate change damages before and after abatement range between 1.9–41.6 percent. Our model's damage values thus do agree fairly well with those in the literature; see, for instance, Creedy and Guest (2008).

Also, all of the cited references have been added to the Reference list.

2. *The introduction of the paper sets out to explain limitations of models such as DICE. It then, seemingly, expands the complexity of the considered processes. What is missing is a careful comparison of the new model with the closest approximation (one may assume DICE to be this models) in terms of the number of parameters, the number of equations, the number of decision variables, and the considered processes. Having the code available in an appendix would also simplify the discussion and the ability to reproduce the results.*

Actually, this observation was also made by the editor. To address this concern, **we have added a new Section 5.2: Comparison to previous studies** in the new ms. doi:10.5194/esd-2016-64

The following paragraph (page 843, lines 20) in ms. esdd-6-819-2015 is also modified as:

The CoCEB model, as developed in this first part of a two-part study, is sufficiently simple as to be transparent, to allow a range of sensitivity analyses, and to be available for a number of further extensions. The current model version analyzes the carbon policy problem in a single-**box** global model with the aim of **understanding** theoretically the dynamic effects of using the abatement share as a climate change mitigation strategy. To be able to draw more concrete, quantitative policy recommendations is it important to account for regional disparities, an essential development left to future research.

The code can be made available upon request. We would be quite happy to put it on the website if the editors think it is necessary, and in agreement with the journal's policies. We added the following under Acknowledgements (page 845): **The CoCEB model code is available from the authors upon request.**

Also, all of the cited references have been added to the Reference list.

3. *Several assumptions are difficult to understand. For example, why does only governmental spending on abatement affect production possibilities (p. 828, L. 13)?*

As to why only governmental spending on abatement affects the size of per capita GDP, we note that economic activity intensifies greenhouse gas emissions (GHGs) that in turn cause economic damage due to climate change; the government in our economy uses resources for abatement activities G_E (Eq. 5) that reduce emissions of CO_2. **On the one hand, an increase in abatement activities, leads to a higher value of the abatement share $\tau_b > 0$, and it makes the difference $1-\left[\tau\left(1+\tau_b\right)+c\left(1-\tau\right)\right]$ in Eqs. (9) and (10) smaller. Hence the two factors of production — per capita physical capital and per capita human capital — decrease, and hence production in turn decreases. On the other hand, a reduction in CO_2 emissions that is due to the government's spending on abatement activities lessens the intensity of GHGs and hence the climate-change related damages to the economy.**

To make things clearer, the above explanation is now inserted to replace the sentence starting in line 12 and ending in line 13 on page 828 in the originally submitted ms. esdd-6-819-2015 (and also in our new ms. doi:10.5194/esd-2016-64).

4. *The paper contains several claims that are not substantiated by / easily accessible from the provided evidence. Examples include:*

a. Motivation of IAMs (p. 822, L. 25-27).

We tried to make the text clearer and more self contained. Lines 25-29 on page 822 and lines 1-5 on page 823 now read:

Our model explicitly includes the causal links between economic growth and the climate change–related damages via the increase of CO_2 emissions. In particular, it can show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system; see Diesendorf (2014, p. 143) and Equation (14) below.

b. Does (UNFCCC, 1992) really call for a two degree C limit? In which article?

No, UNFCCC (1992) doesn't really call for a 2^{o} C limit, however, the framework stated, "The ultimate objective … is to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 2009; see also Nordhaus 2013b). At the recommendation of leading world climatologists, in 1996 the European Council made the decision that the "average global temperature of the pre-industrial level should not be exceeded by more than 2^{o} C; therefore, global efforts for restricting or reducing the emissions must be oriented at an atmospheric concentration of CO_2 of no more than 958.5–1171.5 GtC" (Akaev, 2015). The warming limit of 2^{o} C was confirmed by the United Nations in the Declaration adopted at the 2009 United Nations Conference on Climate Change (Copenhagen Summit) (Akaev, 2015; Nordhaus 2013b).

In view of the above, we have changed lines 1-4 on page 839 to:

Now, according to the United Nations Framework Convention on Climate Change (UNFCCC, 2009, 2015), the average global SAT should not exceed its pre industrial level by more than 2^{o} C; see also Akaev (2015) and Kuckshinrichs and Hake (2015, pp. 1 and 289). This SAT target means that global efforts to restrict or reduce CO_2 emissions must aim at an atmospheric CO_2 concentration of no more than 958.5–1171.5 GtC by year 2100 (Akaev, 2015).

We also added the following sentence in our new ms. doi:10.5194/esd-2016-64:

A number of studies (Calvin et al., 2009; Edmonds et al., 2013; Bowen, 2014; Clarke et al., 2014, and references therein; DDPP, 2015; Rogelj et al., 2015) have shown that achieving even smaller increases of SAT than the 2 °C level by 2100 is technologically feasible and that it is also likely to be economically affordable. Our $\tau_b = 0.145$ scenario, however, cannot guarantee a deviation from pre-industrial SAT that is substantially less than 2 °C by 2100.

Also, all of the cited references have been added to the Reference list.

c. *Is this really a "win-win situation" (p. 843, L. 4). Figure 1e suggests that current generations may loose something.*

Yes, in the longer run, it is a win-win situation in the following sense: subject to the assumption that anthropogenic GHGs are the result of economic activities, one would expect high economic growth to be accompanied by high GHG emissions, that is, you win economic-growth–wise but loose in terms of climate deterioration via emitting more GHGs into the atmosphere. But upon investing in abatement measures, the results (see Figures 1a and 1e) show that higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions, that is you win economic-growth–wise and also win by emitting less GHGs into the atmosphere. In other words, "increases in abatement spending yield a win-win situation" means "a rise in abatement activities both reduces greenhouse gas emissions and raises economic growth" (see also, Greiner, 2004; Greiner and Semmler, 2008, pp. 95 and 120). Of course, the result that a win-win situation or double dividend may be observed crucially depends on the specification of the functional relation between the economic damage and climate change; see also Greiner (2004) and Greiner and Semmler (2008, p. 120).

As shown in Table 3, the losses from mitigation in the near future are outweighed by the later gains in averted damage.

Of course mitigation costs do hinder economic growth over the next few decades, up to the mid-21st century, at the latest, but this growth reduction is compensated later on by having avoided negative impacts of climate change on the economy. To the contrary, as the CoCEB model shows, taking no abatement measures to reduce GHGs leads eventually to a slowdown in economic growth implying that future generations will be less able to invest in emissions control or adapt to the detrimental impacts of climate change.

To clarify things, we replaced the sentence starting in line 2 and ending in line 8 on page 843, with the following:

Few studies, though, focus on devising climate policy that aims to combine economic growth with emissions reductions (Pielke, 2010, p. 66). The CoCEB model shows that an increase in the abatement share of investments can yield a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions and, as a consequence, with a decrease in average global SATs and in the ensuing damages; see also Greiner (2004), Greiner and Semmler (2008, pp. 95 and 120), and Sterner and Coria (2012, p. 154). These results hold when considering the entire transition path from now to 2100, as a whole. Such a positive outcome's realization in practice depends crucially, though, on the correctness of the functional relation between the economic damage and climate change assumed herein; see also Greiner (2004) and Greiner and Semmler (2008, p. 120).

5. *What is the logic behind the mapping of the 2 degree target to a single atmospheric CO2 concentration (p. 839)? What about an overshoot?*

Of course, the prudent thing would have been to map the 2^{o} C target to a given range of atmospheric CO_2 concentrations. However, we got this value of atmospheric CO_2 concentration from Akaev (2015), although he later says that "the specified value of CO_2 concentration in the atmosphere that should not be exceeded became 958.5–1171.5 GtC …" We are thus led to believe that an overshoot of atmospheric CO_2 concentration is not compatible with achieving, eventually, the 2^{o} C target; instead, the excess global average surface temperatures above pre-industrial would surpass 2^{o} C for good and trigger, therewith, major Earth instabilities and tipping points; see, for instance, Nordhaus (2013b, pp. 200–204). However, we have not found any scientific evidence in the literature to support this belief (*idem*, p. 200).

To remove any ambiguity in using a single value of atmospheric CO_2 concentration, we modify the text by using the range:

958.5–1171.5 GtC by year 2100 (Akaev, 2015).

6. *The language needs a careful round of editing to address issues with word choices, grammar, and style.*

We have done so, to the best of our ability.

7. *The wording is often ambiguous. For example:*

a. *How is a "best approach" defined (p. 824, L. 21)?*

To remove any ambiguous wordings, we have made the necessary modifications to all the sections in our new ms. doi:10.5194/esd-2016-64

b. *What does it mean when future values are "not known" (p. 824. L. 2)? Does this not apply to all other projected numbers?*

Yes it does. We just chose to repeat this here because it is one of the novelties of our model and it is good, therefore, to emphasize it.

c. *What does it mean to "enhance the quality of life for all" (p. 843. L. 2) in the framework of this model?*

Indeed, this is too general, thank you. We replaced "enhance the quality of life for all" with "**enhance economic growth and hence wealth**".

8. *The citations are imprecise. For example, on which chapter and page in "(IPCC, 2013)" should the reader look to see the support for the claims on page 837?*

To remove the lack of precision, we rephrased the reference in line 19 on page 837, as: **(IPCC, 2013, p. 23, Table SPM.2)**.

We also inserted in line 25 the following reference: **(IPCC, 2013, p. 27, Table SPM.3)**

9. *What is the relevance of the discussion on the "finite-horizon optimal climate change control solution" (p. 843)?*

Like every other model, CoCEB has its own limitations and simplifications. The "finite-horizon optimal climate change control solution" discussion, among other discussions in Subsection 5.2 (now in the current manuscript it is Subsection 5.3), outlines a possible extension to the CoCEB model to address its current limitations. We modified the text to make this clearer. We took the sentence "The determination of an optimal abatement path along the lines above will be the object of future work." and moved it to the beginning of the paragraph, with the necessary changes. Now the paragraph — in our new ms. doi:10.5194/esd-2016-64 — reads:

The determination of an optimal set of abatement paths (Smirnov, 2005; Pivovarchuk, 2008) being the object of future work, we discuss here a number of improvements and extensions that will facilitate the formulation of the optimal control problem associated with the CoCEB model; see, for instance, Maurer et al. (2015).

Also, all of the cited references have been added to the Reference list.

Referee #2:

The climate module

I am not an expert on climate models, but it appears to me that the authors should seriously consider to use a more recent version. For example, the carbon cycle comprises the parameter β_2 *that equals 0.49. This means that 51% of all emissions in a year are immediately removed and do not contribute to the accumulation of carbon in the atmosphere. This problem has been discussed with respect to the DICE model in the literature (Kaufmann, 1997).*

We appreciate the reviewer's concerns and presume that by suggesting that we use "a more recent version of the climate model", s/he means "a more detailed version", for example, replacing the carbon cycle in Eq. (2) with three equations where a three-reservoir model is calibrated to current scientific carbon-cycle models, as in Nordhaus and Boyer (2000) or using a pulse response function, i.e. a Green's function (e.g., Hasselmann et al., 1996; Joos et al., 1996; Siegenthaler and Oeschger, 1978), or utilizing a time- or, more generally, a state-dependent rate of carbon removal (Traeger, 2014). Of course, doing so might mitigate the possibility that our model's solutions, like those of the original DICE (see Nordhaus, 1994), understate carbon retention because a constant decay of atmospheric excess carbon is assumed. The reviewer's concerns suggest a worthwhile line of future work.

However, the DICE model – and hence the CoCEB model – is a typical climate–economic model where the essence of particular relationships is examined to try to further the understanding of key elements within a complex and interrelated environment. The DICE model interacts with the economy through only one variable, temperature. Therefore, a complex model that provides dynamic estimates for carbon-dioxide is not needed; see Hof et al. (2012) for a summary of the various representation of the carbon cycle in IAMs. In any case the climate module of the DICE model is calibrated against a more complex climate model and follows the results of the more complex model very closely (Nordhaus and Boyer, 2000; see also Sanderson, 2002).

In our case, a more detailed representation of the carbon-cycle, akin to the three-reservoir model used by Nordhaus and Boyer (2000) (see also, Van Vuuren et al., 2011; Glotter et al., 2014, and the references therein), would not allow the coupling of biomass and the related exchanges of CO_2 into the climate model as done in paper 2 (see Ogutu et al., 2015).

Furthermore, Hof et al. (2012) showed that in the longer term, beyond 2100, most IAM parameterizations of the carbon cycle imply lower CO_2 concentrations compared to a model that captures IPCC Fourth Assessment Report (AR4) knowledge more closely, e.g. the carbon-cycle climate Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) 6. This result of Hof et al. (2012) combined with the fact that in this study we confine our investigations to the transition path for the next 110 years from the baseline year 1990 renders our results useful (see also, Gerlagh and Van der Zwaan, 2003; Traeger, 2014).

We have therefore added the following sentence before equation (2) in our new ms. doi:10.5194/esd-2016-64.

Humanity's most important influence on the climate system is via the carbon cycle (Richardson et al., 2011, p. 92). While there is some discussion on the representation of the carbon cycle in IAMs (see Glotter et al., 2014; Traeger, 2014), we represent the evolution C of the concentration of CO_2 in the atmosphere, following Uzawa (2003), Greiner and Semmler (2008), and **Greiner (2015), by ….**

Also, all of the cited references have been added to the Reference list.

Now, according to IPCC, $\beta_2 = 0.49$ for the time period 1990 to 1999 for CO_2 emissions (IPCC, 2001, p. 39). Furthermore, the fraction of carbon dioxide found in the atmosphere is currently around 50% of the total anthropogenic emissions, with a slight upward trend (Raupach et al., 2008; Hüsler and Sornette, 2014). We therefore strongly feel $\beta_2 = 0.49$ is reasonable to use in our case (see also, Greiner and Semmler, 2008, p. 62).

We have also added the following references after line 21 on page 826:

(see IPCC, 2001, p. 39; Hüsler and Sornette, 2014).

Again, all of the cited references have been added to the Reference list.

The economic module

The economic module deviates from the original DICE model because (i) it assumes a fixed savings, (ii) technological progress in form of increasing human capital H is an externality that depends on investments into macro-economic capital and (iii) abatement activities are a government activity that is financed from income tax that is fixed share of individual incomes. The variable parameter is the share τ_b of the tax revenue that is allocated to abatement activities. This is the policy parameter. It is worth to mention that the model does not consider carbon pricing (e.g. via a tax on emissions). It is also worth to mention that the macroeconomic production function only considers per capita capital and per capita human capital as inputs. Note that the present model, like DICE, does *not consider energy as an input to the production function. This is a common assumption in models that have a focus on the energy sector.*

The CoCEB model is a highly simplified representation of the complex climate and economic realities. One example of simplification is the use of a constant global tax rate and thus ignores the structure of the tax system. This is particularly important for energy and capital taxes, which have large effects on energy use and on the rates of return used in making long-term decisions in the energy sector. The structure of tax systems is particularly important for estimation of the optimal level of carbon pricing or taxation because of the need to consider the interaction of carbon pricing with the structure of pre-existing tax and regulatory distortions; see, in particular, the several important studies collected in Goulder, 2002; see also Nordhaus, 2013b).

The purpose of the CoCEB model, as clearly stated in Section 1 and Section 5.1, is not to exactly replicate real-world processes, but to provide overall insights into the effect of abatement policies or their absence on economic welfare and climate preservation. Hence we feel that the greater detail needed to capture the international and sectoral reactions to changes, say in tax policies, would not contribute much to achieving this paper's purpose.

We thank the reviewer for his/her observations and good advice; we have added the following after line 11 on page 828 (of the originally submitted ms. esdd-6-819-2015):

Our model's macroeconomic production function only considers per capita physical capital and per capita human capital as inputs and, like in the DICE model, does not consider, at this point, energy as an input to the production function. Nor does the CoCEB model version in this paper consider carbon pricing, e.g. via a tax on emissions.

The following sentence is also added — in the new ms. doi:10.5194/esd-2016-64 — in Section 5.3: Way forward :

…. Moreover, in order to understand the dynamic role of energy production and consumption in this broader context, we also plan to extend the CoCEB model by introducing energy as a production factor that can be substituted by labor and capital, which is not the case in most IAMs; see also Garrett (2015, and references therein).

Equation 8 describes the population growth rate. Equation 18 describes the population development. What is the relationship between Equation 8 and 18 , and why are these two equations not treated together?

The human population growth rate n as given in Eq. (8) does not depend on human population size L, which is exogenous. However the evolution of human population is precomputed using Eqs. (18) and (8). As for treating them together, n is introduced first because it is used in the per capita physical capital Eq. (7) and in subsequent equations, while L is only used later in getting per capita GDP from aggregate GDP; see line 10–15 on page 829 of the originally submitted ms. esdd-6-819-2015.

Emissions module

The paper basically builds on the Kaya identity. The approach is to use logistic curves that mimic the introduction of non-fossil technologies as well as changes in the carbon intensity of the fossil fuels in order to derive the relevant CO_2 emissions. It appears to me that his dynamic is driven fully time driven. However, the authors say that emissions depend on τ_b, but I was not able to find it in the equations of this section. Therefore, the reader is left with some confusion. It seems to me that the authors have introduced simply another way to calibrate and tune the trajectory for the emissions per unit of GDP. The development of this parameter seems to be completely time driven.

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14) (now Eq. 15 in our new ms. doi:10.5194/esd-2016-64); the carbon intensity σ, cf. Eq. (15) (now Eq. 16 in our new ms. doi:10.5194/esd-2016-64); and the de-carbonization of the economy (Eq. 16) (now Eq. 17 in our new ms. doi:10.5194/esd-2016-64). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0\left[1/\left(1-\alpha_\tau\tau_b\right)\right]$ (now Eq. 14 in our new ms. doi:10.5194/esd-2016-64), where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from τ_b = 0 to 0.145.

To remove any confusion on the reader's part, we have rearranged line 19 on p. 830 so that the parameter $\psi = \psi_0\left[1/\left(1-\alpha_\tau\tau_b\right)\right]$ is now labeled as Eq. (14) and the numbering of the subsequent equations has been modified accordingly.

Of course, as the reviewer rightly observes, the de-carbonization of the economy, i.e. the declining growth rate of the carbon intensity σ in Eq. (16), apart from its depending on the specific value of the abatement share τ_b, is also assumed to be time-dependent, to be able to account for a gradual de-carbonization process. Fossil-fuel consumption has been subject to such a process since the early times of industrialization, by a transition—in chronological order—from the use of wood to coal, from coal to oil, and in the most recent past from coal and oil to natural gas (see also, Gerlagh and Van der Zwaan, 2003). The effect of the abatement share τ_b is to make this process slower or faster.

We captured this observation after line 13 on page 831.

Once more, all of the cited references have been added to the Reference list.

Abatement share

It appears to me that the relationship between the costs (percentage reduction of BAU GDP) and the emission reduction (percent deviation from BAU) is quite similar to what Nordhaus did. The calibration is done given a broad range of studies summarized by IPCC. However, it is not clear what they really did. Also it is not clear to me what the trigger for the choice of the abatement activity (climate policy) is. I guess that it is simply set exogenously.

Our choice of the abatement share, which is the key policy tool in our CoCEB model, was explained already in the originally submitted ms. esdd-6-819-2015, Section 2.6 (now in the new ms. doi:10.5194/esd-2016-64, it is Section 2.5). The remark of the referee points to a lack of clarity on our part. To make things clearer we add the following at the beginning of this section:

We now determine the abatement share, τ_b, which is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and is being used here as a policy tool. The abatement share is used in the de-carbonization of the economy, cf. Eq. (16), through the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$; see also Eq. (14).

We combined Sections 2.4 and 2.6 of the originally submitted ms. esdd-6-819-2015 into one Section 2.5 in the new ms. doi:10.5194/esd-2016-64; and also moved the whole of Section 2.5 of ms. esdd-6-819-2015 into an Appendix A in the new ms. doi:10.5194/esd-2016-64.

Assessment of the model set up

It appears to me that the authors have transformed the DICE model from a CBA analysis tool based on a Ramsey growth model into a policy evaluation tool based on a Solow model with a spill-over from physical investment to human capital formation. This also means that the authors have substituted the endogenous policy by an exogenous one. Moreover, I cannot see where the novelty is that the authors indicate in the title of the paper ("…investment in low-carbon Technologies"). As far as I can understand the model set-up there is no endogenous investment in any particular technology.

Hoping not to be repeating ourselves:

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14); the carbon intensity σ, cf. Eq. (15); and the de-carbonization of the economy (Eq. 16). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$, where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b , the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from τ_b = 0 to 0.145.

The endogenous growth part would be interesting to analyze in an integrated climate-economy model, if the investment rate can be adjusted, but here the investment rate is given. The point would be to ask whether the direct cost of climate change are smaller or larger than the full economic impact, when the second order effects via the macro-economy are considered.

As the referee observes in the "The economic module" section, abatement activities are a government activity that is financed from income tax that is a fixed share of individual incomes. The *variable* parameter is the abatement share τ_b of the tax revenue that is allocated to abatement activities. This is the policy parameter. As we responded under the "Emissions module" section, we reiterate that by considering various values of the abatement share τ_b in the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing from τ_b = 0 to 0.145.

In Table 3, we compare per capita abatement costs $G_E = \tau_b X = \tau_b \tau Y$ and the damage costs $(1-D)Y$ for the year 2100, for each one of our emission reduction paths; these are given in Eqs. (5) and (20), respectively in the current manuscript. From the table one notices that, not surprisingly, the more one invests in abatement, the more emissions are reduced relative to BAU and the less the cost of damages from climate change.

Also, I do not understand the reason for having the term Biosphere in the model acronym. I have not found the bio-sphere in the model description.

This article is based on a new integrated assessment model; its structure is extended in a subsequent twin article by the same authors; this article is under consideration by the same journal as ESDD-6-865-2015/esd-2015-14. The term Biosphere as used in the acronym is for the purpose of anticipating the coupling of biomass and the related exchanges of CO_2 into the climate model as done in Paper 2 (see Ogutu et al., 2015). The intent of extending the model, by the inclusion of the "Biosphere", in paper 2 is clearly indicated in line 19 on page 822, line 6 on page 823, and line 1 on page 845. We added a further clarification on p. 3, lines. 85–86 of the revised manuscript, as follows:

…. In Part 2 of this paper, we report on work along these lines, by introducing a biosphere module into CoCEB. This model version allows us to study relevant economic aspects of deforestation control and carbon

sequestration in forests, as well as the widespread application of CCS technologies as alternative policy measures for climate change mitigation.

It is true that one could have combined Paper 1 and 2 into a single paper and put much of the technical details into an appendix. However, the results of Paper 1 require merely a simpler version of the model, while for the results of Paper 2 the inclusion of 2 extra equations is needed. Dividing the material into two allows us to keep Paper 1 self-consistent, as well as short and readable; moreover, it only increases the complexity of the model when it is needed, i.e. in Paper 2. Furthermore, we feel that the methodological aspect, i.e. the construction of a simplified model, is one of the main points of this work, and that relegating it to an appendix would fail giving it its due importance.

Results

There are two major problems with the results.

The emission trajectory peaks in 2060 at 48GtC/yr. Starting with CO2 emissions in 2015 of 35GtCO2/yr (which is a high expectation) the implied growth rate is 3.7%/yr. This is very, very high and has not been observed in the past. Also the emission growth rate is higher than the economic growth rate, which has also not been observed in the past. After the peak the model reverts back to the CO2 emissions of the RCP8.5 scenario by 2100 at emissions below 30GtC/yr. This emission pathway has been assumed to be very high. The authors report the result for 2100, but not for the remarkable peak. They do not give a reason why the baseline emissions trajectory is that high.

The results presented here should be viewed as only suggestive and illustrative. They come from a single model and modeling perspective, and most of the relationships are subject to large uncertainties (see also, Petersen, 2012; Hannart et al., 2013; Wesselink et al., 2015 and the references therein for an insightful uncertainty assessment). However, we can confidently say that our BAU per annum growth rate of CO_2 emissions by 2050 agrees quite well with the Edmonds and Reilly (1983) study which asserts that the CO_2 emissions growth rate will increase to over 3% per year by 2050 (see also, Kuper, 2011). Actually, it has been noted that the global CO_2 emission rate has not only grown along a "business-as-usual" (BAU) trajectory, but has in fact slightly exceeded it (Raupach et al., 2007; Peters et al., 2013; see also Garrett, 2015), in spite of a series of international accords aimed at achieving the opposite (Nordhaus, 2010).

In our new ms. doi:10.5194/esd-2016-64, a closer look at Figure 1a shows that the BAU emission trajectory peaks in 2064 at 48.2 GtC yr^{-1}. After that, the BAU trajectory drops back and, in doing so, approaches the CO_2 emissions of the RCP8.5 scenario by 2100, at an emissions level of 29.3 GtC yr^{-1}. This decrease is due to the fact that the emissions rate shown in Fig. 1f becomes negative, due to the decarbonization of the economy, according to Eqs. (17) and (22e).

In fact, our BAU scenario's energy technology is assumed constant at its 1990 level, in agreement with the IPCC BAU scenario; see Edmonds et al. (2004, p. 77) and Pielke et al. (2008) and Hay (2013, pp. 903–904).

Our BAU CO_2 emissions are fairly similar to other scenarios given in the literature as well; see, for instance IPCC (2007c, Fig. TS.7), and Clarke et al. (2014, Fig. 6.4, left panel).

To explain this further, considering Eq. (12) and dividing through by carbon emissions E_Y and on subtracting the per capita GDP growth rate g_Y from both sides, we get

$$\frac{1}{E_Y}\frac{dE_Y}{dt} - g_Y = g_\sigma + n + g_{ccs} \,. \tag{C.1}$$

The left-hand side of Eq. (C.1) is positive at the beginning of the 1990–2100 study period, and negative later during this period; this means that g_Y is less than and later greater than the growth rate of E_Y. Actually, the right-hand side of Eq. (C.1) is bounded between −0.0545 and 0.0145. In this study, we assumed 1990 as the time when the use of renewable energy sources (biomass and wastes, hydropower, geothermal energy, wind energy, and solar energy) and biofuels became significant in the global energy balance (GEB). As we responded under the "emissions" section to Reviewer #2, the de-carbonization of the economy — i.e. the declining growth rate of the carbon intensity σ, as seen in Eq. (16) of the original manuscript — apart from it depending on the specific value of the abatement share τ_b, is also assumed to be time-dependent, in order to be able to account for a gradual de-carbonization process.

Through the CoCEB model, we were able to demonstrate that an increase in the abatement share of investments yields a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in carbon emissions (as well as the growth rate of carbon emissions) and, as a consequence, to a decrease in average global SATs and the ensuing damages (see also, Greiner, 2004; Greiner and Semmler, 2008, pp. 95 and 120).

Now, Global fossil fuel CO_2 emissions increased by 3.3 % yr^{-1} on average during the decade 2000–2009 compared to 1.3% yr^{-1} in the 1990s and 1.9 % yr^{-1} in the 1980s (see e.g., Canadell et al., 2007). The global financial crisis in 2008–2009 induced only a short-lived drop in global emissions in 2009 (–0.3 %), with the return to high annual growth rates of 5.1% and 3.0% in 2010 and 2011, respectively (IPCC, 2013, p. 489); see also Albanese and Steinberg (1980). Therefore a high CO_2 emissions growth rate — actually higher in comparison to the per capita GDP growth of the same time (see Guest and McDonald, 2007, Table 2; Yakovets et al., 2009, Fig. 8, Tables 2, 10 and 14) — has been observed in the past.

To clarify the issue raised by the reviewer, we add the above bolded paragraph in our new ms. doi:10.5194/esd-2016-64, viz.

A closer look at Figure 1a shows that the BAU emission trajectory peaks in 2064 at 48.2 GtC yr^{-1}. After that, the BAU trajectory drops back and, in doing so, approaches the CO_2 emissions of the RCP8.5 scenario by 2100, at an emissions level of 29.3 GtC yr^{-1}. This decrease is due to the fact that the emissions rate shown in Fig. 1f becomes negative, due to the decarbonization of the economy, according to Eqs. (17) and (22e).

In fact, our BAU scenario's energy technology is assumed constant at its 1990 level, in agreement with the IPCC BAU scenario; see Edmonds et al. (2004, p. 77) and Pielke et al. (2008) and Hay (2013, pp. 903–904).

Our BAU CO_2 emissions are fairly similar to other scenarios given in the literature as well; see, for instance IPCC (2007c, Fig. TS.7), and Clarke et al. (2014, Fig. 6.4, left panel).

Also, all of the cited references have been added to the Reference list.

Second, 1990 is the year for the model calibration and the first year for the policy analysis. This is a quarter of a century before today. Consequently, there is large variation by the year 2010. This can be seen in the emission trajectories as well is in the economic growth rates. In my opinion this is a flawed result. It is common practice for existing models to use 2005 or 2010 as a calibration year, but not 1990 and then let the model start with deviating results from 1990 onwards.

We don't think that the variation between our BAU and non-BAU scenarios with the RCPs is as large by year 2010 as the referee claims (see Table 4). However the existing variation could be minimal if, as Garrett (2012) states, the SRES scenarios which can be mapped onto the RCPs, did not underestimate the CO_2 emissions.

The primary need and rationale of CoCEB is not to provide the best simulation fit to the truth, but CoCEB is a formal framework in which it is possible to represent in a simple way several components of the coupled system and their interactions. While we strive for CoCEB to be a well performing model, we do not think it is necessary for CoCEB to outperform more complex models (see also, Nordhaus, 2013a, b). The revision version of the manuscript makes this point clearer (see also our first response to referee #1 on the main innovation and the main new findings of CoCEB).

The standard way to evaluate the accuracy of a model is to do hindcasts. The hindcast of the model described here is illustrated in Fig. 1, Table 4 and discussed in Section 3. Effectively the model is initialized with current conditions in 1990 and the hindcast made for the 24 year period between 1990 and 2014 (and now 2016). What we show is that the model reproduces fairly well, albeit with little deviations, both the timing and magnitude of observed changes in CO_2 emissions per year and the atmospheric concentrations in the transition path up to year 2100. The implication is that, even though the model that is used is extremely simple, it is nonetheless able to produce accurate enough annual results for CO_2 emissions and concentration, temperature, damage and capita gross domestic product (GDP) growth.

Smaller issues

Page 822, line15: the industrial emissions are assumed constant, but those from fossil fuel combustion are variable right?

The industrial emissions are due to combustion of fossil fuels.

To make things clearer, we add the following in our new ms. doi:10.5194/esd-2016-64:

Anthropogenic GHGs are the result of economic activities (Garrett, 2015) and the growth in CO_2 emissions closely follows the growth in GDP (Creamer and Gao, 2015, p. 5), corrected for improvements in energy efficiency (Friedlingstein, et al., 2010). Thus, the main shortcoming in Greiner's (2004, 2015) approach is that of treating industrial CO_2 emissions, due to combustion of fossil fuels, as constant over time.

Page 822, line 17: what means "zero abatement activities"? is this zero cost or zero emission? Please clarify.

"Zero abatement activities" mean "a total absence of abatement activities". In fact, in the paper, abatement equal to zero corresponds to Business As Usual (BAU). To clarify things, we write as:

Another problematic aspect of Greiner's emissions formulation is its inability to allow for a total absence of abatement activities: in fact, his formulation only holds for a minimum level of abatement.

822, line 25: I guess it is better to substitute analytically by quantitatively.

Lines 25-29 on page 822 and lines 1-5 on page 823 are now rewritten and hopefully clearer:

Our model explicitly includes the causal links between economic growth and the climate change–related damages via the increase of CO_2 emissions. In particular, it can show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system; see Diesendorf (2014, p. 143) and Equation (14) below.

Page 833, line 24ff: it is unclear to me how the choice of the parameter χ (the exponent in the damage function in Equation 19) can have any influence on the emissions in the Business as Usual scenario.

The influence of the parameter χ on the per annum CO_2 emissions, CO_2 concentrations, global mean surface air temperature (SAT), damages and growth rate of per capita GDP is well explained in Section 4.1.

We therefore modify the lines 24-27 on page 833 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 (Riahi et al., 2007; IPCC, 2013, p. 27, Table SPM.3); see Sect. 4.1 for details on our calibration of χ.

822, line 26: IN my perception the term adaptation rather than mitigation is appropriate, if the relationship between climate change and economic growth shall be influenced. Mitigation means to limit climate change to avoid impacts on the economy.

In our understanding the current definitions are the following. Mitigation: consists of actions to reduce emissions and atmospheric concentrations of CO_2 and other greenhouse gases (GHGs); Adaptation: involves learning to cope with a warmer world rather than trying to prevent it; Suffering: adverse impacts that are not avoided by either mitigation or adaptation.

In this paper and in paper 2, we consider the broad range of options available, reducing CO_2 emissions, i.e. for mitigation according to the above definitions. These include: increasing energy efficiency, increasing non-fossil fuel-based energy production, the use of carbon capture and storage (CCS), and deforestation control.

822, line 28ff: I do not understand what it means to use the "abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system". It is simply not clear what abatement share means and how it relates to the investment. To me it seems like a typical allocation problem.

Again we would like to repeat here:

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14); the carbon intensity σ, cf. Eq. (15); and the de-carbonization of the economy (Eq. 16). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$, where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from τ_b = 0 to 0.145.

To make things more clear, we add "**see Equation (14) below**" in the paragraph contained in lines 25-29 on page 822 and lines 1-5 on page 823.

Section 2.3: Section 2.3: the first paragraph can be deleted. It does not really add to the content of the model. It only discusses an approach that is not followed.

Right, we will do exactly that. The following paragraph has been written as:

Here, in order to formulate emissions E_Y so that they may vary over time and to allow abatement to be zero, we specifically utilize the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005) that breaks down CO_2 emissions E_Y (in GtC yr^{-1}) into a product of five components: emissions per unit of energy consumed (carbon intensity of energy), energy use per unit of aggregate GDP (energy intensity), per capita GDP, human population, and carbon emission intensity, as shown below:

Editor's suggestion of 31/10/2015:

"I suggest you undertake a much more serious effort to review the scene of IAM modelling, and then position your model within that. I assume your MS would be a really new one after that effort, as you will also increase the linkages of your results to older studies qualitatively. In any case, you must convince the reader that you have worked through the existing literature describing the existing IAMs and can competently position your new model in that arena."

As you will notice in our new ms. doi:10.5194/esd-2016-64, we have revised once more the manuscript by modifying all the sections and by adding the Section: "Comparison to previous studies," based on your suggestion.

We finally would like to add the following in the acknowledgements: **It is a pleasure to thank Hermann Held, Axel Kleidon and two anonymous reviewers for thoughtful and constructive comments that contributed to improve an earlier version of this manuscript.**

Once more, we would like to thank the two referees for their thoughtful and critical reviews of the originally submitted ms. esdd-6-819-2015 which have been extremely helpful at refining the new ms. doi:10.5194/esd-2016-64. We are greatly appreciative of the effort that went into it and hope that our answers are satisfying. If there are still things unclear or incomplete, we are happy to receive further comments. While there clearly is room for improvement, we hope that the ms. doi:10.5194/esd-2016-64 is now fully acceptable for publication in *Earth System Dynamics*.

References

All references are found in the originally submitted ms. esdd-6-819-2015 (Appendix B) or our reply to the reviewers of ms. esdd-6-819-2015 (Appendix A), as well as in our new ms. doi:10.5194/esd-2016-64.

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement efficacy of low-carbon technologies

Keroboto B. Z. Ogutu[1, 2], Fabio D'Andrea[2], Michael Ghil[2, 3, 4], and Charles Nyandwi[5]

[1]Department of Mathematics & Physical Sciences, School of Science, Dedan Kimathi University of Technology, P.O Box 657−10100, Nyeri, Kenya
[2]LMD/IPSL, Ecole normale supérieure, PSL Research University, Ecole polytechnique, Université Paris-Saclay, Sorbonne Universités, UPMC Univ Paris 06, CNRS, 24 rue Lhomond, 75005, Paris, France
[3]Environmental Research & Teaching Institute, Ecole Normale Supérieure and PSL Research University, F-75230, Paris Cedex 05, France
[4]Department of Atmospheric & Oceanic Sciences, University of California at Los Angeles, 3839 Slichter Hall, 405 Hilgard Ave., Los Angeles, USA
[5]Department of Applied & Industrial Mathematics, School of Mathematics, University of Nairobi, P.O. Box 30197−00100, Nairobi, Kenya

Correspondence to: K. B. Z. Ogutu (okeroboto@gmail.com)

Abstract. 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 is composed of a physical climate module, based on Earth's energy balance, and an economy module that uses endogenous economic growth with physical and human capital accumulation. We concentrate on the interactions between the two subsystems: the effect of climate on the economy, via damage functions, and the effect of the economy on climate, via control of greenhouse gas emissions. Simple functional forms of the relation between the two subsystems permit simple interpretations of the coupled effects. The CoCEB model is used to evaluate hypotheses on the long-term effect of investment in emission abatement, and on the comparative efficacy of different approaches to abatement. In this paper, we consider investments in low-carbon technologies. Carbon capture and storage (CCS), along with deforestation reduction, will be dealt with in Part 2. The CoCEB model is highly flexible and transparent; as such, it allows one to easily formulate and compare different functional representations of climate change mitigation policies. Using different mitigation measures and their cost estimates, as found in the literature, one is able to compare these measures in a coherent way. While many studies in the climate–economic literature treat abatement costs merely as an unproductive loss of income, this paper shows that mitigation costs do slow down economic growth over the next few decades, but only up to the mid-21st century or even earlier; growth reduction is compensated later on by having avoided negative impacts of climate change on the economy.

1 Introduction and motivation

Global warming is one of the most profound and urgent challenges in environmental research because of its potential impacts on society and the economy (Dong et al., 2013; Chang et al., 2016). The vast evidence for the changes in Earth's climate being due to a major extent to the anthropogenic increase in greenhouse gases (GHGs) is comprehensively compiled in the successive reports of the Intergovernmental Panel on Climate Change (IPCC, 1996a, 2001, 2007a, 2013), carbon dioxide (CO_2) being the largest contributor (Mokhov et al., 2012); see also Hay (2013, p. 899) or Idso et al. (2013).

Over 80 % of today's energy comes from fossil fuels (Akaev, 2015): together with land-use change, they are the major anthropogenic source of CO_2 (Palmer and Engel, 2009; Diesendorf, 2012; Akaev, 2015). There is widespread consensus that significant carbon emission reductions, including reductions to zero net carbon during the 21st century, must be an integral part of a common strategy for addressing climate change (Bowen, 2014; Schellnhuber et al., 2016). Low-carbon technologies for the production, delivery, and conversion of energy will play a key role in these strategies; see also Barron and McJeon (2015). A key remaining question, though, is that of the effect on economic growth of the various measures that might be taken to keep the end-of-century warming below 2 degrees Celsius (2 °C) above pre-industrial levels.

Typically, the link of the global economy to GHG emissions and the effect of global warming on the economic system are modeled using integrated assessment models [IAMs; Garrett (2015)]. There are more than 20 IAMs used so far in climate policy analyses (Rosen, 2016). They differ with respect to modeling structure, complexity and assumptions regarding the way the climate system and the socio-economic system function and interact (Zaddach, 2016, p. 5). Ortiz and Markandya (2009) and Stanton et al. (2009) review some of these models; see also Meyers (2012, pp. 5399–5428), Pindyck (2013), Stern (2013), Brock et al. (2014) and Brock and Xepapadeas (2015) for a review and critique of the relevant literature on IAMs in climate economics, as well as recent literature on inter-temporal, spatial and dynamic environmental economic modeling.

IAMs are motivated by the need to balance the dynamics of carbon accumulation in the atmosphere and the dynamics of de-carbonization of the economy (Nordhaus, 1994a). Basically, these studies consist in choosing the path for productive investment and emission abatement that maximize welfare (Bréchet et al., 2015). However, in analyzing the economic implications of climate policies, these models often assume that the growth rate of the economy is exogenously given, and feedback effects of lower GHGs concentrations in the atmosphere on economic growth are frequently neglected. For example, Nordhaus and Boyer (2000) analyze different abatement scenarios, in which the Gross Domestic Product (GDP) growth rate is assumed to be an exogenous variable and the results are compared with the social optimum. Also, the fundamental alterations in wealth holdings are systematically downplayed by the practices of current integrated assessment modeling (DeCanio, 2003, p. 12).

In this paper, we study the interaction between global warming and economic growth, along the lines of the Dynamic Integrated model of Climate and the Economy (DICE) of Nordhaus (1994a), with subsequent updates in Nordhaus and Boyer (2000), Nordhaus (2007, 2008) and Nordhaus and Sztorc (2013), while removing some of the limitations above.

Greiner (2004, 2015) extended the DICE framework by including endogenous growth, to account for the fact that environmental policy affects not only the level of economic variables but also the long-run growth rate; see also Greiner and Semmler (2008). Using the extended DICE model, Greiner argues that higher abatement activities reduce GHG emissions and may lead to a rise or decline in growth. The net effect on growth depends on the specification of the function between the economic damage and climate change.

Anthropogenic GHGs are the result of economic activities (Garrett, 2015) and the growth in CO_2 emissions closely follows the growth in GDP (Creamer and Gao, 2015, p. 5), corrected for improvements in energy efficiency (Friedlingstein, et al., 2010). Thus, the main shortcoming in Greiner's (2004, 2015) approach is that of treating industrial CO_2 emissions, due to combustion of fossil fuels, as constant over time. Another problematic aspect of Greiner's emissions formulation is its inability to allow for a total absence of abatement activities: in fact, his formulation only holds for a minimum level of abatement.

We address these issues in the present Part 1 of a two-part paper by using a novel approach to formulating emissions that depend on economic growth and vary over time; in this approach, abatement equal to zero corresponds to Business As Usual (BAU). Our model explicitly includes the causal links between economic growth and the climate change–related damages via the increase of CO_2 emissions. In particular, it can show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system; see Diesendorf (2014, p. 143) and Equation (14) below.

The companion paper, Part 2, complements the model by introducing a biosphere component, along with a representation of carbon capturing and storing (CCS) technologies and control of deforestation, as well as increasing photosynthetic biomass sinks as a method of controlling atmospheric CO_2 and consequently the intensity and frequency of climate change related damages.

Our Coupled Climate–Economy–Biosphere (CoCEB) model is not intended to give a detailed quantitative description of all the processes involved nor to make specific predictions for the latter part of this century. The CoCEB model is a reduced-complexity model that tries to incorporate the climate–economy–biosphere interactions and feedbacks with the minimum amount of variables and equations needed. We thus wish to trade greater detail for greater flexibility and transparency of the dynamical interactions between the different variables.

As different types of fossil fuels produce different volumes of CO_2 in combustion, the dynamics of fossil fuel consumption — that is, the relative shares of coal, oil, and natural gas — has to be taken into account when calculating the future dynamics of CO_2 emission; see also Akaev (2015). These shares are not known at the present time (Akaev, 2015) nor is it easy to predict their evolution. In order to describe the dynamics of hydrocarbon-based energy share in the global energy balance of the 21st century and their replacement with renewable energy sources we use, following Sahal (1985), logistic functions; see also Garrett (2015).

Various climate change mitigation measures have been considered heretofore. Still, many IAMs in the contribution of Working Group 3 to the Fifth Assessment Report of the IPCC (Clarke et al., 2014) treat abatement costs merely as an unproductive loss of income (Edenhofer et al., 2015; Stoknes, 2015, p. 59) and conclude that limiting total human-induced warming to less than 2 °C can be achieved by carbon emissions reductions and establishment of a low-carbon economy on their own; see also Edmonds et al. (2013), Wasdell (2015), DDPP (2015), and Rogelj et al. (2015, Table 1). Our CoCEB model innovates in (i) making emissions depend on economic growth; and (ii) treating investment in abatement not as a pure loss but as a way to increase the overall energy efficiency of the economy and decrease the overall carbon intensity of the energy system.

Our study will also point to the fact that investment in low- and zero-carbon technologies alone is a necessary (Kriegler et al., 2014, and references therein) but not sufficient step towards global climate stabilization: no matter how fast CO_2 emissions are reduced, the 2 °C target will still be violated; see also Held et al. (2009), Pielke (2010), Scott (2014, p. 21), Akaev (2015) and Wasdell (2015). The inability of low- and zero-carbon technologies alone to produce effective climate change mitigation may partly be attributed to the warming from the carbon stock already in the atmosphere (e.g., Held et al., 2009; Steffen, 2012; Wasdell, 2015) and the "rebound effect" (Jevon's paradox) whereby gains in efficiency are offset by increased consumption or new uses for energy (Garrett, 2012; Palmer, 2012).

The CoCEB model is, like all models, sensitive to the choice of key parameters. We do carry out a sensitivity study, but do not intend to make precise calibrations for a quantitative projection of the climate-and-economy evolution throughout the 21^{st} century. Rather, we want to provide a tool for studying qualitatively how various climate policies affect the economy.

The next section describes the theoretical model, especially detailing the additions with respect to Nordhaus and Sztorc (2013), Greiner (2004, 2015) and Greiner and Semmler (2008). Section 3 discusses the numerical simulations and results, while Sect. 4 tests the sensitivity of the results to key parameters. Section 5 concludes, compares CoCEB to previous studies, and offers caveats and avenues for future research.

2 Model description

In this section we present our theoretical model. First, we sketch the physical climate module and then we describe the interrelation between economic activities and the change in the average global surface temperature.

2.1 Climate module

The time evolution of the average surface air temperature T (SAT) on Earth is given by

$$\frac{\mathrm{d}T}{\mathrm{d}t}=\frac{(1-\alpha_{\mathrm{T}})\mathrm{Q}}{4c_{\mathrm{h}}}-\frac{\varepsilon\sigma_{\mathrm{T}}\tau_{\mathrm{a}}}{c_{\mathrm{h}}}T^{4}+\frac{6.3\beta_{1}(1-\xi)}{c_{\mathrm{h}}}\ln\left(\frac{C}{\hat{C}}\right), \tag{1}$$

see, for instance, Ghil and Childress (1987, Ch. 10), McGuffie and Henderson-Sellers (2005, pp. 81–85), Hans and Hans (2013, Ch. 2) or Fraedrich et al. (2016). Here the first and second terms on the right-hand side are incoming and outgoing radiative fluxes respectively, while the third term is radiative forcing due to increase in GHGs (Kemfert, 2002; Greiner and Semmler, 2008; Greiner, 2015); σ_{T} is the Stefan-Boltzmann constant, τ_{a} the infrared (long-wave) transmissivity of the atmosphere, ε the emissivity that gives the ratio of actual emission to blackbody emission, α_{T} the mean planetary albedo, Q is the average solar constant.

The specific heat capacity c_{h} of Earth as a whole is largely determined by the oceans (Levitus et al., 2005); here it is taken equal to 16.7 W m^{-2} K^{-1} (Schwartz, 2007, 2008), which corresponds to an ocean fractional area of 0.71 and a depth of 150-700 m of the ocean active layer; see also Abdussamatov (2016). The current CO_2 concentration C is given in gigatons of carbon (GtC, 1 Gt = 10^{15} g) and $\hat{C}$ is the pre-industrial CO_2 concentration. All the feedbacks of GHG concentration on global temperature are represented in this highly idealized model by the factor β_1, which is usually assumed to take values between 1.1 and 3.4 (Greiner and Semmler, 2008, p. 62; Greiner, 2015); in this study, we took $\beta_1=3.3$. The parameter $\xi=0.23$ captures the fact that part of the warmth generated by the greenhouse effect is absorbed by the oceans and transported from their upper layers to the deep sea (Greiner and Semmler, 2008; Greiner, 2015). The other parameters have standard values that are listed in Table 1.

At equilibrium, that is for $\mathrm{d}T/\mathrm{d}t=0$, Eq. (1) gives an average SAT of 14 °C for the pre-industrial GHG concentration, i.e. for $C=\hat{C}$; see also Nordhaus and Boyer (2000) and Dong et al. (2013, p. 164, Fig. 3.22). Doubling the CO_2 concentration in Eq. (1) yields an increase of about 3 °C in equilibrium temperature, to 17 °C. This increase lies within the range of IPCC estimates, between about 1.5 and 4.5 °C (Charney et al., 1979; IPCC, 2013, pp. 924–926) with a best estimate of about 3.0 °C (IPCC, 2007a, p. 12).

Humanity's most important influence on the climate system is via the carbon cycle (Richardson et al., 2011, p. 92). While there is some discussion on the representation of the carbon cycle in IAMs (see Glotter et al., 2014; Traeger, 2014), we represent the evolution C of the concentration of CO_2 in the atmosphere, following Uzawa (2003), Greiner and Semmler (2008), and Greiner (2015), by

$$\frac{dC}{dt}=\beta_{2}E_{\mathrm{Y}}-\mu_{\mathrm{o}}\left(C-\hat{C}\right). \tag{2}$$

Here E_{Y} stands for the industrial CO_2 emissions. The fact that part of the emissions leaves the atmosphere and is taken up by the oceans is reflected in Eq. (2) by the parameter β_2 (see IPCC, 2001, p. 39; Hüsler and Sornette, 2014); the excess C

above pre-industrial level is reduced by the combined effect of land and ocean sinks. The inverse of the atmospheric lifetime of CO_2 equals μ_o and it is estimated in the literature to lie within an uncertainty range that spans 0.005–0.2 (IPCC, 2001, p. 38); we take it here to equal $\mu_o = 1/120 = 0.0083$, i.e. closer to the lower end of the range (IPCC, 2001, p. 38); see also Nordhaus (1994a, p. 21).

2.2 Economy module

In Greiner (2004, 2015) and Greiner and Semmler (2008) the per capita GDP, Y, is given by a modified version of a constant-return-to scale Cobb–Douglas production function (Cobb and Douglas, 1928; see also Romer, 2012),

$$Y = AK^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right). \quad (3)$$

Here K is the per capita physical capital, H is the per capita human capital, $A>0$ the total factor of productivity, $0<\alpha<1$ is the capital share, and $D\left(T-\hat{T}\right)$ is the damage, expressed as a function of the temperature difference due to climate change. The damage function is described in Sect. 2.4 below.

The economy income identity in per capita variables is given by

$$Y - X = I + M_{\mathrm{E}} + G_{\mathrm{E}}, \quad (4)$$

with $X=\tau Y$ the (per capita) tax revenue, $0<\tau<1$ the per annum tax rate, I investment, M_{E} consumption, and G_{E} abatement activities. This means that national income after tax is used for investment, consumption, and abatement. We assume that G_{E} is expressed as a fraction of X,

$$G_{\mathrm{E}} = \tau_{\mathrm{b}} X = \tau_{\mathrm{b}}\tau Y, \quad (5)$$

with $0 \le \tau_{\mathrm{b}} < 1$ the ratio of per annum abatement share, used as a policy tool. Consumption is also expressed as a fraction of Y after tax, that is,

$$M_{\mathrm{E}} = c\left(1-\tau\right)Y, \quad (6)$$

with $0<c<1$ the global annual consumption share.

The accumulation of per capita physical capital K is assumed to obey

$$\frac{\mathrm{d}K}{\mathrm{d}t} = Y - X - M_{\mathrm{E}} - G_{\mathrm{E}} - \left(\delta_{\mathrm{K}} + n\right)K, \quad (7)$$

the logistic-type human population growth rate $0<n<1$ is given, in turn, by

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \left(\frac{1}{1+\delta_{\mathrm{n}}} - 1\right)n, \quad (8)$$

with δ_n being the per year decline rate of n, and δ_{K} the per year depreciation rate of physical capital. Substituting the definitions of Y, X, M_{E}, and G_{E} into Eq. (7) we get

$$\frac{\mathrm{d}K}{\mathrm{d}t} = A\left[1-\tau\left(1+\tau_{\mathrm{b}}\right) - c\left(1-\tau\right)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right) - \left(\delta_{\mathrm{K}}+n\right)K. \quad (9)$$

For physical capital to increase, $\mathrm{d}K/\mathrm{d}t > 0$, the parameters must satisfy the inequality $0 < \left[\tau\left(1+\tau_{\mathrm{b}}\right) + c\left(1-\tau\right)\right] < 1$. Now, proceeding as above for K, we assume that the per capita human capital H evolves over time as

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \varphi\left\{A\left[1-\tau\left(1+\tau_{\mathrm{b}}\right) - c\left(1-\tau\right)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\right\} - \left(\delta_{\mathrm{H}}+n\right)H, \quad (10)$$

here $\varphi>0$ is a coefficient that determines how much any unit of investment contributes to the formation of the stock of knowledge and δ_{H} gives the depreciation of knowledge.

Note that we take, as a starting point, the Solow–Swan approach (Solow, 1956; Swan, 1956; Greiner and Semmler, 2008), in which the share of consumption and saving 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 resulting from different preferences. Our model's macroeconomic production function only considers per capita physical capital and per capita human capital as inputs and, like in the DICE model, does not consider, at this point, energy as an input to the production function. Nor does the CoCEB model version in this paper consider carbon pricing, e.g. via a tax on emissions.

Our formulation assumes, furthermore, that government spending, except for abatement, does not affect the size of per capita GDP: on the one hand, an increase in abatement activities, leads to a higher value of the abatement share $\tau_b > 0$, and it makes the difference $1-\left[\tau(1+\tau_b)+c(1-\tau)\right]$ in Eqs. (9) and (10) smaller. Hence the two factors of production — per capita physical capital and per capita human capital — decrease, and hence production in turn decreases. On the other hand, a reduction in CO_2 emissions that is due to the government's spending on abatement activities lessens the intensity of GHGs and hence the climate-change related damages to the economy.

Emissions of CO_2 are a byproduct of production (Barker et al., 1995, p .4) and hence are a function of per capita output relative to per capita abatement activities. This implies that a higher production goes along with higher emissions (Creamer and Gao, 2015, p. 5) for a given level of abatement spending. This assumption is frequently encountered in environmental economics (e.g., Smulders, 1995). It should also be mentioned that CO_2 emissions affect production indirectly by affecting the Earth's climate, which leads to a higher SAT and to an increase in the number and intensity of climate-related disasters (see, e.g., Creamer and Gao, 2015; Wagner and Weitzman, 2015).

2.3 Industrial CO_2 emissions

Here, in order to formulate emissions E_Y so that they may vary over time and to allow abatement to be zero, we specifically utilize the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005) that breaks down CO_2 emissions E_Y (in GtC yr^{-1}) into a product of five components: emissions per unit of energy consumed (carbon intensity of energy), energy use per unit of aggregate GDP (energy intensity), per capita GDP, human population, and carbon emission intensity, as shown below:

$$\begin{aligned} E_Y &= \left(\frac{E_{tot}}{\text{energy}}\right)\left(\frac{\text{energy}}{\bar{Y}}\right)\left(\frac{\bar{Y}}{L}\right)L\left(\frac{E_Y}{E_{tot}}\right) \\ &= c_c e_c Y L \kappa_{ccs} \\ &= \sigma Y L \kappa_{ccs}. \end{aligned} \tag{11}$$

Here $\bar{Y}$ is aggregate GDP, $Y=(\bar{Y}/L)$ is per capita GDP, L is the human population, $c_c = E_{tot}/\text{energy}$ is the carbon intensity of energy, $e_c = \text{energy}/\bar{Y}$ is the energy intensity, $c_c e_c = E_{tot}/\bar{Y} = \sigma$ is the ratio of industrial carbon emissions to aggregate GDP or the economy carbon intensity, $E_Y/E_{tot} = \kappa_{ccs}$ is the fraction of emissions that is vented to the atmosphere and involves CCS.

The E_Y level also depends on abatement activities, as invested in the increase of overall energy efficiency in the economy and decrease of overall carbon intensity of the energy system. The case of $\tau_b = 0$ in Eq. (5) corresponds to unabated emissions, i.e. BAU. Emissions are reduced as the abatement share increases. Taking the natural logarithms and differentiating both sides of the Kaya–Bauer identity yields

$$\frac{dE_Y}{dt} = \left[g_\sigma + g_Y + n + g_{ccs}\right]E_Y, \tag{12}$$

where g_σ is the growth rate of σ, g_Y is the growth rate of Y, n is the population growth rate and g_{ccs} is the CCS growth rate. If CCS is applied, then $E_Y < E_{tot}$. There are many concerns and uncertainties about the CCS approach and it is usually not taken as a really sustainable and environmental friendly mitigation option to reduce emissions over a longer period (Tol, 2010; Bowen, 2014). We will not consider it in this Part 1 of the paper, that is, we take here $E_{\mathrm{Y}} = E_{\mathrm{tot}}$ or $\kappa_{\mathrm{ccs}} = 1$.

We now formulate the technology-dependent carbon intensity σ. We follow the approach of Sahal (1985), who models the replacement of one technology by another using a logistic law. The energy intensity e_{c}, in tons of reference fuel (TRF) (USD 1000 of $\bar{Y}$)$^{-1}$, is the share of hydrocarbon-based energy (coal, oil, and natural gas) in the global energy balance (GEB) of the twenty-first century. Its dynamics are described by a descending logistic function (Akaev, 2015),

$$e_{\mathrm{c}} = f_{\mathrm{c}}\left[1 - \frac{r\exp(\psi t)}{1 + r\left(\exp(\psi t) - 1\right)}\right]. \tag{13}$$

Here we take 1990 as the time when the use of renewable energy sources — biomass and wastes, hydropower, geothermal energy, wind energy, and solar energy — and biofuels became significant in the GEB. The multiplier $f_{\mathrm{c}} = 0.881$ corresponds to 1.0107×10^{10} TRF as the share of fossil fuels in the GEB (1.1472×10^{10} TRF) in 1990 (Akaev, 2015, Table 21.4). The parameters r and ψ are derived by assuming a level of 95 % fossil fuels used for year 2020 and of 5 % for year 2160. They are $r = 0.05$ and

$$\psi = \psi_0\left(\frac{1}{1 - \alpha_\tau \tau_{\mathrm{b}}}\right), \tag{14}$$

with $\psi_0 = 0.042$ and τ_{b} is the abatement share; $\alpha_\tau > 0$ here is an abatement efficiency parameter, chosen such that for the path corresponding to $\tau_{\mathrm{b}} = 0.075$, carbon emissions reduction from BAU is about 50 % by year 2050; see Sect. 2.5 for details. Calculations based on Eq. (13) using these values indicate that the share of fossil fuels will be significant throughout the whole twenty-first century and, when $\tau_{\mathrm{b}} = 0$, this share decreases to 35 % only by its end (Akaev, 2015).

As different types of fossil fuels produce different volumes of CO_2 in combustion, the dynamics of fossil fuel consumption – i.e., the relative shares of coal, oil, and natural gas – should be taken into account when calculating the future dynamics of CO_2 emission. Since these shares are not known at this time, we assume a logistic function for describing a reduction of the carbon intensity of energy c_{c}, in tons of carbon (tC) TRF^{-1}, throughout the 21st century (Akaev, 2015),

$$c_{\mathrm{c}} = c_{-\infty} + \frac{a_{\mathrm{c}}}{1 + r\exp(-\psi t)}, \tag{15}$$

with $a_{\mathrm{c}} > 0$ a constant and $c_{-\infty}$ is the value of c_{c} before 1990.

Thus the carbon intensity σ, which represents the trend in the CO_2-output ratio, can now be given by the product of the energy intensity e_{c} in Eq. (13) and the carbon intensity of energy c_{c} in Eq. (15) as:

$$\sigma = f_{\mathrm{c}}\left[1 - \frac{r\exp(\psi t)}{1 + r\left(\exp(\psi t) - 1\right)}\right]\left[c_{-\infty} + \frac{a_{\mathrm{c}}}{1 + r\exp(-\psi t)}\right]. \tag{16}$$

We can now calculate the de-carbonization of the economy, i.e. the declining growth rate of σ, by taking the natural logarithms of Eq. (16) and getting the derivative with respect to time:

$$g_\sigma = \frac{f_{\mathrm{c}}}{e_{\mathrm{c}}}\left\{\frac{\left[\psi r\exp(\psi t)\right]\left[1 + r\left(\exp(\psi t) - 1\right)\right] - \left[\psi r^2\exp(\psi t)\right]}{\left[1 + r\left(\exp(\psi t) - 1\right)\right]^2}\right\} + \frac{1}{c_{\mathrm{c}}}\left\{\frac{a_{\mathrm{c}}\psi r\exp(-\psi t)}{\left[1 + r\exp(-\psi t)\right]^2}\right\}. \tag{17}$$

We note that the de-carbonization of the economy, i.e. the declining growth rate of the carbon intensity σ in Eq. (16) is also assumed to be time-dependent. Fossil-fuel consumption has been subject to a gradual de-carbonization process since the early times of industrialization, by a transition—in chronological order—from the use of wood to coal, from coal to oil, and in the most recent past from coal and oil to natural gas (see also, Gerlagh and Van der Zwaan, 2003). The effect of the abatement share τ_b is to make this process slower or faster.

In a similar way as Eq. (17) was derived from Eq. (16), the growth rate g_Y of per capita output is obtained from Eq. (3) as

$$\frac{1}{Y}\frac{dY}{dt} = \frac{\alpha}{K}\frac{dK}{dt} + \frac{(1-\alpha)}{H}\frac{dH}{dt} + \frac{1}{D}\frac{dD}{dT}\frac{dT}{dt},$$

or,

$$g_Y = \alpha g_K + (1-\alpha) g_H + \frac{1}{D}\frac{dD}{dT}\frac{dT}{dt}, \quad (18)$$

with g_K the per capita physical capital growth and g_H the per capita human capital growth.

Human population evolves; cf. Golosovsky (2010), as

$$\frac{dL}{dt} = nL\left\{1-\exp\left[-\left(L/L(1990)\right)\right]\right\}, \quad (19)$$

where n is the population growth rate as given in Eq. (8) and $L(1990)$ is the 1990 population. Equation (19) yields $L = 9\times10^9$ people in the year t = 2100. This value is consistent with the 2100 population projections of scenarios in the literature (e.g., Van Vuuren et al., 2012, Table 3; Grinin and Korotayev, 2015, p. 197, Fig. B.12a).

2.4 Damage function

The damage function D gives the decline in Y, the global GDP, which results from an increase of the temperature T above the pre-industrial temperature $\hat{T}$. Nordhaus (1994a) formulates D as

$$D(T-\hat{T}) = \left[1 + m_1\left(T-\hat{T}\right)^{\chi}\right]^{-1}, \quad (20)$$

with both the coefficient m_1 and the exponent χ positive, $m_1 > 0$ and $\chi > 0$, while the damage is defined as $Y - DY = (1-D)Y$. The greater the difference $T-\hat{T}$, the smaller will the value of $D(T-\hat{T})$ be, and thus the smaller the value DY of the remaining GDP, after the damage.

The representation of climate change damages is both a key part and one of the weakest points of IAMs (Tol and Fankhauser, 1998). Nordhaus (1994a) used temperature originally as a proxy for overall climate change. This may have taken the research community's focus off from potentially dangerous changes in climate apart from temperature (Toth, 1995). However, without using a detailed climate model, temperature remains the best option available (Sanderson, 2002). We assume, in choosing this option, that physical and human capitals are distributed across infinitely many areas in the economy, and that the strongly differential damages (Richardson et al., 2011, p. 245) by climate-related natural disasters are uncorrelated across areas. With such an assumption, some version of the law of large numbers can justify a result like Eq. (20) above; see Wouter Botzen and Van den Bergh (2012) and Dell et al. (2014) for an insightful discussion about the damage function.

In the original DICE calculations of Nordhaus (1994a), CO_2 doubling was equivalent to a 3 °C warming, and he first estimated the damage from this doubling to be 1.33 % of global GDP. Additionally, he argued that damage would increase sharply as temperature increases; hence he used a quadratic function, in which $\chi = 2$, and m_1 is chosen to have 1.33 % loss of GDP for a 3 °C warming.

Roughgarden and Schneider (1999), using the same functional form in Eq. (20), derived damage functions for each of the disciplines represented in an expert opinion solicited by a climate change survey (Nordhaus, 1994b). Taking an average of their values, we get $m_1 = 0.0067$; see, for instance, Table 1 in Labriet and Loulou (2003). 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 (Riahi et al., 2007; IPCC, 2013, p. 27, Table SPM.3); see Sect. 4.1 for details on our calibration of χ. In fact, our projected climate change damages before and after abatement, as given by the damage function D in Eq. (20), are consistent with the damages projected in Stern (2007); see also Creedy and Guest (2008), Chen et al. (2012, p. 5), Moyer et al. (2013) , Van Den Bergh (2015), as well as the further discussion in Sect. 5.2 below.

2.5 Abatement measures and abatement share

A key part of the mitigation literature concentrates on the feasibility of different climate targets, often defined by GHG concentrations or by radiative forcing levels, and the associated costs; see Van Vuuren et al. (2012) and the references therein. The broad range of options available for mitigating climate change includes the reduction of CO_2 emissions — increasing energy efficiency, increasing non-fossil fuel-based energy production, and the use of CCS — and CO_2 removal (Bickel and Lane, 2010; Edenhofer et al., 2012; Steckel et al., 2013; Creamer and Gao, 2015).

The Paris Agreement duly reflects the latest scientific understanding of systemic global warming risks. Stabilizing GHG concentrations, and hence temperatures, requires transformational change across the board of modernity (Schellnhuber, 2016); see Appendix A for more details.

We now determine the abatement share, τ_b, which is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and is being used here as a policy tool. The abatement share is used in the de-carbonization of the economy, cf. Eq. (16), through the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right) \right]$; see also Eq. (14).

The abatement costs of several IAMs tend to cluster in the range of about 1–2 % of GDP as the cost of cutting carbon emissions from BAU by 50 % in the period 2025–2050, and about 2.5–3.5 % of GDP as the cost of reducing emissions from BAU by about 70 % by 2075–2100 (Tol, 2010, p. 87, Fig. 2.2; Van Den Bergh, 2015). Clarke et al. (2014) show that, as higher emission reduction targets are set, the uncertainty increases and so does the dispersion of results.

The gross costs in IAMs typically do not include any estimate of the benefits of climate change mitigation and usually do not include offsets from any so-called "co-benefits," such as reduced damages from air pollution on human health and on crop productivity (Barker and Jenkins, 2007), greater energy security, greater access to energy services for the poor, higher rates of innovation (Bowen, 2014), and creation of new industries and jobs (Flavi and Engelman, 2009). Nor do they usually include benefits from policy reforms designed to correct market failures standing in the way of climate change mitigation, apart from carbon pricing to address the central GHG externality (Bowen, 2014). To obviate the shortcomings of this omission, we now include such benefits — albeit in an aggregate, highly idealized manner — in the CoCEB model.

Using the definition of abatement in Eq. (5), the GDP evolution in Eq. (3) and an annual tax rate $\tau = 0.2$ (Greiner and Semmler, 2008), we obtain an abatement share that gives an abatement cost equivalent to 1 % of GDP by 2050 to be

$$\frac{G_E}{Y} = \tau_b \tau = 0.01 \Rightarrow \tau_b = 0.05 . \tag{21}$$

Similarly, the abatement share giving an abatement cost equivalent to 2 % of GDP by 2050 is $\tau_b = 0.1$. We take, as our lower abatement share, the average $\tau_b = 0.075$ of the two abatement shares above; this τ_b–value gives an abatement cost equivalent to 1.5 % of GDP by 2050.

Next, we choose the abatement efficiency parameter $\alpha_\tau = 1.8$ such that, for the path corresponding to $\tau_b = 0.075$, carbon emissions reduction from BAU is about 50 % by 2050. Our scenario corresponding to $\tau_b = 0.075$ also happens to mimic the RCP6.0 by 2100 (Hijioka et al., 2008). For the other non-BAU scenarios, we choose abatement shares of $\tau_b = 0.11$ and 0.145, such that an emissions reduction of 50 % or more from BAU by 2050 and beyond gives a reduction in GDP of 2.2 and 2.9 %, respectively; the scenario given by $\tau_b = 0.11$ also mimics RCP4.5 (Wise et al., 2009). Note that the abatement shares in Greiner (2004) and Greiner and Semmler (2008), which use Eq. (11), are about 10 times lower than the ones chosen here.

2.6 Summary formulation of CoCEB

Our coupled CoCEB model is described by Eqs. (1), (2), (9), (10) and (12). The model describes the temporal dynamics of five variables: per capita physical capital K, per capita human capital H, the average global surface air temperature T, the CO_2 concentration in the atmosphere C, and industrial CO_2 emissions E_Y. The other variables are connected to these five independent variables by algebraic equations. In Part 2, a supplementary equation will be added for the biomass.

The equations are grouped for the reader's convenience below:

$$\frac{dK}{dt} = A\left[1-\tau(1+\tau_b)-c(1-\tau)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)-\left(\delta_K+n\right)K, \tag{22a}$$

$$\frac{dH}{dt} = \varphi\left\{A\left[1-\tau(1+\tau_b)-c(1-\tau)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\right\}-\left(\delta_H+n\right)H, \tag{22b}$$

$$\frac{dT}{dt} = \frac{(1-\alpha_T)Q}{4c_h}-\frac{\varepsilon\tau_a\sigma_T}{c_h}T^4+\frac{(6.3)\beta_1(1-\xi)}{c_h}\ln\left(\frac{C}{\hat{C}}\right), \tag{22c}$$

$$\frac{dC}{dt} = \beta_2 E_Y-\mu_o\left(C-\hat{C}\right), \tag{22d}$$

$$\frac{dE_Y}{dt} = \left[g_\sigma+g_Y+n\right]E_Y. \tag{22e}$$

The parameter values used in the model are as described in the text above and in Table 1 below. They have been chosen according to standard tables and previous papers.

3 Numerical simulations and abatement results

In the following, we confine our investigations to the transition path for the 110 years from the baseline year 1990 to the end of this century. The 1990 baseline is chosen, since it is the baseline often used in the Kyoto Protocol (Richardson et al., 2011, Chap. 13) as well as in a number of other international discussions concerning emissions reductions (Richardson et al., 2011, p. 284).

De Vries (2007) advises that one should not evaluate more than three or four scenarios at a time, because people cannot handle more due to cognitive limitations. We therefore consider four scenarios with an aggregate CO_2 concentration larger than or equal to the pre-industrial level: (i) a BAU scenario, with no abatement activities, i.e., $\tau_b = 0$; and (ii)–(iv) three scenarios with increasing abatement measures that correspond to τ_b = 0.075, 0.11 and 0.145, respectively, as chosen in Sect. 2.5.

The CoCEB model is integrated in time starting from the initial values at year 1990, as listed in Table 1. The damage function exponent χ in Eq. (20) is taken to be super-quadratic, $\chi = 2.43$; all other parameter values are as in Table 1. The time step is 1 year and the integration is stopped at year 2100. The values of CO_2 emissions and concentration, temperature, damage and per capita GDP growth at the end of the integrations are shown in Table 2 for the four scenarios.

From the table, it is clear that, if no action is taken to reduce BAU CO_2 emissions, these will attain 29.3 GtC yr^{-1} by 2100, leading to an atmospheric CO_2 concentration of 1842 GtC, i.e. about 3.1 times the pre-industrial level at that time. As a consequence, global average SAT will rise by 5.2 °C from the pre-industrial level, and the corresponding damage to the per capita GDP will be of 26.9 %. This finding compares favorably with the IPCC results for their RCP8.5 scenario, cf. Table 4 below.

The year-2100 changes in our three non-BAU scenarios' global mean SAT from the pre-industrial level are 3.4, 2.6, and 2 °C. The RCP6.0, RCP4.5, and RCP2.6 give a similar range of change in global SAT of 1.4–3.1 °C with a mean of 2.2 °C, 1.1–2.6 °C with a mean of 1.8 °C, and 0.3–1.7 °C with a mean of 1 °C, respectively (IPCC, 2013, p. 23, Table SPM.2). We note that our changes in temperature from our scenarios are fairly similar in magnitude to the IPCC ones; see also Dong et al. (2013, p. 8, Fig. 2.1).

The cumulative CO_2 emissions for the 1990–2100 period in this study's non-BAU scenarios are 1231, 1037, and 904 GtC. On the other hand, for the 2012–2100 period, RCP6.0 gives cumulative CO_2 emissions in the range of 840–1250 GtC with a mean of 1060 GtC; RCP4.5 gives a range of 595–1005 GtC with a mean of 780 GtC, while RCP2.6 gives a range of 140–410 GtC with a mean of 270 GtC (IPCC, 2013, p. 27, Table SPM.3). The two former RCPs agree rather well with our results, while RCP2.6 is less pessimistic.

In Fig. 1, the time-dependent evolution of the CoCEB output is shown, from 1990 to 2100. The figure shows that an increase in the abatement share τ_b from 0 to 0.145 leads to lower CO_2 emissions per year (Fig. 1a) as well as to lower atmospheric CO_2 concentrations (Fig. 1b) and, as a consequence, to a lower average global SAT (Fig. 1c), compared to the BAU value. This physical result reduces the economic damages (Fig. 1d) and hence the GDP growth decrease is strongly modified (Fig. 1e); see also Bréchet et al. (2015, Figs. 6.1–6.3).

A closer look at Figure 1a shows that the BAU emission trajectory peaks in 2064 at 48.2 GtC yr^{-1}. After that, the BAU trajectory drops back and, in doing so, approaches the CO_2 emissions of the RCP8.5 scenario by 2100, at an emissions level of 29.3 GtC yr^{-1}. This decrease is due to the fact that the emissions rate shown in Fig. 1f becomes negative, due to the decarbonization of the economy, according to Eqs. (17) and (22e).

In fact, our BAU scenario's energy technology is assumed constant at its 1990 level, in agreement with the IPCC BAU scenario; see Edmonds et al. (2004, p. 77) and Pielke et al. (2008) and Hay (2013, pp. 903–904). Our BAU CO_2 emissions are fairly similar to other scenarios given in the literature as well; see, for instance IPCC (2007c, Fig. TS.7), and Clarke et al. (2014, Fig. 6.4, left panel).

Figure 1e is a key result of our study: it shows that abatement policies do pay off in the long run. From the figure, we see that — because of mitigation costs — per capita GDP growth on the paths with nonzero abatement share, $\tau_b \neq 0$, lies below growth on the BAU path for the earlier time period, approximately between 1990 and 2060. Later though, as the damages from climate change accumulate on the BAU path (Fig. 1d), GDP growth on the BAU path (dashed) slows and falls below the level on the other paths (solid, dash-dotted and dotted), i.e., the paths cross. This result agrees with those of many other analyses in the literature, in which economic growth in the long run is higher with mitigation than without it; see, for instance, Guest (2010, Fig. 1), Richardson et al. (2011, p. 320), and Bréchet et al. (2015, Figs. 6.1 and 6.2).

This crossing of the paths means that mitigation allows GDP growth to continue on its upward path in the long run, while carrying on BAU leads to great long-term losses; see also Stern (2007, p. 35) and Bréchet et al. (2015); the simulations in the latter paper reveal that these losses may be much higher than usually appraised with IAMs in the literature because these IAMs define poorly their BAU scenario.

As will be shown in Table 3 below, the losses from mitigation in the near future are outweighed by the later gains in averted damage; see also, Stern (2007, p. 35, Fig. 2.3). The crossover time after which abatement activities pay off occurs around year 2060; its exact timing depends on the definition of damage and on the efficiency of the modeled abatement measures in reducing emissions; see also Bréchet et al. (2015).

The average annual growth rates (AAGRs) of per capita GDP between 1990 and 2100, are given in our model by $(1/110)\sum_{t=1990}^{t=2100} g_Y(t)$ and their values, starting from the BAU scenario, are 2.6, 2.4, 2.1 %, and 1.8 % yr^{-1}, respectively, see again Fig. 1e. Relative to 1990, these correspond to approximate per capita GDP increases of 5.5–14.5 times, that is USD_{1990} 34×10^3–90×10^3 in year 2100, up from an approximate per capita GDP of USD 6×10^3 in 1990. Our scenarios' AAGRs and the 2100-to-1990 per capita GDP ratio agree well with scenarios from other studies, which give AAGRs of 0.4–2.7 % yr^{-1} and a per capita GDP increase of 3–21 fold, corresponding to USD_{1990} 15×10^3–106×10^3 (Nakićenović and Swart, 2000; Schrattenholzer et al., 2005, p. 59; Nordhaus, 2007; Stern, 2007; Van Vuuren et al., 2012; Krakauer, 2014; Bréchet et al., 2015).

Now, according to the United Nations Framework Convention on Climate Change (UNFCCC, 2009, 2015), the average global SAT should not exceed its pre industrial level by more than 2° C; see also Akaev (2015) and Kuckshinrichs and Hake (2015, pp. 1 and 289). This SAT target means that global efforts to restrict or reduce CO_2 emissions must aim at an atmospheric CO_2 concentration of no more than 958.5–1171.5 GtC by year 2100 (Akaev, 2015).

This CO_2 target can be achieved if carbon emissions are reduced to no more than 3.3 GtC yr^{-1}, or nearly half relative to the 1990 level of 6 GtC yr^{-1} (Akaev, 2015). This goal is met, in our highly simplified model, by the path with the highest abatement share of the four, $\tau_b = 0.145$. From Table 2 and Fig. 1, we notice that this level of investment in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system enable emissions to decrease to 2.5 GtC yr^{-1} by year 2100 (Fig. 1a), about a 58 % drop below the 1990 emissions level; see also DDPP (2015). This emissions drop enables the deviation from pre-industrial SAT to reach no higher than 2 °C by year 2100 (Fig. 1c).

A number of studies (Calvin et al., 2009; Edmonds et al., 2013; Bowen, 2014; Clarke et al., 2014, and references therein; DDPP, 2015; Rogelj et al., 2015) have shown that achieving even smaller increases of SAT than the 2 °C level by 2100 is technologically feasible and that it is also likely to be economically affordable. Our $\tau_b = 0.145$ scenario, however, cannot guarantee a deviation from pre-industrial SAT that is substantially less than 2 °C by 2100.

In Table 3, we compare per capita abatement costs $G_E = \tau_b X = \tau_b \tau Y$ and the damage costs $(1-D)Y$ for the year 2100, for each one of our emission reduction paths; these are given in Eqs. (5) and (20), respectively. From the table one notices that, not surprisingly, the more one invests in abatement, the more emissions are reduced relative to BAU and the less the cost of damages from climate change; see also Edenhofer et al. (2015, Table 12.1). Tables 2 and 3 show that limiting global average SAT to no more 2 °C over pre-industrial levels would require an emissions reduction of 92 % from BAU by 2100, at a per capita cost of USD$_{1990}$ 990, i.e., an aggregate of USD$_{1990}$ 8.1 trillion, which translates to 2.9 % of per capita GDP. Our cost of abatement compares fairly well with those found in the literature, e.g., in McJeon et al. (2011). Although attaining the 2 °C goal comes at a price, the damages will be lower all along and the GDP growth better than for BAU starting from the cross-over year 2058.

Recall, moreover, that the benefits of GHG abatement are not limited to the reduction of climate change costs alone. A reduction in CO_2 emissions will often also reduce other environmental problems related to the combustion of fossil fuels (Van Den Bergh, 2015). Other co-benefits cover increased energy security (Jewell et al., 2016), increased agricultural production, and reduced pressure on ecosystems due to decreased tropospheric ozone concentrations (Pachauri, 2012). The size of these so-called secondary benefits is site-dependent (IPCC, 1996b, p. 183), and we plan to take it into consideration in future versions of the CoCEB model. However, the attractiveness of mitigation measures has to be understood and quantified particularly by including co-benefits that are numerous and substantial (Pachauri, 2012; Rosen, 2016).

Table 4 gives a comparative summary of our CoCEB model's results and those from other studies that used more detailed IAM models and specific RCPs from IPCC (2013). We notice that the CO_2 emissions per year and the concentrations in the transition paths up to year 2100 agree fairly well with those of RCP8.5, RCP6.0 and RCP4.5, for τ_b = 0.0 (BAU), 0.075 and 0.11.

4 Sensitivity analysis

Most modelers are careful in specifying their BAU assumptions but they rarely report results from sensitivity analyses; see also Böhringer and Löschel (2004, p. 7) and Rosen (2016). We conducted an analysis to ascertain the robustness of the CoCEB model's results and to clarify the degree to which they depend on three key parameters: the damage function parameters m_1 and χ and the abatement efficiency parameter α_τ. The values of these parameters are varied below in order to gain insight into the extent to which particular model assumptions affect our results in Sect. 3 above.

4.1 Damage function parameters m_1 and χ

Considering the damage function of Eq. (20), the choice of the parameters $m_1 > 0$ and $\chi > 0$ in the literature is ad hoc and based on "informed guesses" (Peck and Teisberg, 1994). Clearly, the exponent χ is more important than the coefficient m_1, as the shape of the damage function varies from linear to cubic, $1 \le \chi \le 3$ (Ackerman et al., 2009), while $0.0022 \le m_1 \le 0.0231$, cf. Roughgarden and Schneider (1999) and Labriet and Loulou (2003).

We modify the values of the parameters m_1 and χ by +50 and −50 % from their respective values of $m_1 = 0.0067$ and $\chi = 2.43$ in Tables 1–4 above, so as to get their ranges into fair agreement with the ones in the literature, and examine how that affects model results for year 2100. In Table 5 are listed the per annum CO_2 emissions, CO_2 concentrations, SAT, damages, and growth rate of per capita GDP. All parameter values are as in Table 1, including $\alpha_\tau = 1.8$.

From Table 5, we notice that reducing m_1 by 50 % lowers the damages at year 2100 to per capita GDP from 26.9 % to 20.3 %, i.e. a 24.5 % decrease for the BAU path. This damage reduction depresses the economy less and contributes to the CO_2 emissions being higher, at 50.8 GtC yr^{-1}. On the other hand, increasing m_1 by 50 % increases the damages from 26.9 % to 30.3 %, i.e. a 12.6 % increase for the BAU path. This increase in damages depresses the economy more and lowers CO_2 emissions in 2100 to 20.4 GtC yr^{-1}.

The sensitivity to the exponent χ is considerably higher. Decreasing it by 50 % reduces the damages to per capita GDP from 26.9 % to about 6.3 %, i.e. a 76.6 % reduction for the BAU path. This reduction contributes to higher economic growth and still to the emissions being higher and equal now to 99.6 GtC yr^{-1}. Conversely, increasing χ by 50 % increases the damages to per capita GDP from 26.9 % to about 41.6 %, i.e. a 54.6 % increase for the BAU path. This increase contributes to a decrease in economic growth and to lower emissions of 6 GtC yr^{-1} in the year 2100.

In Fig. 2, we plot the GDP growth in time for the experiments summarized in Table 5. It is clear from the figure that the growth rate of per capita GDP is more sensitive to the exponent χ than to the coefficient m_1. A decrease of m_1 by 50 % pushes the crossover point further into the future, from year 2058 to 2070 (Fig. 2a), while an increase by 50 % pulls the crossover point closer to the present, to about 2053 (Fig. 2b). Decreasing χ by 50 %, on the other hand, pushes the crossover point even further away, past the end of the century (Fig. 2c), while an increase of χ by 50 % pulls it from year 2058 to about 2037 (Fig. 2d).

4.2 Abatement efficiency parameter α_τ

Next, we modify the value of the parameter α_τ by +50 % and −50 % from the standard value of $\alpha_\tau = 1.8$ used in Tables 1–5 above, and examine in Table 6 how that affects the model emissions reduction from BAU by the year 2100, as well as the per capita abatement costs and the per capita damage costs.

A 50 % decrease of the abatement efficiency gives $\alpha_\tau = 0.9$ in the upper half of the table. There is a substantial decrease in emissions reduction for all three scenarios with $\tau_b > 0$, compared to Table 3, and hence more damages for the same abatement costs. Furthermore, the increased damages increase the depression of the economy and contribute to low economic growth.

On the other hand, a 50 % increase in the abatement efficiency, to $\alpha_\tau = 2.7$, leads to an increase in the emissions reduction from BAU by 2100. This reduces the damages and hence lessens the depression to the economy, enabling economic growth to increase.

5 Conclusions, comparison to previous studies, and way forward

5.1 Summary

In this paper, we introduce a simple coupled climate–economy (CoCEB) model with the goal of understanding the various feedbacks involved in the system and also for use by policy makers in addressing the climate change challenge. In this Part 1 of our study, economic activities are represented through a Cobb–Douglas output function with constant returns to scale of the two factors of production: per capita physical capital and per capita human capital. The income after tax is used for investment, consumption, and abatement.

Climate change enters the model through the emission of GHGs arising in proportion to economic activity. These emissions accumulate in the atmosphere and lead to a higher global mean surface air temperature (SAT). This higher temperature then causes damages by reducing output according to a damage function. The CoCEB model, as formulated here, was summarized in Eqs. (22a)–(22e) in Sect. 2.6.

Using this model, we investigate in Sect. 3 the relationship between investing in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system through abatement activities. The time evolution, from 1990 to 2100, of the growth rate of the economy under threat from climate change–related damages is likewise studied. The CoCEB model shows that taking no abatement measures to reduce GHGs leads eventually to a slowdown in economic growth; see also Kovalevsky and Hasselmann (2014, Fig. 2).

This slowdown implies that future generations will be less able to invest in emissions control or adapt to the detrimental impacts of climate change (Krakauer, 2014; Wagner and Weitzman, 2015). Therefore, the possibility of a long-term economic slowdown due to lack of abating climate change heightens the urgency of reducing GHGs by investing in low-carbon technologies; see Xu et al. (2014) for innovative approaches towards low-carbon economics. Even if this incurs short-term economic costs, the transition to a de-carbonized economy is both feasible and affordable, according to Azar and Schneider (2002), Weber et al. (2005), Stern (2007), and would, in the long term, enhance economic growth and hence wealth (Hasselmann, 2010).

Few studies, though, focus on devising climate policy that aims to combine economic growth with emissions reductions (Pielke, 2010, p. 66). The CoCEB model shows that an increase in the abatement share of investments can yield a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions and, as a consequence, with a decrease in average global SATs and in the ensuing damages; see also Greiner (2004), Greiner and Semmler (2008, pp. 95 and 120), and Sterner and Coria (2012, p. 154). These results hold when considering the entire transition path from now to 2100, as a whole. Such a positive outcome's realization in practice depends crucially, though, on the correctness of the functional relation between the economic damage and climate change assumed herein; see also Greiner (2004) and Greiner and Semmler (2008, p. 120).

5.2 Comparison to previous studies

The CoCEB model is a simplified version of the DICE 2013 model. The purpose of this simplification is to achieve greater flexibility and transparency. These features make it feasible to carry out systematic sensitivity studies and gain insight into the importance of model assumptions in terms of achieving desirable policy goals.

We now compare CoCEB to the performance of the climate module in the models used in Clarke et al.'s (2014) assessment, such as the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC). MAGICC has been used in all IPCC Assessment reports, dating back to 1990. In particular, Working Group 1 of IPCC (2013) uses MAGICC for Projections of Global and Regional Climate Change (chapter 5), and DICE itself is calibrated to an earlier version of the MAGICC model (Nordhaus, 2008, p. 54; Traeger, 2014). The climate model in MAGICC is an upwelling–diffusion model building on a hemispherically averaged energy balance equation. It models carbon uptake and warming feedbacks — both transient and long-run — in much greater detail than DICE's simple three-box linear carbon cycle and temperature delay equations (Nordhaus and Boyer, 2000).

CoCEB only endogenizes fossil fuel–based CO_2 emissions. In contrast, MAGICC explicitly models the dynamics of a large set of GHGs. The IPCC's emission scenarios vary CO_2 emissions, as well as the emission levels of other GHGs. Still, our model represents fairly well the different RCP scenarios (see Tables 2 and 4), solely by adjusting endogenous CO_2 emissions. Thus our highly simplified IAM replicates the responses to more comprehensive policy approaches regulating several GHGs just by endogenizing the main source of GHGs; see also Traeger (2014) for a further discussion.

The need for a hierarchy of models of increasing complexity is an idea that dates back in the climate sciences to the beginnings of numerical modeling (e.g., Schneider and Dickinson, 1974), and has been broadly developed and applied since (Ghil, 2001, 2016, and references therein). The climate model hierarchy ranges from simple, conceptual ordinary differential equation (ODE) models (e.g., Rombouts and Ghil, 2015), like the one formulated and analyzed herein, through intermediate models of varying complexity (e.g., Claussen et al., 2002; Eby et al., 2009) and all the way up to full-scale general circulation models or global climate models (GCMs; e.g., Brönnimann, 2015, and references therein). There is an equivalent need for such a model hierarchy to deal with the higher-complexity problems at the interface of the physical climate sciences and of socio-economic policy.

The CoCEB model and the results of this paper have to be viewed in the broader perspective of the hierarchy of climate models. CoCEB lies toward the highly idealized end of such a hierarchy. It cannot, nor does it claim to, represent the details of the real world. Simple models do not provide a quantitative description of the fully coupled dynamics of the real climate–economy–biosphere system; on the other hand, though, the study of such models provides insights and makes it possible to understand the qualitative mechanisms of the coupled-system processes and to evaluate their possible consequences. The role of the intermediate models is to refine these insights and bridge the gap between the simple models and the GCMs (Ghil, 2001; Claussen et al., 2002): on the one hand, they are still simple enough to allow a fairly thorough analysis of their behavior; on the other, they may be detailed enough for a direct comparison with the GCMs and with increasingly more plentiful and accurate observational data sets (see, e.g., Lu, 2015).

Moving from the climate module of IAMs to their economic module, we note that, in the DICE model, the economic costs associated with addressing and coping with climate warming are quantified by coupling a system of economic equations to an intermediate-complexity climate model. Given a variable-and-parameter space whose dimension is of the order of 19×65, the DICE model's outcome is an optimized trajectory for long-term societal welfare to which policy measures can be compared (Nordhaus and Sztorc, 2013).

The CoCEB model has 5 variables and 36 parameters**.** The dimension 5×36 of its variable-and-parameter space is thus considerably smaller than that of DICE. At the same time, CoCEB builds upon previous work on coupled models of global climate–economy interactions. It can thus be used to study not just one optimized trajectory, but a large variety of them, as well as their sensitivity to model assumptions and parameter values, while still maintaining a fairly reasonable degree of credibility.

CoCEB's year 2100 climate change damages before and after abatement range between 1.9–41.6 percent. Our model's damage values thus do agree fairly well with those in the literature; see, for instance, Creedy and Guest (2008).

For the damage function specifications of the DICE (Nordhaus, 2008), FUND (Anthoff et al, 2009) and PAGE (Hope, 2006) IAMs, however, even massive climate change damages have little effect on long-term economic growth; see, for instance, Wagner and Weitzman (2015). This common IAM feature may be explained by the Ramsey model of optimal economic growth used as the basis for DICE, a model which assumes that economic growth is not limited by natural resources or environmental changes (Costanza et al., 2007).

Several other authors test alternative representations of climate damages (e.g., Ackerman et al, 2010), but all yield economies that grow even in the presence of large climate damages. The robustness of growth in these models suggests that their specification of climate damages may not reflect the full range of possible harms of climate change; see also Stern (2013), Wagner and Weitzman (2015), and Rosen (2016).

Technological change in CoCEB is modeled in a simple way by using logistic functions, in which growth depends on abatement investment. This is a novel approach with respect to most other IAM studies in the climate change mitigation literature, in which technological change is assumed to be independent of public policy; see, for instance, the DICE (Nordhaus, 2007) and FOR-DICE (Eriksson, 2015) models, Tol's (2010) FUND and Van Vuuren et al.'s (2006a) IMAGE model.

While there clearly is room for improvement in our highly idealized CoCEB model, it is no worse in reproducing temperature responses for our set of emission scenarios than the RCP 8.0, 6.0 and 4.5 scenarios used in the most recent IPCC Assessment Report (IPCC, 2013). The largest deviation in CoCEB from the IAMs reviewed by Clarke et al. (2014), e.g., MAGICC, occurs for our scenario corresponding to $\tau_b = 0.145$, the highest abatement share of the four.

5.3 Way forward

The CoCEB model, as developed in this first part of a two-part study, is sufficiently simple as to be transparent, to allow a range of sensitivity analyses, and to be available for a number of further extensions. The current model version analyzes the carbon policy problem in a single-box global model with the aim of understanding theoretically the dynamic effects of using the abatement share as a climate change mitigation strategy. To be able to draw more concrete, quantitative policy recommendations is it important to account for regional disparities, an essential development left to future research.

The determination of an optimal set of abatement paths (Smirnov, 2005; Pivovarchuk, 2008) being the object of future work, we discuss here a number of improvements and extensions that will facilitate the formulation of the optimal control problem associated with the CoCEB model; see, for instance, Maurer et al. (2015).

Concerning first the damage function, Stern (2007) states that "Most existing IAMs also omit other potentially important factors — such as social and political instability and cross-sector impacts. And they have not yet incorporated the newest evidence on damaging warming effects," and he continues "A new generation of models is needed in climate science, impact studies and economics with a stronger focus on lives and livelihoods, including the risks of large-scale migration and conflicts" (Stern, 2013, 2016).

Nordhaus and Sztorc (2013) suggest, more specifically, that the damage function needs to be reexamined carefully and possibly reformulated in cases of higher warming or catastrophic damages. Although there is considerable uncertainty surrounding climate-related damages, we find that, in our CoCEB model, assuming greater damages, via higher values of the exponent χ, has the effect of advancing the crossover time, starting at which the abatement-related costs start paying off in terms of increased per capita GDP growth. It seems, therefore, that it is compatible with better overall outcomes to assume a damage function that is more nonlinear.

A major drawback of current IAMs is that they mainly focus on mitigation in the energy sector (Van Vuuren et al., 2006b, p. 166) and mostly aim at reducing fossil fuel emissions. For example, the RICE and DICE (Nordhaus and Boyer, 2000) models consider emissions from deforestation as exogenous. Nevertheless, GHG emissions from deforestation and current terrestrial uptake are significant and deserve greater attention for determining the potential of CO_2 mitigation strategies; see Palmer and Engel (2009), Ciais et al. (2013), Scott (2014), and references therein. Several studies provide evidence that forest carbon sequestration can help reduce atmospheric CO_2 concentration significantly and in a cost-efficient way (e.g., Bosetti et al., 2011).

In Part 2 of this paper, we report on work along these lines, by introducing a biosphere module into CoCEB. This model version allows us to study relevant economic aspects of deforestation control and carbon sequestration in forests, as well as the widespread application of CCS technologies as alternative policy measures for climate change mitigation. Moreover, in order to understand the dynamic role of energy production and consumption in this broader context, we also plan to extend the CoCEB model by introducing energy as a production factor that can be substituted by labor and capital, which is not the case in most IAMs; see also Garrett (2015, and references therein).

Finally, current IAMs disregard endogenous variability and represent both climate and the economy as a succession of equilibrium states with no endogenous dynamics. This shortcoming can be overcome by introducing business cycles into the economic module (e.g., Chiarella et al., 2005, and references therein; Akaev, 2007; Hallegatte et al., 2008; Grasselli and Huu, 2015) and by taking them into account in considering the impact of natural, climate-related, as well as purely economic shocks (Hallegatte and Ghil, 2008; Groth et al., 2016).

Appendix A: Abatement policies

Although it is questionable how quickly the energy system could be transformed (Smil, 2010), GHG mitigation strategy proposals call for major, and relatively rapid, changes in the global energy system (Barker and Jenkins, 2007; Miller, 2013). For reasons of political feasibility as well as of efficiency, the focus of climate policy has been on energy intensity and carbon intensity of energy, and not on population and wealth (Pielke, 2010, p. 109; Tol, 2010; Miller, 2013). All the popular policies point to increased de-carbonization efforts, i.e. to an increase in g_σ. The historical record, however, shows quite clearly that global and regional rate of de-carbonization have seen no acceleration during the recent decade and in some cases even show evidence of re-carbonization (Prins et al., 2009; Garrett, 2015). This situation is inconsistent with a path of keeping T below 2 °C over pre-industrial levels, and poses the risk of humanity's having to confront policy-relevant climatic shifts in the 21st century (Richardson et al., 2011, p. 163; Rockström et al., 2015) that could lead to potentially irreversible and unpredictable dynamical interactions (Rydge and Bassi, 2014).

When the costs of reducing emissions vary greatly between different entities (as they do for GHG emissions), market-based (economic) instruments are likely to be more efficient compared to command-and-control regulation (Baumol and Oates, 1971, 1988). Among the various economic instruments adopted to reduce CO_2 emissions, *carbon taxes* and *tradable permits* — as well as various hybrids of the two (Hepburn, 2010) — are the most widely discussed *cost-efficient* policies, both at a national and international level (Uzawa, 2003; Böhringer and Lange, 2005; Pizer, 2006; Nordhaus, 2008; Edenhofer et al., 2015). Both approaches provide incentives for producers and consumers to reduce emissions, and both should stimulate behavioral and technological change to conserve energy, or produce it from renewable sources (Dryzek et al., 2013, p. 59). Sometimes, neither permits nor taxes can be used, and the lack of information, uncertainty as well as the asymmetric information problems can make policy design quite complicated (Sterner and Coria, 2012, p. 163). Hence the need of having flexible and transparent model results to guide policy makers.

Forestry policies, particularly deforestation control, also emerge as additional low cost measures for the reduction of CO_2 emissions (see also, Sohngen, 2010). Deforestation control would cut CO_2 emissions and increased afforestation would sequester CO_2 from the atmosphere (see, e.g., Bosetti et al., 2011; Scott, 2014). However, one should not be too quick to reach general conclusions about which type of instrument is best suited. Choices should be made carefully, on a case-by-case basis (Sterner and Coria, 2012, p. 7), and follow-up on the present paper and Part 2 will bring in this approach into the CoCEB model in order to help decision makers.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was supported by the Energy and Prosperity Chair of the Fondation du Risque, Paris, and by Dedan Kimathi University of Technology (DeKUT), whose views it does not claim to represent. It is a pleasure to thank Hermann Held, Axel Kleidon and two anonymous reviewers for thoughtful and constructive comments that contributed to improve an earlier version of this manuscript. The CoCEB model code is available from the authors upon request.

References

Abdussamatov, H. I.: The New Little Ice Age Has Started, in: Evidence-Based Climate Science: Data Opposing CO_2 Emissions as the Primary Source of Global Warming, 2nd Edn., edited by Easterbrook, D. J., Elsevier, Amsterdam, Oxford, pp. 307–328, 2016.

Ackerman, F., Stanton, E. A., and Bueno, R.: Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE, Ecol. Econ., 69, 1657–1665, 2010.

Ackerman, F., Stanton, E. A., Hope, C., and Alberth, S.: Did the Stern Review underestimate US and global climate damages? Energ. Policy, 37, 2717–2721, 2009.

Akaev, A. A.: Derivation of the general macroeconomic dynamics equation describing the joint interaction of long-term growth and business cycles, Dokl. Math., 76, 879–881, 2007.

Akaev, A. A.: Stabilization of Earth's climate in the 21st century by the stabilization of per capita consumption, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 499–554, 2015.

Anthoff, D., Tol, S. J. R., and Yohe, G. W.: Risk aversion, time preference, and the social cost of carbon, Environ. Res. Lett., 4, 1–7, 2009.

Azar, C. and Schneider, S. H.: Are the economic costs of stabilizing the atmosphere prohibitive?, Ecol. Econ., 42, 73–80, 2002.

Barker, T. and Jenkins, K.: The costs of avoiding dangerous climate change: Estimates derived from a meta-analysis of the literature, A briefing paper for the United Nations Human Development Report 2007, contract No. 40015, Cambridge Centre for Climate Change Mitigation Research (4CMR), University of Cambridge, Cambridge, UK, 2007.

Barker, T., Ekins, P. and Johnstone, N.: Global Warming and Energy Demand, Routledge, London, UK, and New York, NY, USA, 281 pp., 1995.

Barron, R. and McJeon, H.: The differential impact of low-carbon technologies on climate change mitigation cost under a range of socioeconomic and climate policy scenarios, Energ. Policy, 80, 264–274, 2015.

Bauer, N.: Carbon capturing and sequestration – an option to buy time, PhD thesis, Faculty of Economics and Social Sciences, University Potsdam, Potsdam, Germany, 336 pp., 2005.

Baumol, W. J. and Oates, W. E.: The use of standards and prices for protection of the environment, in: The Economics of Environment: Papers from Four Nations, edited by: Bohm, P., and Kneese, A. V., Palgrave Macmillan, London and Basingstoke, UK, pp. 53–65, 1971.

Baumol, W. J. and Oates, W. E.: The Theory of Environmental Policy, 2nd Edn., Cambridge University Press, New York, NY, USA, 299 pp., 1988.

Bickel, J. E. and Lane, L.: Climate engineering, in: Smart Solutions to Climate Change: Comparing Costs and Benefits, edited by: Lomborg, B., Cambridge University Press, New York, NY, USA, pp. 9–51, 2010.

Böhringer, C. and Löschel, A. (Eds.): Climate Change Policy and Global Trade, Springer, Berlin, Heidelberg, Germany, 386 pp., 2004.

Böhringer, C. and Lange, A. (Eds.): Applied Research in Environmental Economics, Physica-Verlag, Heidelberg, Germany, 314 pp., 2005.

Bosetti, V., Lubowski, R., Golub, A., and Markandya, A.: Linking reduced deforestation and global carbon market: Implications for clean energy technology and policy flexibility, Environ. Dev. Econ., 16, 479–505, 2011.

Bowen, A.: The scope for "green growth" and a new technological revolution, in: The Global Development of

Policy Regimes to Combat Climate Change, edited by: Stern, N. H., Bowen, A., and Whalley, J., World Scientific Publ. Co., Singapore, pp. 133–155, 2014.

Bréchet, T., Camacho, C., and Veliov, V. M.: Adaptive model-predictive climate policies in a multicountry setting, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 114–138, 2015.

Brock, W. A. and Xepapadeas, A.: Modeling coupled climate, ecosystems, and economic systems, Department of International and European Economic Studies, Athens University of Economics and Business, Working Paper Series 15-08, 2015.

Brock, W.A., Xepapadeas, A., and Yannacopoulos, A. N.: Optimal control in space and time and the management of environmental resources, Annu. Rev. Resour. Economics, 6, 33–68, 2014.

Brönnimann, S.: Climatic Changes Since 1700, Springer, Switzerland, 373 pp., 2015.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S. H., Kyle, P., Smith, S. J., Thomson, A., and Wise, M.: 2.6: Limiting climate change to 450 ppm CO_2 equivalent in the 21st century, Energ. Econ., 31, 107–120, 2009.

Chang, C.-P., Ghil, M., Latif, M., and Wallace, J. M. (Eds.): Climate Change: Multidecadal and Beyond, World Scientific Publ. Co./Imperial College Press, Singapore, 388 pp., 2016.

Charney, J. G., Arakawa, A., Baker, D. J., Bolin, B., Dickinson, R. E., Goody, R. M., Leith, C. E., Stommel, H. M., and Wunsch, C. I.: Carbon Dioxide and Climate: A Scientific Assessment, National Academic Press, Washington, DC, USA, 22 pp., 1979.

Chen, W.-Y., Seiner, J., Suzuki, T., and Lackner, M. (Eds.): Handbook of Climate Change Mitigation, Springer, New York, NY, USA, 2158 pp., 2012.

Chiarella, C., Flaschel, P., and Franke, R.: Foundations for a Disequilibrium Theory of the Business Cycle: Qualitative Analysis and Quantitative Assessment, Cambridge University Press, New York, NY, USA, 2005.

Ciais, P., Gasser, T., Paris, J. D., Caldeira, K., Raupach, M. R., Canadell, J. G., Patwardhan, A., Friedlingstein, P., Piao, S. L., and Gitz, V.: Attributing the increase in atmospheric CO_2 to emitters and absorbers, Nat. Clim. Change, 3, 926–930, 2013.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., Van der Zwaan, B. C. C., and Van Vuuren, D. P.: Assessing Transformation Pathways, in: Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Edenhofer, O., Pichs Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., Von Stechow, C., Zwickel, T. and Minx, J. C., Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA, 2014.

Claussen, M., Mysak, L. A., Weaver, A. J., Crucifix, M., Fichefet, T., Loutre, M. F., Weber, S. L., Alcamo, J., Alexeev, V. A., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohman, G., Lunkeit, F., Mokhov, I. I., Petoukhov, V., Stone, P., and Wang, Z.: Earth system models of intermediate complexity: Closing the gap in the spectrum of climate system models, Clim. Dynam., 18, 579–586, 2002.

Cobb, C. W. and Douglas, P. H.: A theory of production, Am. Econ. Rev., 18, 139–165, 1928.

Costanza, R., Leemans, R., Boumans, R. M. J., and Gaddis, E.: Integrated Global Models, in: Sustainability or Collapse?: An Integrated History and Future of People on Earth, Report of the 96th Dahlem Workshop on Integrated History and future Of People on Earth (IHOPE) Berlin, June 12–17, 2005, edited by: Costanza, R., Graumlich, L. J., and Steffen, W., Massachusetts Institute of Technology and Freie Universität Berlin, Cambridge, MA, UK, 417–446, 2007.

Creamer, A. E. and Gao, B.: Carbon Dioxide Capture: An Effective Way to Combat Global Warming, Springer, Cham, Heidelberg, New York, Dordrecht, London, 62 pp., 2015.

Creedy, J. and Guest, R.: Sustainable preferences and damage abatement: Value judgments and implications for consumption streams, Research Paper 1026, Department of Economics, University of Melbourne, Melbourne, Australia, 2008.

De Vries, B. J. M.: Scenarios guidance for an uncertain and complex world?, in: Sustainability or Collapse?: An Integrated History and Future of People on Earth, Report of the 96th Dahlem Workshop on Integrated History and future Of People on Earth (IHOPE) Berlin, June 12–17, 2005, edited by: Costanza, R., Graumlich, L. J., and Steffen, W., Massachusetts Institute of Technology and Freie Universität Berlin, Cambridge, MA, UK, 379–397, 2007.

DeCanio, S. J.: Economic Models of Climate Change: A Critique, Palgrave Macmillan, New York, NY, USA, 218 pp., 2003.

DDPP (Deep Decarbonization Pathways Project): Pathways to deep decarbonization 2015 report, Sustainable Development Solutions Network (SDSN) & Institute for Sustainable Development and International Relations (IDDRI), 2015.

Dell, M., Jones, B. F., and Olken, B. A.: What do we learn from the weather? The new climate economy literature, J. Econ. Lit., 52, 740–798, 2014.

Diesendorf, M.: Redesigning Energy Systems, in: The Oxford Handbook of Climate Change and Society, edited by: Dryzek, J. S., Norgaard, R. B., and Schlosberg, D., Oxford University Press, New York, NY, USA, 561–579, 2012.

Diesendorf, M.: Sustainable Energy Solutions for Climate Change Mitigation, University of New South Wales Press Ltd, Sydney, Australia, 142–143, 2014.

Dong, W., Ren, F., Huang, J., and Guo, Y.: The Atlas of Climate Change: Based on SEAP-CMIP5: Super-Ensemble Projection and Attribution (SEAP) of Climate Change, Springer, Berlin, Heidelberg, Germany, 210 pp., 2013.

Dryzek, J. S., Norgaard, R. B., and Schlosberg, D.: Climate-Challenged Society, Oxford University Press, New York, NY, USA, 193 pp., 2013.

Eby, M., Zickfeld, K., Montenegro, A., Archer, D., Meissner, K. J., and weaver, A. J.: Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations, J. Climate, 22, 2501–2511, 2009.

Edenhofer, O., Flachsland, C., Jakob, M., and Lessmann, K.: The atmosphere as a global commons: Challenges for international cooperation and governance, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 260–296, 2015.

Edenhofer, O., Carraro, C., and Hourcade, J. C.: On the economics of de-carbonization in an imperfect world, Climatic Change, 114, 1–8, 2012.

Edmonds, J., Joos, F., Nakićenović, N., Richels, R. G., and Sarmiento, J. L.: Scenarios, Targets, Gaps, and Costs, in: The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World, edited by Field, C. B. and Raupach, M. R., Scientific Committee on Problems of the Environment (SCOPE) 62, Island Press, Paris, France, 2004.

Edmonds, J., Luckow, P., Calvin, K., Wise, M., Dooley, J., Kyle, P., Kim, S. H., Patel, P., and Clarke, L.: Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy and CO_2 capture and storage?, Climatic Change, 118, 29–43, 2013.

Eriksson, M.: The role of the forest in an integrated assessment model of the climate and the economy, Climate Change Economics, 6:1550011, 1–29, 2015.

Erk, N., Çabuk, A., and Ateş, S.: Long-run growth and physical capital-human capital concentration, METU International Economic Conference II, 9–12 September 1998, Ankara, 1998.

Flavi, C. and Engelman, R.: The perfect storm, in: 2009 State of the World: Into a Warming World, Worldwatch Institute, 5–12, 2009.

Fraedrich, K., Bordi, I., and Zhu, X.: Climate dynamics on global scale: Resilience, hysteresis and attribution of change, in: The Fluid Dynamics of Climate, edited by: Provenzale, A., Palazzi, E., and Fraedrich, K., Springer, Udine, Italy, 143–159, 2016.

Friedlingstein, P., Houghton, R. A., Marland, G., Hackler, J., Boden, T. A., Conway, T. J., J. Canadell, J. G., Raupach, M. R., Ciais, P. and Le Quéré, C.: Update on CO_2 emissions, Nat. Geosci., 3, 811–812, 2010.

Garrett, T. J.: No way out? The double-bind in seeking global prosperity alongside mitigated climate change, Earth Syst. Dynam., 3, 1–17, 2012.

Garrett, T. J.: Long-run evolution of the global economy – Part 2: Hindcasts of innovation and growth, Earth Syst. Dynam., 6, 673–688, 2015.

Gerlagh, R. and Van der Zwaan, B.: Gross world product and consumption in a global warming model with endogenous technological change, Resour. Energ. Econ., 25, 35–57, 2003.

Ghil, M.: Hilbert problems for the geosciences in the 21st century, Nonlinear Proc. Geoph., 8, 211–222, 2001.

Ghil, M.: A mathematical theory of climate sensitivity or, How to deal with both anthropogenic forcing and natural variability?, Ch. 2 in Climate Change: Multidecadal and Beyond, edited by: Chang, C. P., Ghil, M., Latif, M., and Wallace, J. M., World Scientific Publ. Co./Imperial College Press, pp. 31–51, 2016.

Ghil, M. and Childress, S.: Topics in Geophysical Fluid Dynamics: Atmospheric Dynamics, Dynamo Theory and Climate Dynamics, Springer, NY/Berlin/Tokyo, 1987.

Glotter, M. J., Pierrehumbert, R. T., Elliott, J. W., Matteson, N. J., and Moyer, E. J.: A simple carbon cycle representation for economic and policy analyses, Climatic Change, 126, 319–335, 2014.

Gollin, D.: Getting income shares right, J. Polit. Econ., 110, 458–474, 2002.

Golosovsky, M.: Hyperbolic growth of the human population of the Earth: Analysis of existing models, in: History and Mathematics: Processes and Models of Global Dynamics, edited by: Grinin, L., Herrmann, P., Korotayev, A., and Tausch, A., Uchitel, Volgograd, Russia, 188–204, 2010.

Grasselli, M. R. and Huu, A. N.: Inflation and speculation in a dynamic macroeconomic model, J. Risk Financial Manag., 8, 285–310, 2015.

Greiner, A.: Anthropogenic climate change in a descriptive growth model, Environ. Dev. Econ., 9, 645–662, 2004.

Greiner, A.: Climate change and second-best abatement in a multiregion world with endogenous growth, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, 204–221, 2015.

Greiner, A. and Semmler, W.: The Global Environment, Natural Resources and Economic Growth, Oxford University Press, New York, NY, 60–68, 2008.

Grinin, L. and Korotayev, A.: Great Divergence and Great Convergence: A Global Perspective, Springer, Switzerland, 261 pp., 2015.

Groth, A., Dumas, P., Ghil, M., and Hallegatte, S.: Impacts of natural disasters on a dynamic economy, in: Extreme Events: Observations, Modeling and Economics, edited by: Chavez, M., Ghil, M., and Urrutia-Fucugauchi, J., Geophysical Monograph 214, American Geophysical Union & Wiley, Washington, DC, USA, pp. 343–359, 2016.

Guest, R.: The economics of sustainability in the context of climate change: An overview, J. World Bus., 45, 326–335, 2010.

Gueymard, C.: The Sun's total and spectral irradiance for solar energy applications and solar radiation models, Sol. Energy, 76, 423–452, 2004.

Hallegatte, S. and Ghil, M.: Natural disasters impacting a macroeconomic model with endogenous dynamics, Ecol. Econ., 68, 582–592, 2008.

Hallegatte, S., Ghil, M., Dumas, P., and Hourcade, J. C.: Business cycles, bifurcations and chaos in a neoclassical model with investment dynamics, J. Econ. Behav. Organ., 67, 57–77, 2008.

Hannart, A., Ghil, M., Dufresne, J.-L., and Naveau, P.: Disconcerting learning on climate sensitivity and the uncertain future of uncertainty, Climatic Change, 119, 585–601, 2013.

Hans, G. K. and Hans, E.: Mathematics and Climate, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, Pennsylvania, USA, 318 pp., 2013.

Hasselmann, K.: The climate change game, Nat. Geosci., 3, 511–512, 2010.

Hay, W. W.: Experimenting on a Small Planet, Springer, Berlin, Heidelberg, Germany, 998 pp., 2013.

Held, H., Kriegler, E., Lessmann, K., and Edenhofer, O.: Efficient climate policies under technology and climate uncertainty, Energ. Econ., 31, S50–S61, 2009.

Hepburn, C.: Carbon Taxes, Emissions Trading, and Hybrid Schemes, in: The Economics and Politics of Climate Change, edited by: Helm, D. and Hepburn, C., Oxford University Press, New York, NY, USA, 365–384, 2010.

Hijioka, Y., Matsuoka, Y., Nishomoto, H., Masui, M., and Kainuma, M.: Global GHG emission scenarios under GHG concentration stabilization targets, J. Global Environ. Eng., 13, 97–108, 2008.

Hope, C.: The marginal impact of CO_2 from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern, IAJ, 6, 19–56, 2006.

Hüsler, A. D. and Sornette, D.: Human population and atmospheric carbon dioxide growth dynamics: Diagnostics for the future, Eur. Phys. J-Spec. Top., 223, 2065–2085, 2014.

Idso, C. D., Carter R. M., and Singer, S. F. (Eds.): Climate Change Reconsidered II: Physical Science, The Heartland Institute, Chicago, Illinois, USA, 868 pp., 2013.

IPCC: Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the IPCC, Cambridge University Press, Cambridge, 588 pp., 1996a.

IPCC: Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the IPCC, edited by: Bruce, J. P., Lee, H., and Haites, E. F., Cambridge University Press, Cambridge, 438 pp., 1996b.

IPCC: Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, Cambridge, 881 pp., 2001.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. M. B., Miller Jr., H. L., and Chen, Z., Cambridge University Press, Cambridge, 1206 pp., 2007a.

IPCC: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2007b.

IPCC: Summary for Policymakers, in: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the IPCC, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A., Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA, 2007c.

IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by: Stocker, T. F., Qin, D., Plattner, G.- K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, 1535 pp., 2013.

Jewell, J., Vinichenko, V., McCollum, D., Bauer, N., Riahi, K., Aboumahboub, T., Fricko, O., Harmsen, M., Kober, T., Krey, V., Marangoni, G., Tavoni, M., Van Vuuren, D. P., Van der Zwaan, B., and Cherp, A.: Comparison and interactions between the long-term pursuit of energy independence and climate policies, Nature Energ., 1, 1–9, 2016.

Kaya, Y.: Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios, Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, 1990.

Kemfert, C.: An integrated assessment model of economy–energy–climate – the model Wiagem, Integrat. Ass., 3, 281–298, 2002.

Kovalevsky, D. V. and Hasselmann, K.: Assessing the transition to a low-carbon economy using actor-based system-dynamic models, in: Proceedings of the 7th International Congress on Environmental Modeling and Software (iEMSs), edited by: Ames, D. P., Quinn, N. W. T., and Rizzoli, A. E., 15–19 June 2014, San Diego, California, USA, 1865–1872, available at: http: //www.iemss.org/society/index.php/iemss-2014-proceedings (last access: 5 October 2014), 2014.

Krakauer, N. Y.: Economic growth assumptions in climate and energy policy, Sustainability, 6, 1448–1461, 2014.

Kriegler, E., Weyant, J., Blanford, G. J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R. G., Rose, S., Tavoni, M., and Van Vuuren, D. P.: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies, Climatic Change, 123, 353 – 367, 2014.

Kuckshinrichs, W. and Hake, J.-F. (Eds.): Carbon Capture, Storage and Use: Technical, Economic, Environmental and Societal Perspectives, Springer, Switzerland, 352 pp., 2015.

Labriet, M. and Loulou, R.: Coupling climate damages and GHG abatement costs in a linear programming framework, Environ. Model. Assess., 8, 261–274, 2003.

Lenton, T. M.: Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model, Tellus B, 52, 1159–1188, 2000.

Levitus, S., Antonov, J., and Boyer, T.: Warming of the world ocean, 1955–2003, Geophys. Res. Lett., 32, L02604, 2005.

Lu, Q.-B.: New Theories and Predictions on the Ozone Hole and Climate Change, World Scientific Publ. Co., Singapore, 308 pp., 2015.

Maurer, H., Preuß, J. J., and Semmler, W.: Policy scenarios in a model of optimal economic growth and climate change, in: The Oxford Handbook of the Macroeconomics of Global Warming, edited by: Bernard, L. and Semmler, W., Oxford University Press, New York, NY, USA, pp. 82–113, 2015.

McGuffie, K. and Henderson-Sellers, A.: A Climate Modeling Primer, 3rd Edn., Wiley, Chichester, England, UK, 287 pp., 2005.

Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A. (Eds.): Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA, 863 pp., 2007.

Meyers, R. A. (Ed.): Encyclopedia of Sustainability Science and Technology, Springer, New York, Dordrecht, Heidelberg, London, 12678 pp., 2012.

Miller, C. A.: Energy resources and policy: Vulnerability of energy resources and resource availability – fossil fuels (oil, coal, natural gas, oil shale), in: Climate Vulnerability Understanding and Addressing Threats to Essential Resources, Volume 3: Vulnerability of Energy to Climate, edited by: Pielke Sr., R. A., Adegoke, J., Wright, C.Y., Niyogi, D., Kallos, G., Seastedt, T., Suding, K., Hossain, F., Academic Press, Oxford, UK, pp. 518–532, 2013.

Mokhov, I. I., Smirnov, D. A., and Karpenko, A. A.: Assessments of the relationship of changes of the global surface air temperature with different natural and anthropogenic factors based on observations, Dokl. Earth Sci., 443, 381–387, 2012.

Moyer, E. J., Woolley, M. D., Glotter, M. J., and Weisbach, D. A.: Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon, The University of Chicago, Coase-Sandor Institute for Law and Economics Working Paper no. 652, 2013.

Nakićenović, N. and Swart, R. J. (Eds.): IPCC Special Report on Emissions Scenarios, Cambridge University Press, Cambridge, UK, 608 pp., 2000.

Nordhaus, W. D.: Managing the Global Commons: The Economics of Climate Change, MIT Press, Cambridge, 1994a.

Nordhaus, W. D.: Expert opinion on climatic change, Am. Sci., 82, 45–51, 1994b.

Nordhaus, W. D.: The Challenge of Global Warming: Economic Models and Environmental Policy, Yale University Press, New Haven, CT, USA, 253 pp., 2007.

Nordhaus, W. D.: A Question of Balance: Weighing the Options on Global Warming Policies, Yale University Press, New Haven, CT, USA, 249 pp., 2008.

Nordhaus, W. D. and Boyer, J.: Warming the World: Economic Models of Global Warming, MIT Press, Cambridge, MA, 245 pp., 2000.

Nordhaus, W. D. and Sztorc, P.: DICE 2013R: Introduction and User's Manual, 2nd Edn., available at: www.econ.yale.edu/~nordhaus/homepage/documents/DICE2013R_Manual_2ndEd.pdf (last access: 6 October 2013), 2013.

Ortiz, R. A. and Markandya, A.: Integrated impact assessment models of climate change: A literature review, BC3 Working Paper Series, 2009-06, 2009.

Pachauri, R. K.: The way forward in climate change mitigation, WIREs Energy Environ., 1, 3–8, 2012.

Palmer, C. & Engel, S. (Eds.) Avoided Deforestation: Prospects for Mitigating Climate Change, Routledge Explorations in Environmental Economics, Routledge, London, UK & New York, USA, 273 pp., 2009.

Palmer, G.: Does energy efficiency reduce emissions and peak demand? A case study of 50 years of space heating in Melbourne, Sustainability, 4, 1525–1560, 2012.

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.

Pielke Jr., R. A.: The Climate Fix: What Scientists and Politicians Won't Tell You About Global Warming, Basic Books, New York, NY, USA, 290 pp., 2010.

Pielke Jr., R. A., Wigley, T. M. L., and Green, C.: Dangerous assumptions, Nature, 452, 531–532, 2008.

Pindyck, R. S.: Climate change policy: What do the models tell us?, J. Econ. Lit., 51, 860–872, 2013.

Pivovarchuk, D.: Consistency between Long-term Climate Target and Short-term Abatement Policy, IIASA Interim Report, IR-08-017, 2008.

Pizer, W. A.: Choosing price or quantity controls for greenhouse gases, in: The RFF Reader in Environmental and Resource Policy, 2nd Edn., edited by: Oates, W. E., Resources for the Future Press, Washington, DC,

USA, 225–234, 2006.
Prins, G., Cook, M., Green, C., Hulme, M., Korhola, A., Korhola, E.-R., Pielke, Jr. R. A., Rayner, S., Sawa, A., Sarewitz, D., Stehr, N., and Von Storch, H.: How to get climate policy back on course, Institute for Science, Innovation and Society, University of Oxford, Oxford, UK, 15 pp., 2009.
Riahi, K., Gruebler, A., and Nakićenović, N.: Scenarios of long-term socio-economic and environmental development under climate stabilization, Technol. Forecast. Soc. Change, 74, 887–935, 2007.
Richardson, K., Steffen, W., Liverman, D., Barker, T., Jotzo, F., Kammen, D. M., Leemans, R., Lenton, T. M., Munasinghe, M., Osman-Elasha, B., Schellnhuber, H. J., Stern, N. H., Vogel, C., and Wæver, O.: Climate Change: Global Risks, Challenges and Decisions, Cambridge University Press, New York, NY, USA, 541 pp., 2011.
Rockström, J., Klum, M., and Miller, P.: Big World, Small Planet: Abundance Within Planetary Boundaries, Yale University Press, New Haven, USA, & London, UK, 208 pp., 2015.
Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V. and Riahi, K.: Energy system transformations for limiting end-of-century warming to below 1.5 °C, Nat. Clim. Change, 5, 519–528, 2015.
Rombouts, J. and Ghil, M.: Oscillations in a simple climate–vegetation model, Nonlinear Proc. Geoph., 22, 275–288, 2015.
Romer, D.: Advanced Macroeconomics, 4th Edn., McGraw-Hill, New York, NY, USA, 738 pp., 2012.
Rosen, R. A.: Is the IPCC's 5th assessment a denier of possible macroeconomic benefits from mitigating climate change?, Clim. Change Econ., 7:1640003, 1–30, 2016.
Roughgarden, T. and Schneider, S. H.: Climate change policy: Quantifying uncertainties for damages and optimal carbon taxes, Energ. Policy, 27, 415–429, 1999.
Rydge, J. and Bassi, S.: Global cooperation and understanding to accelerate climate action, in: The Global Development of Policy Regimes to Combat Climate Change, edited by: Stern, N. H., Bowen, A., and Whalley, J., World Scientific Publ. Co., Singapore, pp. 1–22, 2014.
Sahal, D.: Technical Progress: Concepts, Models, Assessment, Moscow: Finances and Statistics, 1985.
Sanderson, J.: An analysis of climate change impact and adaptation for South East Asia, PhD thesis, Centre for Strategic Economic Studies, Victoria University of Technology, Melbourne, Australia, 285 pp., 2002.
Schellnhuber, H. J., Rahmstorf, S., and Winkelmann, R.: Why the right climate target was agreed in Paris, Nat. Clim. Change, 6, 649–653, 2016.
Schneider, S. H. and Dickinson, R. E.: Climate modeling, Rev. Geophys. Space. Ge., 12, 447–493, 1974.
Schrattenholzer, L., Miketa, A., Riahi, K., and Roehrl, R. A.: Achieving a Sustainable Global Energy System: Identifying Possibilities Using Long-Term Energy Scenarios, Edward Elgar, Cheltenham, UK, & Northampton, MA, USA, 233 pp., 2005.
Schwartz, S. E.: Heat capacity, time constant, and sensitivity of Earth's climate system, J. Geophys. Res., 112:D24S05, 1–12, 2007.
Schwartz, S.E.: Reply to comments by G. Foster et al., R. Knutti et al. and N. Scafetta on ‘‘Heat capacity, time constant, and sensitivity of Earth's climate system.’’ J. Geophys. Res., 113, D15105, 1–10, 2008.
Scott, C. E.: The Biogeochemical Impacts of Forests and the Implications for Climate Change Mitigation, doctoral thesis accepted by the University of Leeds, UK, Springer, Switzerland, 142 pp., 2014.
Smil, V.: Energy Transitions: History, Requirements, Prospects, Praeger, Santa Barbara, CA, 2010.
Smirnov, A.: Attainability Analysis of the DICE Model, IIASA Interim Report, IR-05-049, 2005.
Smulders, S.: Entropy, environment, and endogenous growth, Int. Tax Public Finan., 2, 319–340, 1995.

Sohngen, B.: Forestry carbon sequestration, in: Smart Solutions to Climate Change – Comparing Costs and Benefits, edited by: Lomborg, B., Cambridge University Press, New York, NY, USA, pp. 114–132, 2010.

Solow, R. M.: A contribution to the theory of economic growth, Q. J. Econ., 70, 65–94, 1956.

Stanton, E. A., Ackerman, F., and Kartha, S.: Inside the integrated assessment models: Four issues in climate economics, Clim. Dev., 1, 166–185, 2009.

Steckel, J. C., Brecha, R. J., Jakob, M., Strefler, J., and Luderer, G.: Development without energy? Assessing future scenarios of energy consumption in developing countries, Ecol. Econ., 90, 53–67, 2013.

Steffen, W.: A truly complex and diabolical policy problem, in: The Oxford Handbook of Climate Change and Society, edited by: Dryzek, J. S., Norgaard, R. B., and Schlosberg, D., Oxford University Press, New York, NY, USA, pp. 22–36, 2012.

Stern, N. H.: The Economics of Climate Change: The Stern Review, Cambridge University Press, Cambridge and New York, 2007.

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.

Stern, N. H.: Current climate models are grossly misleading, Nature, 530, 407–409, 2016.

Sterner, T. and Coria, J.: Policy Instruments for Environmental and Natural Resource Management, 2nd Edn., RFF Press, New York, NY, USA & London, UK, 657 pp., 2012.

Stoknes, P. E.: What We Think About When We Try Not To Think About Global Warming: Toward a New Psychology of Climate Action, Chelsea Green Publ., Vermont, VT, USA, 2015.

Swan, T. W.: Economic growth and capital accumulation, Econ. Rec., 32, 334–361, 1956.

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.

Tol, S. J. R. and Fankhauser, S.: On the representation of impact in integrated assessment models of climate change, Environ. Model. Assess., 3, 63–74, 1998.

Traeger, C. P.: A 4-Stated DICE: Quantitatively addressing uncertainty effects in climate change, Environ. Resource Econ., 59:1–37, 2014.

UNFCCC: Copenhagen Accord, United Nations, New York, NY, USA, 2009.

UNFCCC: United Nations Framework Convention on Climate Change, Adoption of the Paris Agreement: Proposal by the President, Report No. FCCC/CP/2015/L.9/Rev.1, 2015, Geneva, Switzerland, 32 pp., 2015.

Uzawa, H.: Economic Theory and Global Warming, Cambridge University Press, New York, NY, USA, 293 pp., 2003.

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.

Van Vuuren, D. P., Eickhout, B., Lucas, P. L., and Den Elzen, M. G. J.: Long-term multi-gas scenarios to stabilize radiative forcing – exploring costs and benefits within an integrated assessment framework, Energ. J., 27, 201–233, 2006a.

Van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakićenović, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S. K., and Arnell, N.: A proposal for a new scenario framework to support research and assessment in different climate research communities, Global Environ. Change, 22, 21–35, 2012.

Van Vuuren, D. P., Den Elzen, M. G. J., Lucas, P. L., Eickhout, B., Strengers, B. J., Van Ruijven, B., Berk, M. M., De Vries, H. J. M., Hoogwijk, M., Meinshausen, M., Wonink, S. J., Van den Houdt, R., and Oostenrijk, R.: Stabilizing greenhouse gas concentrations at low levels: An assessment of options and costs, Report

500114002/2006 Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands, 273 pp., 2006b.

Wagner, G. and Weitzman, M. L.: Climate Shock: The Economic Consequences of a Hotter Planet, Princeton University Press, Princeton, USA, & Oxford, UK, 265 pp., 2015.

Wasdell, D.: Climate dynamics: Facing the harsh realities of now − climate sensitivity, target temperature and the carbon budget: Guidelines for strategic action, Apollo-Gaia Project, Unit for Research into Changing Institutions, London, UK, 2015.

Weber, M., Barth, V., and Hasselmann, K.: A multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth, Ecol. Econ., 54, 306–327, 2005.

Wigley, T. M. L.: A simple inverse carbon cycle model, Global Biogeochem. Cy., 5, 373–382, 1991.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S. J., Janetos, A., and Edmonds, J.: Implications of limiting CO_2 concentrations for land use and energy, Science, 324, 1183–1186, 2009.

Wouter Botzen, W. and Van den Bergh, J. C. J. M.: How sensitive is Nordhaus to Weitzman? Climate policy in DICE with an alternative damage function, Econ Lett., 117, 372–374, 2012.

Xu, J., Yao, L., and Lu, Y.: Innovative Approaches Towards Low Carbon Economics: Regional Development Cybernetics, Springer, Berlin, Heidelberg, Germany, 453 pp., 2014.

Zaddach, J. O.: Climate Policy Under Intergenerational Discounting: An Application of the Dynamic Integrated Climate-Economy Model, master thesis Albert-Ludwigs-University of Freiburg, 2015 u.d.t., Springer, Fachmedien Wiesbaden, Germany, 67 pp., 2016.

Table 1. List of variables and parameters and their values used.

Symbol	Meaning	Value	Units	Source
Independent variables				
K	Per capita physical capital		10^4 USD_{1990}	
H	Per capita human capital		10^4 USD_{1990}	
T	Average global surface temperatures		Kelvin (K)	
C	Atmospheric CO_2 concentration		GtC	
E_Y	Industrial CO_2 emissions		GtC yr^{-1}	
Initial (1990) values for independent variables				
k_0	Per capita physical capital-human capital ratio K_0/H_0	8.1	Ratio	Erk et al. (1998)
K_0		0.8344	10^4 USD_{1990}	Nordhaus and Boyer (2000)
H_0		0.1039	10^4 USD_{1990}	K_0/k_0
T_0		287.77	Kelvin (K)	Dong et al. (2013, Fig. 3.22)
C_0		735	GtC	Nordhaus and Boyer (2000)
E_{Y0}		6	GtC yr^{-1}	Lenton (2000)
Parameters and other symbols				
Economy module				
n	Population growth rate		% yr^{-1}	Nordhaus and Sztorc (2013)
L	Human population		Millions	
L_0	1990 world population	5632.7	Millions	Nordhaus and Boyer (2000)
n_0	1990 population growth rate	1.57	% yr^{-1}	Nordhaus and Boyer (2000)
A	Total factor productivity	2.9		Greiner and Semmler (2008)
c	Consumption share	80	% yr^{-1}	Greiner and Semmler (2008)
φ	External effect coefficient	0.1235		
δ_K	Depreciation rate of K	7.5	% yr^{-1}	Greiner and Semmler (2008)
δ_H	Depreciation rate of H	7.2	% yr^{-1}	
δ_n	Decline rate of n	2.22	% yr^{-1}	Nordhaus and Boyer (2000)
α	Physical capital share	0.35		Gollin (2002)
τ	Tax rate	20	% yr^{-1}	Greiner and Semmler (2008)
τ_b	Abatement share	0;0.075;0.11; 0.145	Ratio	
Damage function				
m_1		0.0067		Roughgarden and Schneider (1999)
χ		2.43		
Climate module (carbon cycle & surface temperature)				
β_2	Part of CO_2 emissions taken up by oceans and do not enter the atmosphere	0.49		IPCC (2001, p. 39)
μ_o	Rate of CO_2 absorption from the atmosphere into the ocean	0.0083		Nordhaus (1994a)
$\hat{C}$	Pre-industrial CO_2 concentration	596.4	GtC	Wigley (1991)
e_c	Energy intensity		TRF (USD 10^3 of $\bar{Y}$ $)^{-1}$	Akaev (2015)
c_c	Carbon intensity of energy		tC TRF^{-1}	Akaev (2015)
g_{ec}	Growth rate of e_c			
g_{cc}	Growth rate of c_c			
σ	Carbon intensity		tC (USD 10^3 of $\bar{Y}$ $)^{-1}$	Akaev (2015)
g_σ	Rate of decline of σ			
σ_0	1990 level σ	0.274	tC (USD 10^3 of $\bar{Y}$ $)^{-1}$	Nordhaus and Boyer (2000)
ψ_0		0.042		Akaev (2015)
α_τ	Abatement efficiency	1.8		
r		0.05		Akaev (2015)

$c_{-\infty}$	c_c used before 1990	0.1671	tC TRF^{-1}	
a_c		0.169		Akaev (2015)
c_h	Earth specific heat capacity	16.7	W m^{-2} K^{-1}	Schwartz (2008)
α_T	Planetary/Surface albedo	0.3		Greiner (2015)
ε	Emissivity	0.95		Greiner (2015)
σ_T	Stefan-Boltzmann constant	5.67x10^{-8}	W m^{-2} K^{-4}	Greiner (2015)
τ_a	Infrared transmissivity	0.6526		McGuffie and Henderson-Sellers (2005)
Q	Solar constant	1366	W m^{-2}	Gueymard (2004)
ξ	T rise absorbed by the oceans	0.23		Greiner and Semmler (2008)
β_1	Feedback effect	3.3		Greiner (2015)
$\hat{T}$	Pre-industrial T	287.17	K	Dong et al. (2013, Fig. 3.22)

Table 2. **Target values of key variables for our policy scenarios at year 2100, with $\chi = 2.43$.**

Abatement share τ_b	Emissions E_Y (GtC yr^{-1})	CO_2 $C/\hat{C}$	SAT deviation from pre-industrial $T-\hat{T}$ (°C)	Damages (% Y)	Per capita GDP growth g_Y (% yr^{-1})
0	29.3	3.1	5.2	26.9	1.1
0.075	11.8	2.1	3.4	11.6	2.1
0.11	5.9	1.7	2.6	6.6	2.2
0.145	2.5	1.5	2.0	3.5	2.0

Table 3. **Per capita abatement costs and damage costs at year 2100, with $\chi = 2.43$.**

Abatement share τ_b	% emissions (E_Y) reduction from BAU	Per capita abatement costs (% Y)	Per capita damage costs (% Y)
0	0	0	26.9
0.075	60	1.5	11.6
0.11	80	2.2	6.6
0.145	92	2.9	3.5

Table 4. **Comparison between global results of alternative policies.**

Global industrial CO_2 emissions (GtC yr^{-1})							
Policy Scenario	1995	2005	2010	2020	2030	2050	2100
CoCEB model: $\tau_b = 0$	7.1	10.8	13.2	19.3	27.0	43.4	29.3
CoCEB model: $\tau_b = 0.075$	6.8	9.2	10.6	13.8	17.0	21.6	11.8
CoCEB model: $\tau_b = 0.11$	6.7	8.6	9.6	11.7	13.5	14.7	5.9
RCP8.5 (Riahi et al., 2007)	–	8	8.9	11.5	13.8	20.2	28.7
RCP6.0 (Hijioka et al., 2008)	–	8	8.5	9	10	13	13.8
RCP4.5 (Wise et al., 2009)	–	8	8.6	9.9	11	11	4.2
Global atmospheric CO_2 concentration (GtC)							
	1995	2010	2020	2030	2050	2075	2100
CoCEB model: $\tau_b = 0$	743	793	852	939	1206	1612	1842
CoCEB model: $\tau_b = 0.075$	743	785	826	880	1014	1168	1231
CoCEB model: $\tau_b = 0.11$	743	781	816	858	948	1027	1037
RCP8.5 (Riahi et al., 2007)	–	829	886	956	1151	1529	1993
RCP6.0 (Hijioka et al., 2008)	–	829	872	914	1017	1218	1427
RCP4.5 (Wise et al., 2009)	–	829	875	927	1036	1124	1147

Table 5. **Policy scenario values at year 2100 with $\alpha_\tau = 1.8$, varying m_1, and χ.**

		Abatement share τ_b	Emissions E_Y (GtC yr^{-1})	CO_2, $C/\hat{C}$	Deviation from pre-industrial, $T-\hat{T}$ (°C)	Damages (% Y)	GDP growth g_Y (% yr^{-1})
m_1 =0.034 (−50 %)	χ =2.34	0	50.8	3.7	5.9	20.3	1.8
		0.075	16.0	2.2	3.7	7.3	2.5
		0.11	7.3	1.8	2.8	3.8	2.4
		0.145	2.8	1.5	2.1	1.9	2.1
m_1 =0.01 (+50 %)		0	20.4	2.8	4.7	30.3	0.7
		0.0175	9.3	2.0	3.2	14.4	1.8
		0.11	5.0	1.7	2.5	8.6	2
		0.145	2.2	1.5	1.9	4.8	1.9
χ =1.215 (−50 %)	m_1 =0.0067	0	99.6	4.5	6.7	6.3	3.6
		0.075	19.1	2.3	3.8	3.3	3.0
		0.11	7.8	1.8	2.8	2.3	2.6
		0.145	2.9	1.5	2.1	1.6	2.2
χ =3.645 (+50 %)		0	6.0	2.1	3.6	41.6	-0.2
		0.075	4.9	1.8	2.8	22.9	1.0
		0.11	3.5	1.6	2.4	13.5	1.6
		0.145	1.9	1.5	1.9	6.6	1.8

Table 6. **Effect of varying α_τ by year 2100; all other parameter values as in Table 1.**

	Abatement share τ_b	% reduction of emissions (E_Y) from BAU	Per capita abatement costs (% Y)	Per capita damage costs (% Y)	GDP growth g_Y (% yr^{-1})
Abatement efficiency = 0.9 (−50 %)	0	0	0	26.9	1.1
	0.075	48	1.5	13.6	1.8
	0.11	67	2.2	8.8	1.9
	0.145	81	2.9	5.5	1.8
Abatement efficiency = 2.7 (+50 %)	0	0	0	26.9	1.1
	0.075	71	1.5	9.4	2.3
	0.11	90	2.2	4.4	2.4
	0.145	98	2.9	1.9	2.1

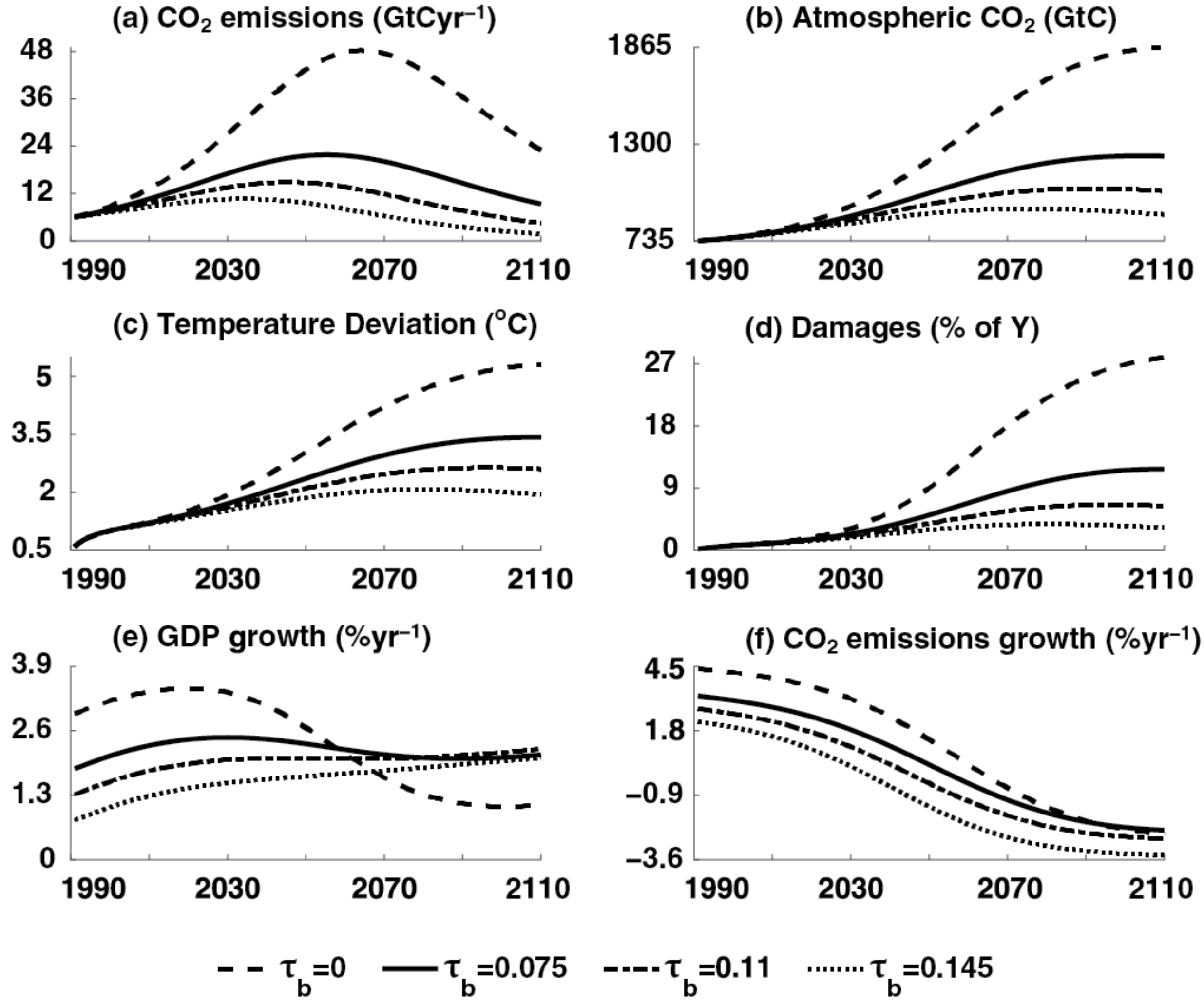

Figure 1. Evolution of several CoCEB model variables in time, for abatement shares τ_b that range from 0.0 (no abatement) to 0.145; see legend for curves, with $\tau_b = 0$ — dashed, $\tau_b = 0.075$ — solid, $\tau_b = 0.11$ — dash-dotted, and $\tau_b = 0.145$— dotted.

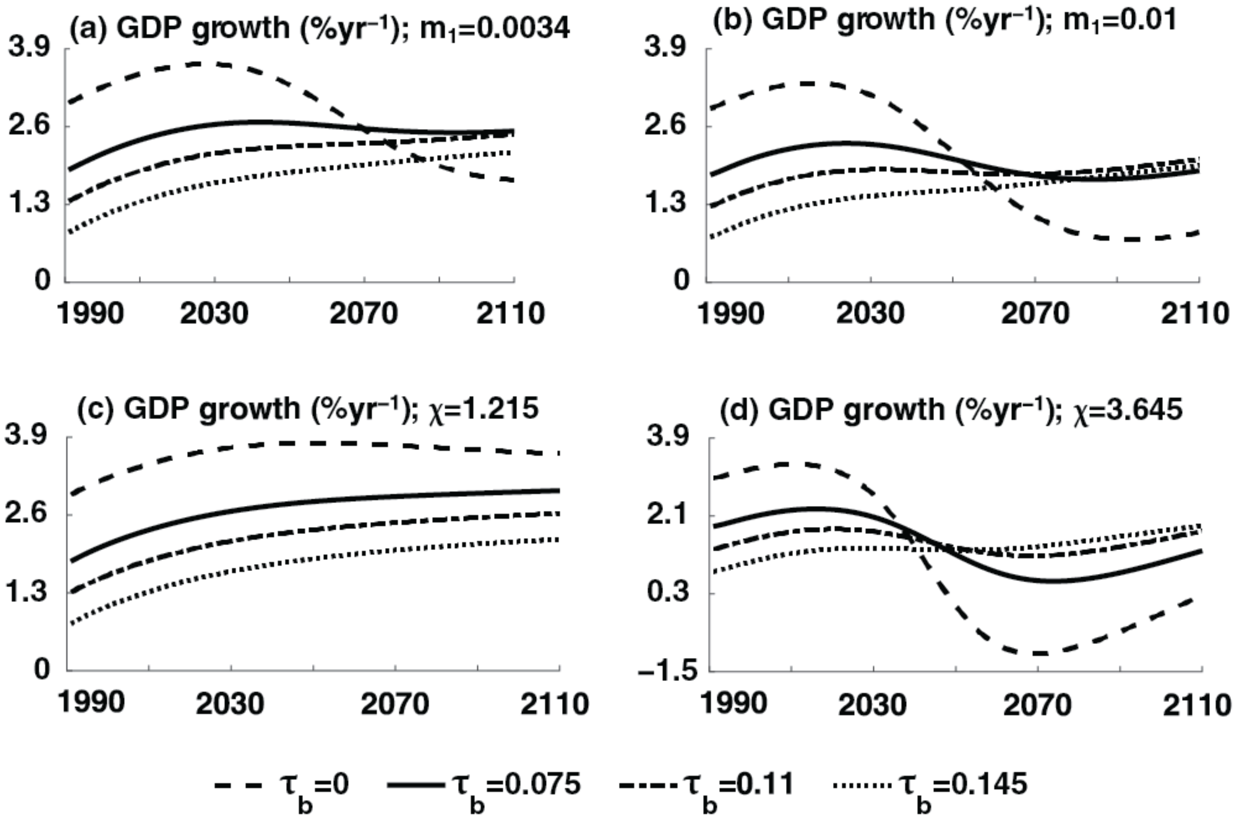

Figure 2. Per capita GDP growth over time as a function of abatement share values τ_b between 0.0 and 0.145; see legend for curve identification, while $\alpha_\tau = 1.8$. Panels (a, b) the coefficient m_1 is larger or smaller by 50 % than the value in Tables 1–4; (c, d) same for the exponent χ .

APPENDIX A

Final Author response to Interactive comments on "Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement share and investment in low-carbon technologies" *by* K. B. Z. Ogutu et al.

K. B. Z. Ogutu et al.

okeroboto@gmail.com

We thank the two Referees for their constructive comments and respond to them herewith. In the following, each 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.

Referees #1:

1. *The paper is unclear about the main innovation and the main new findings. The paper states: "Figure 1e is the key result" (p. 838. L. 4). However, this is a well published and also seems to be an intuitively obvious effect. Abatement in a DICE type setup causes near-term costs and long-term benefits.*

To remove any ambiguity, the abstract is rewritten as:

The Coupled Climate–Economy–Biosphere (CoCEB) model described herein takes an integrated assessment approach to simulating global change. By using an endogenous economic growth module with physical and human capital accumulation, this paper considers the sustainability of economic growth, as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change. Different types of fossil fuels and different technologies produce different volumes of carbon dioxide in combustion. The shares of different fuels and their future evolution are not known. We assume that the dynamics of hydrocarbon-based energy share and their replacement with renewable energy sources in the global energy balance can be modeled into the 21st century by use of logistic functions. Various climate change mitigation policy measures are considered. While many integrated assessment models treat abatement costs merely as an unproductive loss of income, **CoCEB innovates in (i) making emissions depend on economic growth; and (ii) treating investment in abatement not as a pure loss but as a way to increase the overall energy efficiency of the economy and decrease the overall carbon intensity of the energy system.** The paper shows that **mitigation costs do slow down economic growth over the next few decades, but only up to the mid-21st century or even earlier, while this growth reduction is compensated later on by having avoided negative impacts of climate change on the economy.**

Also we rewrite the paragraph in lines 23-29 on page 824 as:

Various climate change mitigation policy measures have been considered heretofore. Many IAMs, though, treat abatement costs merely as an unproductive loss of income (e.g. Nordhaus and Boyer, 2000; Nordhaus, 2007, 2008, 2010, 2013b; see also Stoknes, 2015, p. 59). Our CoCEB model innovates in (i) making emissions depend on economic growth; and (ii) treating investment in abatement not as a pure loss but as a way to increase the overall energy efficiency of the economy and decrease the overall carbon intensity of the energy system.

As will be shown below, the paper's main result is that, over the next few decades, up to or even earlier than the mid-21st century, mitigation costs do interfere with economic growth, but that this growth reduction is compensated later on by having avoided negative impacts of climate change on the economy; see also Stern (2007, p. 35, Fig. 2.3), Guest (2010, Fig. 1) and Kovalevsky and Hasselmann (2014, Fig. 2). This result, as shown in the sensitivity analysis of Section 4.1, is due to an increase with time in climate-related damages (see also, Ackerman et al., 2009) that in turn has the effect of anticipating the crossover time, i.e. the time at which the abatement-related costs start paying off in terms of increased per capita gross domestic product (GDP) growth.

This result calls for urgent, all-inclusive local and global solutions to the climate change challenge (see also, Stoknes, 2015, Ch. 8). Such a now-and-not-later conclusion contradicts, for example that of the DICE model, in which abatement benefits are realized way beyond the year 2100, due to low climate-related damages (Kaufmann, 1997;

Nordhaus and Boyer, 2000; Greiner, 2004; Greiner and Semmler, 2008, p. 68; Ackerman et al., 2009; Stoknes, 2015, p. 62). Analyses based on DICE and similar models usually call, therefore, for less immediate solutions to the challenge of climate change (Kaufmann, 1997; Stoknes, 2015, p. 62).

Also line 4, p. 838 is rewritten as: **Figure 1*e* is a key result of our study: …**

In the sensitivity analysis Section 4.1, p. 840, the following paragraph is inserted:

Considering the damage function of Eq. (20), the choice of $m_1 > 0$ **and** $\chi > 0$ **in the literature is ad hoc and based on "informed guesses" (Peck and Teisberg, 1994). According to these authors,** χ **is more important than** m_1**. Because the shape of the damage function varies from linear to cubic,** $1 \le \chi \le 3$ **(Tol, 1996; see also Tol, 2002; Ackerman et al., 2009) while** $0.0022 \le m_1 \le 0.0231$**, cf. Roughgarden and Schneider (1999) and Labriet and Loulou (2003).**

We modify the values of the parameters m_1 and χ by +50 and –50% from their respective values of $m_1 = 0.0067$ and $\chi = 2.43$ in Tables 1–4 above, **so as to get their ranges into fair agreement with the ones in the literature**, and examine how that affects model results for year 2100. In Table 5 are listed the per annum CO_2 emissions, CO_2 concentrations, SAT, damages, and growth rate of per capita GDP. All parameter values are as in Table 1, including $\alpha_\tau = 1.8$.

Furthermore, the following is added on page 841, after line 4:

We also observe that the 2100 climate change damages before and after abatement range between 1.9–41.6%. Our damage figures thus agree fairly well with those in the literature; see, for instance, Creedy and Guest (2008), Ackerman (2009), and Chen et al. (2012, p. 5; and references therein).

Also, the following references have been added to the Bibliography:

Ackerman, F., Stanton, E. A., Hope, C., and Alberth, S.: Did the Stern Review underestimate US and global climate damages? Energ. Policy, 37, 2717–2721, 2009.

Kaufmann, R. K.: Assessing the DICE model: uncertainty associated with the emission and retention of greenhouse gases, Climatic Change, 35, 435–448, 1997.

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.

Stoknes, P. E.: What We Think About When We Try Not To Think About Global Warming: Toward a New Psychology of Climate Action, Chelsea Green Publishing, USA, 2015.

Tol, R. S. J.: The damage costs of climate change towards a dynamic representation, Ecol. Econ., 19, 67–90, 1996.

Tol, R. S. J.: Estimates of the damage costs of climate change – Part 2: dynamic estimates, Environ. Resource Econ., 21, 35–160, 2002.

Weinstein, M. P., Turner, R. E., and Ibáñez, C.: The global sustainability transition: it is more than changing light bulbs, Sustainability: Science, Practice, and Policy, 9, 4–15, 2013.

2. *The introduction of the paper sets out to explain limitations of models such as DICE. It then, seemingly, expands the complexity of the considered processes. What is missing is a careful comparison of the new model with the closest approximation (one may assume DICE to be this models) in terms of the number of parameters, the number of equations, the number of decision variables, and the considered processes. Having the code available in an appendix would also simplify the discussion and the ability to reproduce the results.*

In Section 5.2, we replace the first paragraph (page 843, lines 10-19) with the following:

In the decadal time step ran Dynamic Integrated model of Climate and the Economy (DICE), the economic costs associated with addressing and coping with climate warming are quantified by coupling a system of economic equations to an intermediate-complexity climate model. The DICE model makes aggregate regionally-based assessments of the economics of production, investment, consumption, welfare, discount rates, population and rates of technological change (Nordhaus, 2007, pp. 39–41). These economic functions are coupled to functions for atmospheric temperature and climate damage. The decision variables that are available to the world economy are the rate of investment in physical capital and the rate of emissions reductions of GHGs. Given a variable-and-parameter space of order 18 x 65, the model outcome is an optimized trajectory for long-term societal welfare to which policy measures can be compared (Nordhaus and Boyer, 2000, pp. 181–187; Nordhaus, 2008, pp. 205–208; Nordhaus, 2013b, p. 1109; see also Garrett, 2012).

The annual time step ran CoCEB model has a considerably smaller number of variables and parameters — equal to 5 and 38, respectively — and it builds upon previous work on coupled models of global climate–economy interactions, starting from the pioneering work of Nordhaus (1994a), as extended by Greiner (2004) with the inclusion of endogenous growth. Greiner (2004) treated industrial CO_2 emissions as constant over time, while excluding the particular case of no-abatement activities (BAU); in fact, his model only applies for a minimum level of abatement. The present paper takes into account, more generally, emissions that depend on economic growth and vary over time, while including the case of abatement equal to zero, i.e. BAU. To do so, we used logistic functions (Sahal, 1981) in formulating equations for the evolution of energy intensity and carbon intensity of energy throughout the whole 21st century (Akaev, 2012). CoCEB's damage function specification allows abatement benefits to be realized earlier than the mid-21st century as compared to DICE, while the latter shows that abatement benefits are only feasible way beyond the 21st century.

The following paragraph (page 843, lines 20) is also modified as:

The CoCEB model, as developed in this first part of a two-part study, is sufficiently simple as to be transparent, to allow a range of sensitivity analyses, and to be available for a number of further extensions. The current model version analyzes the carbon policy problem in a single-region global model with the aim to understand theoretically the dynamic effects of using the abatement share as a climate change mitigation strategy. To be able to draw more concrete, quantitative policy recommendations is it important to account for regional disparities, an essential development left to future research.

The code can be made available upon request. We would be quite happy to put it on the website if the editors think it is necessary, and in agreement with the journal's policies. We added the following under Acknowledgements (page 845): **The CoCEB model code is available from the authors upon request.**

Also, the following reference has been added to the reference list:

Garrett, T. J.: No way out? The double-bind in seeking global prosperity alongside mitigated climate change, Earth Syst. Dynam., 3, 1–17, doi:10.5194/esd-3-1-2012, 2012.

3. *Several assumptions are difficult to understand. For example, why does only governmental spending on abatement affect production possibilities (p. 828, L. 13)?*

As to why only governmental spending on abatement affects the size of per capita GDP, we note that as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change; the government in our economy uses resources for abatement activities G_{E} (Eq. 5) that reduce emissions of CO_2. On the one hand, an increase in abatement activities, implying a higher value of the abatement share $\tau_{\mathrm{b}} > 0$, makes the difference $1-\left[\tau\left(1+\tau_{\mathrm{b}}\right)+c\left(1-\tau\right)\right]$ in Eqs. (9) and (10) smaller and hence decreases both production factors: (a) per capita physical capital, and (b) per capita human capital; hence production, in turn, decreases. On the other hand, a reduction in CO_2 emissions, due to the government's spending on abatement activities, lessens the damage to the economy due to climate change and hence improves per capita GDP.

To make things clearer, the above explanation is now inserted to replace the sentence starting in line 12 and ending in line 13 on page 828 in the original manuscript.

4. *The paper contains several claims that are not substantiated by / easily accessible from the provided evidence. Examples include:*

a. *Motivation of IAMs (p. 822, L. 25-27).*

We tried to make the text clearer and more self contained. Lines 25-29 on page 822 and lines 1-5 on page 823 now read:

Our model explicitly includes the causal links between economic growth and the climate change–related damages via the increase of CO_2 emissions. In particular, the model can show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system; see Equation (14) below and Diesendorf (2014, p. 143).

b. *Does (UNFCCC, 1992) really call for a two degree C limit? In which article?*

No, UNFCCC (1992) doesn't really call for a 2^{o} C limit, however, the framework stated, "The ultimate objective … is to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations, 2009; see also Nordhaus 2013b). At the recommendation of leading world climatologists, in 1996 the European Council made the decision that the "average global temperature of the pre-industrial level should not be exceeded by more than 2^{o} C; therefore, global efforts for restricting or reducing the emissions must be oriented at an atmospheric concentration of CO_2 of no more than 958.5–1171.5 GtC" (Akaev, 2012; see also Rozenberg et al., 2015). The warming limit of 2^{o} C was confirmed by the United Nations in the Declaration adopted at the 2009 United Nations Conference on Climate Change (Copenhagen Summit) (Akaev, 2012; Nordhaus 2013b).

In view of the above, we have changed lines 1-4 on page 839 to:

Now, according to the United Nations Framework Convention on Climate Change (UNFCCC, 2009), the average global SAT should not exceed its pre industrial level by more than 2^{o} C; see also UNFCCC (1992), European Council (2005), Yakovets et al. (2009), Akaev (2012), Nordhaus (2013b), Kuckshinrichs and Hake (2015, pp. 1 and 289) and Rozenberg et al. (2015). This SAT target means that global efforts to restrict or reduce CO_2 emissions must aim at an atmospheric CO_2 concentration of no more than **958.5–1171.5 GtC (Akaev, 2012); see also Rozenberg et al. (2015).**

We also added the following before the sentence beginning in line 21 on page 839:

see also Held et al. (2009) whose study suggests that stringent mitigation strategies cannot guarantee a very high probability of limiting warming to 2 °C since preindustrial time under current uncertainty about climate sensitivity and climate response time scale.

The following references were also added to the Bibliography:

European Council: Presidency conclusions, European Council, Brussels, 2005.

Held, H., Kriegler, E., Lessmann, K., and Edenhofer, O.: Efficient climate policies under technology and climate uncertainty, Energ. Econ., 31, S50–S61, 2009.

UN – United Nations: Copenhagen Accord, United Nations, New York, 2009.

Kuckshinrichs, W. and Hake, J-F.: Carbon Capture, Storage and Use: Technical, Economic, Environmental and Societal Perspectives, Springer International Publishing, Switzerland, 2015.

Rozenberg, J., Davis, S. J., Narloch, U., and Hallegatte, S.: Climate constraints on the carbon intensity of economic growth, Environ. Res. Lett., 10, 1–9, 2015.

c. *Is this really a "win-win situation" (p. 843, L. 4). Figure 1e suggests that current generations may loose something.*

Yes, in the longer run, it is a win-win situation in the following sense: subject to the assumption that anthropogenic GHGs are the result of economic activities, one would expect high economic growth to be accompanied by high GHG emissions, that is, you win economic-growth–wise but loose in terms of climate deterioration via emitting more GHGs into the atmosphere. But upon investing in abatement measures, the results (see Figures 1*a* and 1*e*) show that higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions, that is, you win economic-growth–wise and also win by emitting less GHGs into the atmosphere. In other words, "increases in abatement spending yield a win-win situation" means "a rise in abatement activities both reduces greenhouse gas emissions and raises economic growth" (see also, Greiner, 2004; Greiner and Semmler, 2008, pp. 95 and 120). Of course, the result that a win-win situation or double dividend may be observed crucially depends on the specification of the functional relation between the economic damage and climate change; see also Greiner (2004) and Greiner and Semmler (2008, p. 120).

As shown in Table 3, the losses from mitigation in the near future are outweighed by the later gains in averted damage.

Of course mitigation costs do hinder economic growth over the next few decades, up to the mid-21st century, at the latest, but this growth reduction is compensated later on by having avoided negative impacts of climate change on the economy. To the contrary, as the CoCEB model shows, taking no abatement measures to reduce GHGs leads eventually to a slowdown in economic growth implying that future generations will be less able to invest in emissions control or adapt to the detrimental impacts of climate change.

To clarify things, we replaced the sentence starting in line 2 and ending in line 8 on page 843, with the following:

The great flexibility and transparency of the CoCEB model has helped us demonstrate that an increase in the abatement share of investments yields a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions and, as a consequence, to a decrease in average global SATs and in the ensuing damages; see also Greiner (2004) and Greiner and Semmler (2008, pp. 95 and 120). These results hold when considering the entire transition path from now to 2100, as a whole. Of course, the result that a win-win situation or double dividend may be observed crucially depends on the specification of the functional relation between the economic damage and climate change; see also Greiner (2004) and Greiner and Semmler (2008, p. 120).

5. *What is the logic behind the mapping of the 2 degree target to a single atmospheric CO2 concentration (p. 839)? What about an overshoot?*

Of course, the prudent thing would have been to map the 2^{o} C target to a given range of atmospheric CO_2 concentrations. However, we got this value of atmospheric CO_2 concentration from Akaev (2012), although he later says that "the specified value of CO_2 concentration in the atmosphere that should not be exceeded became 958.5–1171.5 GtC …" We are thus led to believe that an overshoot of atmospheric CO_2 concentration is not compatible with achieving, eventually, the 2^{o} C target; instead, the excess global average surface temperatures above pre-industrial would surpass 2^{o} C for good and trigger, therewith, major Earth instabilities and tipping points; see, for instance, Nordhaus (2003b, pp. 200–204). However, we have not found any scientific evidence in the literature to support this belief (*idem*, p. 200).

To remove any ambiguity in using a single value of atmospheric CO_2 concentration, we modify the text by using the range:

958.5–1171.5 GtC (Akaev, 2012); see also Rozenberg et al. (2015).

6. *The language needs a careful round of editing to address issues with word choices, grammar, and style.*

We have done so, to the best of our ability.

7. *The wording is often ambiguous. For example:*

a. *How is a "best approach" defined (p. 824, L. 21)?*

To remove any ambiguity, we have rewritten the sentence beginning in line 17 and ending in line 22 on page 824, as:

This shortcoming can be remedied by including endogenous technological change in IAMs either through direct price-induced, **research-and-development–induced**, or **through** learning-induced approaches (see Popp et al., 2010 for details), **but** there is no **agreement** in the climate change mitigation literature **as to which single approach to utilize** (Grubb et al., 2002; Popp et al., 2010**, p. 925**).

b. *What does it mean when future values are "not known" (p. 824. L. 2)? Does this not apply to all other projected numbers?*

Yes it does. We just chose to repeat this here because it is one of the novelties of our model and it is good, therefore, to emphasize it.

c. *What does it mean to "enhance the quality of life for all" (p. 843. L. 2) in the framework of this model?*

Indeed, this is too general, thank you. We replaced "enhance the quality of life for all" with "**enhance economic growth and hence wealth**".

8. *The citations are imprecise. For example, on which chapter and page in "(IPCC, 2013)" should the reader look to see the support for the claims on page 837?*

To remove the lack of precision, we rephrased the reference in line 19 on page 837, as: **(IPCC, 2013, p. 23, Table SPM.2)**.

We also inserted in line 25 the following reference: **(IPCC, 2013, p. 27, Table SPM.3)**

9. *What is the relevance of the discussion on the "finite-horizon optimal climate change control solution" (p. 843)?*

Like every other model, CoCEB has its own limitations and simplifications. The "finite-horizon optimal climate change control solution" discussion, among other discussions in Subsection 5.2, outlines a possible extension to the CoCEB model to address its current limitations. We modified the text to make this clearer. We took the sentence "The determination of an optimal abatement path along the lines above will be the object of future work." and moved it to the beginning of the paragraph, with the necessary changes. Now the paragraph reads:

The determination of an optimal abatement path being the object of future work, a finite-horizon optimal climate change control solution can be gotten by assuming that the government takes per capita consumption and the annual tax rate as given and sets abatement such that welfare is maximized. **The usual approach to welfare in the macroeconomic literature is to assume it to be given** by the discounted stream of per capita utility times the number of individuals over a finite time horizon**; cf. Nordhaus and Boyer (2000), Nordhaus (2008); see also Greiner et al. (2010) and Maurer et al. (2013) and the references therein.** ….

We also add the following reference in the reference list:

Greiner, A., Gruene, L., and Semmler, W.: Growth and climate change: threshold and multiple equilibria, in: Dynamic Systems, Economic Growth, and the Environment, edited by: Crespo Cuaresma, J, Palokangas, T., and Tarasyev, A., Springer, New York, USA, pp. 63–78, 2010.

Referees #2:

The climate module

I am not an expert on climate models, but it appears to me that the authors should seriously consider to use a more recent version. For example, the carbon cycle comprises the parameter β_2 *that equals 0.49. This means that 51% of all emissions in a year are immediately removed and do not contribute to the accumulation of carbon in the atmosphere. This problem has been discussed with respect to the DICE model in the literature (Kaufmann, 1997).*

We appreciate the reviewer's concerns and presume that by suggesting that we use "a more recent version of the climate model", s/he means "a more detailed version", for example, replacing the carbon cycle in Eq. (2) with three equations where a three-reservoir model is calibrated to current scientific carbon-cycle models, as in Nordhaus and Boyer (2000) or using a pulse response function, i.e. a Green's function (e.g., Hasselmann et al., 1996; Joos et al., 1996; Siegenthaler and Oeschger, 1978), or utilizing a time- or, more generally, a state-dependent rate of carbon removal (Traeger, 2014). Of course, doing so might mitigate the possibility that our model's solutions, like those of the original DICE (see Nordhaus, 1994), understate carbon retention because a constant decay of atmospheric excess carbon is assumed. The reviewer's concerns suggest a worthwhile line of future work.

However, the DICE model – and hence the CoCEB model – is a typical climate–economic model where the essence of particular relationships is examined to try to further the understanding of key elements within a complex and interrelated environment. The DICE model interacts with the economy through only one variable, temperature. Therefore, a complex model that provides dynamic estimates for carbon-dioxide is not needed; see Hof et al. (2012) for a summary of the various representation of the carbon cycle in IAMs. In any case the climate module of the DICE model is calibrated against a more complex climate model and follows the results of the more complex model very closely (Nordhaus and Boyer, 2000; see also Sanderson, 2002).

In our case, a more detailed representation of the carbon-cycle, akin to the three-reservoir model used by Nordhaus and Boyer (2000) (see also, Van Vuuren et al., 2011; Glotter et al., 2014 and the references therein), would not allow the coupling of biomass and the related exchanges of CO_2 into the climate model as done in paper 2 (see Ogutu et al., 2015).

Furthermore, Hof et al. (2012) showed that in the longer term, beyond 2100, most IAM parameterizations of the carbon cycle imply lower CO_2 concentrations compared to a model that captures IPCC Fourth Assessment Report (AR4) knowledge more closely, e.g. the carbon-cycle climate Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) 6. This result of Hof et al. (2012) combined with the fact that in this study we confine our investigations to the transition path for the next 110 years from the baseline year 1990 renders our results useful (see also, Gerlagh and Van der Zwaan, 2003; Traeger, 2014).

We have therefore added the following sentence before line 12 on page 826:

There is some discussion on the representation of the carbon cycle in IAMs (see Hasselmann et al., 1996; Janssen, 1996; Joos et al., 1996; Kaufmann, 1997; Siegenthaler and Oeschger, 1978; Nordhaus and Boyer, 2000; Van Vuuren et al., 2011; Hof et al., 2012; Glotter, et al., 2014; Traeger, 2014).

The following references are also added in the reference list:

Glotter, M. J., Pierrehumbert, R. T., Elliott, J. W., Matteson, N. J., and Moyer, E. J.: A simple carbon cycle representation for economic and policy analyses, Climatic Change, 126, 319–335, 2014.

Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V., and Van Storch, H.: Optimization of CO_2 emissions using coupled integral climate response and simplified cost models: a sensitivity study, Max-Planck Institut für Meteorologie, Report No 192, Hamburg Germany, 1996.

Hof, A. F., Hope, C. W., Jason, L., Mastrandrea, M. D., Malte, M., and Van Vuuren D. P.: The benefits of climate change mitigation in integrated assessment models: the role of the carbon cycle and climate component, Climatic Change 113, 897–917, 2012.

Janssen, M. A.: Meeting Targets: Tools to Support Integrated Assessment Modelling of Global Change, Cip-Genevens Koninklijke Bibliotheek, Den Haag, 1996.

Joos, F., Bruno, M., Fink, R., Stocker, T. F., Siegenthaler, U., LeQuere, C., and Sarmiento, J. L.: An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake, Tellus B, 48, 397-417, 1996.

Siegenthaler, U. and Oeschger, H.: Predicting future atmospheric carbon dioxide levels, Science, 199, 388–395, 1978.

Traeger, C. P.: A 4-Stated DICE: quantitatively addressing uncertainty effects in climate change, Environ. Resource Econ., 59:1–37, 2014.

Van Vuuren, D. P., Lowe, J., Stehfest, E., Gohar, L., Hof, A., Hope, C., Warren, R., Meinshausen, M., and Plattner, G.: How well do integrated assessment models simulate climate change? Climatic Change, 104, 255–285, 2011.

Now, according to IPCC, $\beta_2 = 0.49$ for the time period 1990 to 1999 for CO_2 emissions (IPCC, 2001, p. 39). Furthermore, the fraction of carbon dioxide found in the atmosphere is currently around 50% of the total anthropogenic emissions, with a slight upward trend (Raupach et al., 2008; Hüsler and Sornette, 2014). We therefore strongly feel $\beta_2 = 0.49$ is reasonable to use in our case (see also, Greiner and Semmler, 2008, p. 62).

We have also added the following references after line 21 on page 826:

(see IPCC, 2001, p. 39; Greiner and Semmler, 2008, p. 62; Raupach et al., 2008; Hüsler and Sornette, 2014)

The following references have been added to the Bibliography:

Hüsler, A. D. and Sornette, D.: Human population and atmospheric carbon dioxide growth dynamics: Diagnostics for the future, Eur. Phys. J. Special Topics, 223, 2065–2085, doi:10.1140/epjst/e2014-02250-7, 2014.

Raupach, M. R., Canadell, J. G., and Le Quéré, C.: Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction, Biogeosciences Discussions, 5, 2867–2896, 2008.

The economic module

The economic module deviates from the original DICE model because (i) it assumes a fixed savings, (ii) technological progress in form of increasing human capital H is an externality that depends on investments into macro-economic capital and (iii) abatement activities are a government activity that is financed from income tax that is fixed share of individual incomes. The variable parameter is the share τ_b of the tax revenue that is allocated to abatement activities. This is the policy parameter. It is worth to mention that the model does not consider carbon pricing (e.g. via a tax on emissions). It is also worth to mention that the macroeconomic production function only considers per capita capital and per capita human capital as inputs. Note that the present model, like DICE, does not consider energy as an input to the production function. This is a common assumption in models that have a focus on the energy sector.

The CoCEB model is a highly simplified representation of the complex climate and economic realities. One example of simplification is the use of a constant global tax rate and thus ignores the structure of the tax system. This is particularly important for energy and capital taxes, which have large effects on energy use and on the rates of return used in making long-term decisions in the energy sector. The structure of tax systems is particularly important for estimation of the optimal level of carbon pricing or taxation because of the need to consider the interaction of carbon pricing with the structure of pre-existing tax and regulatory distortions; see, in particular, the several important studies collected in Goulder, 2002; see also Nordhaus, 2013b).

The purpose of the CoCEB model, as clearly stated in Section 1 and Section 5.1, is not to exactly replicate real-world processes, but to provide overall insights into the effect of abatement policies or their absence on economic welfare and climate preservation. Hence we feel that the greater detail needed to capture the international and sectoral reactions to changes, say in tax policies, would not contribute much to achieving this paper's purpose.

We thank the reviewer for his/her observations and good advice; we have added the following after line 11 on page 828:

Our model's macroeconomic production function only considers per capita physical capital and per capita human capital as inputs, and like in the DICE model, does not consider energy as an input to the production function. It is also worth to note that the CoCEB model does not consider carbon pricing (e.g. via a tax on emissions).

Equation 8 describes the population growth rate. Equation 18 describes the population development. What is the relationship between Equation 8 and 18 , and why are these two equations not treated together?

The human population growth rate n as given in Eq. (8) does not depend on human population size L, which is exogenous. However the evolution of human population is precomputed using Eqs. (18) and (8). As for treating them together, n is introduced first because it is used in the per capita physical capital Eq. (7) and in subsequent equations, while L is only used later in getting per capita GDP from aggregate GDP; see line 10–15 on page 829 of the original manuscript.

Emissions module

The paper basically builds on the Kaya identity. The approach is to use logistic curves that mimic the introduction of non-fossil technologies as well as changes in the carbon intensity of the fossil fuels in order to derive the relevant CO_2 emissions. It appears to me that his dynamic is driven fully time driven. However, the authors say that emissions depend on τ_b, but I was not able to find it in the equations of this section. Therefore, the reader is left with some confusion. It seems to me that the authors have introduced simply another way to calibrate and tune the *trajectory for the emissions per unit of GDP. The development of this parameter seems to be completely time driven.*

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14); the carbon intensity σ, cf. Eq. (15); and the de-carbonization of the economy (Eq. 16). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0 \left[1 / \left(1 - \alpha_\tau \tau_b \right) \right]$, where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from $\tau_b = 0$ to 0.145.

To remove any confusion on the reader's part, we have rearranged line 19 on p. 830 so that the parameter $\psi = \psi_0 \left[1 / \left(1 - \alpha_\tau \tau_b \right) \right]$ is now labeled as Eq. (14) and the numbering of the subsequent equations has been modified accordingly.

Of course, as the reviewer rightly observes, the de-carbonization of the economy, i.e. the declining growth rate of the carbon intensity σ in Eq. (16), apart from its depending on the specific value of the abatement share τ_b, is also assumed to be time-dependent, to be able to account for a gradual de-carbonization process. Fossil-fuel consumption has been subject to such a process since the early times of industrialization, by a transition—in chronological order—from the use of wood to coal, from coal to oil, and in the most recent past from coal and oil to natural gas (see also, Gerlagh and Van der Zwaan, 2003).

We captured this observation after line 13 on page 831.

The following references have been added to the Bibliography:

Gerlagh, R. and Van der Zwaan, B.: Gross world product and consumption in a global warming model with endogenous technological change, Resour. Energ. Econ., 25, 35–57, 2003.

Abatement share

It appears to me that the relationship between the costs (percentage reduction of BAU GDP) and the emission reduction (percent deviation from BAU) is quite similar to what Nordhaus did. The calibration is done given a broad range of studies summarized by IPCC. However, it is not clear what they really did. Also it is not clear to me what the trigger for the choice of the abatement activity (climate policy) is. I guess that it is simply set exogenously.

Our choice of the abatement share, which is the key policy tool in our CoCEB model, was explained already in the original version of the paper, Section 2.6. The remark of the referee points to a lack of clarity on our part. To make things clearer we add the following at the beginning of this section:

In this section, we determine the abatement share, τ_b, which is the ratio of abatement spending to the tax revenue (see Equation 5) and is being used here as a policy tool. The abatement share is used in the de-carbonization of the economy, cf. Eq. (16), through the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$; see also Eq. (14).

Assessment of the model set up

It appears to me that the authors have transformed the DICE model from a CBA analysis tool based on a Ramsey growth model into a policy evaluation tool based on a Solow model with a spill-over from physical investment to human capital formation. This also means that the authors have substituted the endogenous policy by an exogenous one. Moreover, I cannot see where the novelty is that the authors indicate in the title of the paper ("…investment in low-carbon Technologies"). As far as I can understand the model set-up there is no endogenous investment in any particular technology.

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14); the carbon intensity σ, cf. Eq. (15); and the de-carbonization of the economy (Eq. 16). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right) \right]$, where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from $\tau_b = 0$ to 0.145.

The endogenous growth part would be interesting to analyze in an integrated climate-economy model, if the investment rate can be adjusted, but here the investment rate is given. The point would be to ask whether the direct cost of climate change are smaller or larger than the full economic impact, when the second order effects via the macro-economy are considered.

As the referee observes in the "The economic module" section, abatement activities are a government activity that is financed from income tax that is a fixed share of individual incomes. The *variable* parameter is the abatement share τ_b of the tax revenue that is allocated to abatement activities. This is the policy parameter. As we responded under the "Emissions module" section, we reiterate that by considering various values of the abatement share τ_b in the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right) \right]$, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing from $\tau_b = 0$ to 0.145.

Now, the per capita abatement costs $G_E = \tau_b X = \tau_b \tau Y$ from Eq. (5) and the damage costs $\left(1-D\right)Y$ from Eq. (19) for the various emission reduction paths are given in Table 3 for the year 2100. From the table we notice that, generally, the more one invests in abatement, the more emissions are reduced relative to baseline and the less the cost of damages from climate change.

Also, I do not understand the reason for having the term Biosphere in the model acronym. I have not found the bio-sphere in the model description.

This article is based on a new integrated assessment model; its structure is extended in a subsequent twin article by the same authors; this article is under consideration by the same journal as ESDD-6-865-2015/esd-2015-14. The term Biosphere as used in the acronym is for the purpose of anticipating the coupling of biomass and the related exchanges of CO_2 into the climate model as done in Paper 2 (see Ogutu et al., 2015). The intent of extending the model, by the inclusion of the "Biosphere", in paper 2 is clearly indicated in line 19 on page 822, line 6 on page 823, and line 1 on page 845. We added a further clarification on p. 3, lines. 85–86 of the revised manuscript, as follows:

The model's biosphere component is added in Part 2. The resulting CoCEB model is still a reduced-complexity model that tries to incorporate the climate–economy–biosphere interactions and feedbacks with the minimum amount of variables and equations needed.

It is true that one could have combined Paper 1 and 2 into a single paper and put much of the technical details into an appendix. However, the results of Paper 1 require merely a simpler version of the model, while for the results of Paper 2 the inclusion of 2 extra equations is needed. Dividing the material into two allows us to keep Paper 1 self-consistent, as well as short and readable; moreover, it only increases the complexity of the model when it is needed, i.e. in Paper 2. Furthermore, we feel that the methodological aspect, i.e. the construction of a simplified model, is one of the main points of this work, and that relegating it to an appendix would fail giving it its due importance.

Results

There are two major problems with the results.

The emission trajectory peaks in 2060 at 48GtC/yr. Starting with CO2 emissions in 2015 of 35GtCO2/yr (which is a high expectation) the implied growth rate is 3.7%/yr. This is very, very *high and has not been observed in the past. Also the emission growth rate is higher than the economic growth rate, which has also not been observed in the past. After the peak the model reverts back to the CO2 emissions of the RCP8.5 scenario by 2100 at emissions below 30GtC/yr. This emission pathway has been assumed to be very high. The authors report the result for 2100, but not for the remarkable peak. They do not give a reason why the baseline emissions trajectory is that high.*

The results presented here should be viewed as only suggestive and illustrative. They come from a single model and modeling perspective, and most of the relationships are subject to large uncertainties (see also, Petersen, 2012; Hannart et al., 2013; Wesselink et al., 2015 and the references therein for an insightful uncertainty assessment). However, we can confidently say that our BAU per annum growth rate of CO_2 emissions by 2050 agrees quite well with the Edmonds and Reilly (1983) study which asserts that the CO_2 emissions growth rate will increase to over 3% per year by 2050 (see also, Kuper, 2011). Actually, it has been noted that the global CO_2 emission rate has not only grown along a “business-as-usual” (BAU) trajectory, but has in fact slightly exceeded it (Raupach et al., 2007; Peters et al., 2013; see also Garrett, 2015), in spite of a series of international accords aimed at achieving the opposite (Nordhaus, 2010).

Our baseline emissions trajectory is assumed to be high because, as Garrett (2012) states, the IPCC Special Report on Emission Scenarios (SRES) — which can be mapped onto the Representative Concentration Pathways (RCPs), cf. Van Vuuren and Carter (2014) — underestimates the energy consumption in economic activities and hence CO_2 emissions; see also Pielke Jr. et al. (2008), Hay (2013, pp. 903–904). Therefore our BAU scenario’s energy technology is assumed constant at its 1990 level contrary to the IPCC BAU and similar scenarios which assume two thirds or more built-in emissions reducing technological change; see also Edmonds et al. (2004, p. 77) and Pielke Jr. et al. (2008). Our BAU CO_2 emissions is fairly similar to the scenarios given in the literature; see, for instance, Edmonds et al. (2004, p. 78, Figure 4.1) and Nakićenović (2004, p. 227, Figure 11.1).

Considering Eq. (12) and dividing through by carbon emissions E_{Y} and on subtracting the per capita GDP growth rate g_{Y} from both sides, we get

$$\frac{1}{E_{\mathrm{Y}}}\frac{\mathrm{d}E_{\mathrm{Y}}}{\mathrm{d}t}-g_{\mathrm{Y}}=g_{\sigma}+n+g_{\mathrm{ccs}}. \quad \text{(C.1)}$$

The left-hand side of Eq. (C.1) is positive at the beginning of the 1990–2100 study period, and negative later during this period; this means that g_Y is less than and later greater than the growth rate of E_Y. Actually, the right-hand side of Eq. (C.1) is bounded between -0.0545 and 0.0145. In this study, we assumed 1990 as the time when the use of renewable energy sources (biomass and wastes, hydropower, geothermal energy, wind energy, and solar energy) and biofuels became significant in the global energy balance (GEB). As we responded under the "emissions" section to Reviewer #2, the de-carbonization of the economy — i.e. the declining growth rate of the carbon intensity σ, as seen in Eq. (16) — apart from it depending on the specific value of the abatement share τ_b, is also assumed to be time-dependent, in order to be able to account for a gradual de-carbonization process.

Through the CoCEB model, we were able to demonstrate that an increase in the abatement share of investments yields a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in carbon emissions (as well as the growth rate of carbon emissions) and, as a consequence, to a decrease in average global SATs and the ensuing damages (see also, Greiner, 2004; Greiner and Semmler, 2008, pp. 95 and 120).

Now, Global fossil fuel CO2 emissions increased by 3.3% yr^{-1} on average during the decade 2000–2009 compared to 1.3% yr^{-1} in the 1990s and 1.9% yr^{-1} in the 1980s (see e.g., Canadell et al., 2007). The global financial crisis in 2008–2009 induced only a short-lived drop in global emissions in 2009 (–0.3%), with the return to high annual growth rates of 5.1% and 3.0% in 2010 and 2011, respectively (IPCC, 2013, p. 489); see also Albanese and Steinberg (1980). Therefore a high CO_2 emissions growth rate— actually higher in comparison to the per capita GDP growth of the same time (see Guest and McDonald, 2007, Table 2; Yakovets et al., 2009, Fig. 8, Tables 2, 10 and 14) — has been observed in the past.

To clarify the issue raised by the reviewer, we add the following paragraph after line 17 on page 838:

We also observe from Figure 1a that the BAU emission trajectory peaks in 2064 at 48.2 $GtCyr^{-1}$ and then reverts back to the CO_2 emissions of the RCP8.5 scenario by 2100, at an emissions level of 29.3 $GtCyr^{-1}$. Our baseline emissions trajectory is assumed to be high

because, as Garrett (2012) states, the IPCC Special Report on Emission Scenarios (SRES) — which can be mapped onto the RCPs, cf. Van Vuuren and Carter (2014) — underestimates the energy consumption in economic activities and hence CO_2 emissions; see also Hay (2013, pp. 903–904). Therefore our BAU scenario's energy technology is assumed constant at its 1990 level contrary to the IPCC BAU and similar scenarios which assume two thirds or more built-in emissions reducing technological change; see also Edmonds et al. (2004, p. 77) and Pielke Jr. et al. (2008). Our BAU CO_2 emissions is fairly similar to the scenarios given in the literature; see, for instance, Edmonds et al. (2004, p. 78, Figure 4.1), Nakićenović (2004, p. 227, Figure 11.1) and Moss et al. (2010, Figure 5b).

We also add the following references in the reference list:

Edmonds, J., Joos, F., Nakićenović, N., Richels, R. G., and Sarmiento, J. L.: Scenarios, Targets, Gaps, and Costs, in: The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World, edited by Field, C. B. and Raupach, M. R., Scientific Committee on Problems of the Environment (SCOPE) 62, Island Press, Paris, France, 2004.

Garrett, T. J.: No way out? The double-bind in seeking global prosperity alongside mitigated climate change, Earth Syst. Dynam., 3, 1–17, doi:10.5194/esd-3-1-2012, 2012.

Hay, W. W.: Experimenting on a Small Planet, Springer Verlag, Berlin, Heidelberg, doi:10.1007/978-3-642-28560-8_5, 2013.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakićenović, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, doi:10.1038/nature08823, 2010.

Nakićenović, N.: Socioeconomic driving forces of emissions scenarios, in: The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World, edited by Field, C. B.

and Raupach, M. R., Scientific Committee on Problems of the Environment (SCOPE) 62, Island Press, Paris, France, 2004.

Pielke Jr., R. A., Wigley, T., and Green, C.: Dangerous assumptions, Nature, 452, 531–532, 2008.

Van Vuuren, D P. and Carter, T. R..: Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old, Climatic Change, 122, 415–429, doi:10.1007/s10584-013-0974-2, 2014.

Second, 1990 is the year for the model calibration and the first year for the policy analysis. This is a quarter of a century before today. Consequently, there is large variation by the year 2010. This can be seen in the emission trajectories as well is in the economic growth rates. In my opinion this is a flawed result. It is common practice for existing models to use 2005 or 2010 as a calibration year, but not 1990 and then let the model start with deviating results from 1990 onwards.

We don't think that the variation between our BAU and non-BAU scenarios with the RCPs is as large by year 2010 as the referee claims (see Table 4). However the existing variation could be minimal if, as Garrett (2012) states, the SRES scenarios which can be mapped onto the RCPs, did not underestimate the CO_2 emissions.

The primary need and rationale of CoCEB is not to provide the best simulation fit to the truth, but CoCEB is a formal framework in which it is possible to represent in a simple way several components of the coupled system and their interactions. While we strive for CoCEB to be a well performing model, we do not think it is necessary for CoCEB to outperform more complex models (see also, Nordhaus, 2013a, b). The revision version of the manuscript makes this point clearer (see also our first response to referee #1 on the main innovation and the main new findings of CoCEB).

The standard way to evaluate the accuracy of a model is to do hindcasts. The hindcast of the model described here is illustrated in Fig. 1, Table 4 and discussed in Section 3. Effectively the model is initialized with current conditions in 1990 and the hindcast made for the 24 year period between 1990 and 2014. What we show is that the model reproduces fairly well, albeit with little deviations, both the timing and magnitude of observed changes in CO_2 emissions per year and the atmospheric concentrations in the transition path up to year 2100. The implication is that, even though the model that is used is extremely simple, it is nonetheless able to produce accurate enough annual results for CO_2 emissions and concentration, temperature, damage and capita gross domestic product (GDP) growth.

Smaller issues

Page 822, line15: the industrial emissions are assumed constant, but those from fossil fuel combustion are variable right?

The industrial emissions are due to combustion of fossil fuels.

To make things clearer, we add:

Since anthropogenic GHGs are the result of economic activities, the main shortcoming in Greiner's (2004) approach is that of treating industrial CO_2 emissions, **due to combustion of fossil fuels,** as constant over time.

Page 822, line 17: what means "zero abatement activities"? is this zero cost or zero emission? Please clarify.

"Zero abatement activities" mean "a total absence of abatement activities". In fact, in the paper, abatement equal to zero corresponds to Business As Usual (BAU). To clarify things, we write as:

Another problematic aspect of Greiner's emissions formulation is its inability to allow for **a total absence of abatement activities: in** fact, his formulation only holds for a minimum level of abatement.

822, line 25: I guess it is better to substitute analytically by quantitatively.

Lines 25-29 on page 822 and lines 1-5 on page 823 are now rewritten and hopefully more clear:

Our model explicitly includes the causal links between economic growth and the climate change–related damages via the increase of CO_2 emissions. In particular, the model can show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system; see Equation (14) below and Diesendorf (2014, p. 143).

Page 833, line 24ff: it is unclear to me how the choice of the parameter χ (the exponent in the damage function in Equation 19) can have any influence on the emissions in the Business as Usual scenario.

The influence of the parameter χ on the per annum CO_2 emissions, CO_2 concentrations, global mean surface air temperature (SAT), damages and growth rate of per capita GDP is well explained in Section 4.1.

We therefore modify the lines 24-27 on page 833 as:

On the other hand, we calibrated the nonlinearity parameter $\chi = 2.43$ so that our model's BAU emissions of $CO_2 yr^{-1}$ and concentrations by 2100 mimic the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2007; IPCC, 2013, **p. 27, Table SPM.3); see Sect. 4.1 for details on our calibration of χ.**

822, line 26: IN my perception the term adaptation rather than mitigation is appropriate, if the relationship between climate change and economic growth shall be influenced. Mitigation means to limit climate change to avoid impacts on the economy.

In our understanding the current definitions are the following. Mitigation: consists of actions to reduce emissions and atmospheric concentrations of CO_2 and other greenhouse gases (GHGs); Adaptation: involves learning to cope with a warmer world rather than trying to prevent it; Suffering: adverse impacts that are not avoided by either mitigation or adaptation.

In this paper and in paper 2, we consider the broad range of options available, reducing CO_2 emissions, i.e. for mitigation according to the above definitions. These include: increasing energy efficiency, increasing non-fossil fuel-based energy production, the use of carbon capture and storage (CCS), and deforestation control.

822, line 28ff: I do not understand what it means to use the "abatement share to invest in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system". It is simply not clear what abatement share means and how it relates to the investment. To me it seems like a typical allocation problem.

The abatement share τ_b is the ratio of abatement spending to the tax revenue, cf. Eq. (5), and it is used here as a policy tool. This share is used in the energy intensity e_c, cf. Eq. (13); the carbon intensity of energy c_c, cf. Eq. (14); the carbon intensity σ, cf. Eq. (15); and the de-carbonization of the economy (Eq. 16). The abatement share τ_b enters into all of these equations via the parameter $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_b\right)\right]$, where $\alpha_\tau > 0$ is an abatement efficiency parameter. By considering various values of the abatement share, τ_b, the overall energy efficiency of the economy increases and the overall carbon intensity of the energy system decreases depending on whether the abatement share is increasing, say from $\tau_b = 0$ to 0.145.

To make things more clear, we add "**see Equation (14) below**" in the paragraph contained in lines 25-29 on page 822 and lines 1-5 on page 823.

Section 2.3: Section 2.3: the first paragraph can be deleted. It does not really add to the content of the model. It only discusses an approach that is not followed.

Right, we will do exactly that. The following paragraph has been written as:

Here, in order to formulate emissions E_Y so that they may vary over time and to allow abatement to be zero, we specifically utilize the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005) that breaks down CO_2 emissions E_Y (in $GtCyr^{-1}$) into a product of five components: emissions per unit of energy consumed (carbon intensity of energy), energy use per unit of aggregate GDP (energy intensity), per capita GDP, human population, and carbon emission intensity, as shown below:

We finally would like to add the following in the acknowledgements: **We also would like to thank the editor and two anonymous reviewers for constructive comments.**

Once more, we would like to thank the two referees for their thoughtful and critical reviews which have been extremely helpful at refining the manuscript. We are greatly appreciative of the effort that went into it and hope that our answers are satisfying. If there are still things unclear or incomplete, we are happy to receive further comments.

References

Ackerman, F., Stanton, E. A., Hope, C., and Alberth, S.: Did the Stern Review underestimate US and global climate damages? Energ. Policy, 37, 2717–2721, 2009.

Akaev, A. A.: Stabilization of the planetary climate in the twenty first century by transition to a new paradigm of energy consumption, Dokl. Earth Sci., 446, 1180–1184, 2012.

Albanese, A. S. and Steinberg, M.: Environmental control technology for atmospheric carbon dioxide, Energy, 5, 641–661, 1980.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M.: WITCH: a world induced technical change hybrid model, Energ. J., 27, 13–38, 2006.

Bosetti, V., De Cian, E., Sgobbi, A., and Tavoni, M.: The 2008 WITCH Model: new model features and baseline, Working Paper No. 85, Fondazione Eni Enrico Mattei, Milan, 2009.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks, P. Natl. Acad. Sci. USA, 104, 18866–18870, 2007.

Chen, W.-Y., Seiner, J., Suzuki, T., and Lackner, M. (Eds.): Handbook of Climate Change Mitigation, Springer, New York, p. 5, doi:10.1007/978-1-4419-7991-9, 2012.

Creedy, J. and Guest, R.: Sustainable preferences and damage abatement: value judgments and implications for consumption streams, Research Paper 1026, Department of Economics, The University of Melbourne, Melbourne, Australia, 2008.

Edmonds, J. A and Reilly, J. M.: A long-term global energy-economic model of carbon dioxide release from fossil fuel use, Energ. Econ., 5, 74–88, 1983.

European Council: Presidency conclusions, European Council, Brussels, 2005.

Garrett, T. J.: No way out? The double-bind in seeking global prosperity alongside mitigated climate change, Earth Syst. Dynam., 3, 1–17, doi:10.5194/esd-3-1-2012, 2012.

Gerlagh, R. and Van der Zwaan, B.: Gross world product and consumption in a global warming model with endogenous technological change, Resour. Energ. Econ., 25, 35–57, 2003.

Ghil, M.: Hilbert problems for the geosciences in the 21st century, Nonlin. Processes Geophys., 8, 211–211, doi:10.5194/npg-8-211-2001, 2001.

Goulder, L.: Environmental Policy Making in Economies with Prior Tax Distortions, Edwin Elgar, Cheltenham, 2002.

Greiner, A.: Anthropogenic climate change in a descriptive growth model, Environ. Dev. Econ., 9, 645–662, 2004.

Greiner, A. and Semmler, W.: The Global Environment, Natural Resources and Economic Growth, Oxford University Press, NY, 60–68, 2008.

Greiner, A., Gruene, L., and Semmler, W.: Growth and climate change: threshold and multiple equilibria, in: Dynamic Systems, Economic Growth, and the Environment, edited by: Crespo Cuaresma, J, Palokangas, T., and Tarasyev, A., Springer, New York, USA, pp. 63–78, 2010.

Grubb, M., Kohler, J., and Anderson, D.: Induced technical change in energy and environmental modeling: analytic approaches and policy implications, Annu. Rev. Energ. Env., 27, 271–308, 2002.

Guest, R. and McDonald, I. M.: Global GDP shares in the 21st century – An equilibrium approach, Econ. Model., 24, 859–877, 2007.

Hannart, A., Ghil, M., Dufresne, J.-L., and Naveau, P.: Disconcerting learning on climate sensitivity and the uncertain future of uncertainty, Climatic Change, 119, 585–601, doi:10.1007/s10584-013-0770-z, 2013.

Hasselmann, K., Hasselmann, S., Giering, R., Ocana, V., and Van Storch, H.: Optimization of CO_2 emissions using coupled integral climate response and simplified cost models: a sensitivity study, Max-Planck Institut für Meteorologie, Report No 192, Hamburg Germany, 1996.

Held, H., Kriegler, E., Lessmann, K., and Edenhofer, O.: Efficient climate policies under technology and climate uncertainty, Energ. Econ., 31, S50–S61, 2009.

Hof, A. F., Hope, C. W., Jason, L., Mastrandrea, M. D., Malte, M., and Van Vuuren D. P.: The benefits of climate change mitigation in integrated assessment models: the role of the carbon cycle and climate component, Climatic Change 113, 897–917, 2012.

Hüsler, A. D. and Sornette, D.: Human population and atmospheric carbon dioxide growth dynamics: Diagnostics for the future, Eur. Phys. J. Special Topics, 223, 2065–2085, doi:10.1140/epjst/e2014-02250-7, 2014.

IPCC: Climate Change 2013: the Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, 1535 pp., 2013.

Janssen, M. A.: Meeting Targets: Tools to Support Integrated Assessment Modelling of Global Change, Cip-Genevens Koninklijke Bibliotheek, Den Haag, 1996.

Joos, F., Müller-Fürstenberger, G., and Stephan, G.: Correcting the carbon cycle representation: How important is it for the economics of climate change? Environ. Model. Assess., 4, 133–140, 1999.

Joos, F., Bruno, M., Fink, R., Stocker, T. F., Siegenthaler, U., LeQuere, C., and Sarmiento, J. L.: An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake, Tellus B, 48, 397-417, 1996.

Kaufmann, R. K.: Assessing the DICE model: uncertainty associated with the emission and retention of greenhouse gases, Climatic Change, 35, 435–448, 1997.

Kovalevsky, D. V. and Hasselmann, K.: Assessing the transition to a low-carbon economy using actor-based system-dynamic models, in: Proceedings of the 7th International Congress on Environmental Modeling and Software (iEMSs), edited by: Ames, D. P., Quinn, N. W. T., and Rizzoli, A. E., 15–19 June 2014, San Diego, California, USA, 1865–1872, available at: http://www.iemss.org/society/index.php/iemss-2014-proceedings, last access: 5 October 2014.

Kuckshinrichs, W. and Hake, J-F.: Carbon Capture, Storage and Use: Technical, Economic, Environmental and Societal Perspectives, Springer International Publishing, Switzerland, 2015.

Kuper, G. H.: Dynamics and Stability of Global Carbon Dioxide Emissions, Department of Economics, Econometrics and Finance, University of Groningen, Netherlands, 2011.

Labriet, M. and Loulou, R.: Coupling climate damages and GHG abatement costs in a linear programming framework, Environ. Model. Assess., 8, 261–274, 2003.

Lucas Jr., R. E.: Econometric policy evaluation: a critique, Carnegie-Rochester Conference Series on Public Policy, 1, 19–46, 1976.

Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A. (Eds.): Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the IPCC, Cambridge University Press, 2007.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakićenović, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747–756, doi:10.1038/nature08823, 2010.

Nordhaus, W. D.: Managing the Global Commons: the Economics of Climate Change, MIT Press, Cambridge, 1994.

Nordhaus, W. D.: The challenge of global warming: economic models and environmental policy, Yale University Press, New Haven, CT, USA, 2007.

Nordhaus, W. D.: A Question of Balance: Weighing the Options on Global Warming Policies, Yale University Press, New Haven, CT, USA, 2008.

Nordhaus, W. D.: RICE-2010 model, Yale University Press, New Haven, CT, USA, 2010.

Nordhaus, W. D.: The Climate Casino: Risk, Uncertainty, and Economics for a Warming World, Yale University Press, New Haven, London, p. 11, 2013a.

Nordhaus, W. D.: Integrated Economic and Climate Modeling, in: Handbook of Computable General Equilibrium Modeling edited by: Dixon, P. B. and Jorgenson, D. W., Elsevier B. V., Oxford, UK, 1069–1131, 2013b.

Nordhaus, W. D. and Boyer, J.: Warming the World: Economic Models of Global Warming, MIT Press, Cambridge, MA, 2000.

Ogutu, K. B. Z., D'Andrea, F., Ghil, M., Nyandwi, C., Manene, M. M., and Muthama, J. N.: Coupled Climate–Economy–Biosphere (CoCEB) model – Part 2: Deforestation control and investment in carbon capture and storage technologies, Earth Syst. Dynam. Discuss., 6, 865–906, doi:10.5194/esdd-6-865-2015, 2015.

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.
Petersen, A.: Simulating nature: a philosophical study of computer-model uncertainties and their role in climate science and policy advice, 2nd edn., CRC Press, Abingdon, 2012.

Petersen, A.: Simulating nature: a philosophical study of computer-model uncertainties and their role in climate science and policy advice, 2nd edn., CRC Press, Abingdon, 2012.

Pielke Jr., R. A., Wigley, T., and Green, C.: Dangerous assumptions, Nature, 452, 531–532, 2008.

Popp, D., Newell, R. G., and Jaffe, A. B.: Energy, the environment and technological change, in: Handbook of the Economics of Innovation, vol. 2, edited by: Hall, B. and Rosenberg, N., Elsevier B. V., Oxford, UK, 873–937, doi:10.1016/S0169-7218(10)02001-0, 2010.

Probert, D., Granstrand, O., Nagel, A., Tomlin, B., Herstatt, C., Tschirky, H., and Durand, T. (Eds.): Bringing technology and innovation into the boardroom: strategy, innovation and competences for business value, European Institute for Technology and Innovation Management, Basingstoke, Palgrave MacMillan, 2004.

Raupach, M. R., Canadell, J. G., and Le Quéré, C.: Anthropogenic and biophysical contributions to increasing atmospheric CO_2 growth rate and airborne fraction, Biogeosciences Discussions, 5, 2867–2896, 2008.

Roughgarden, T. and Schneider, S. H.: Climate change policy: quantifying uncertainties for damages and optimal carbon taxes, Energ. Policy, 27, 415–429, 1999.

Rozenberg, J., Davis, S. J., Narloch, U., and Hallegatte, S.: Climate constraints on the carbon intensity of economic growth, Environ. Res. Lett., 10, 1–9, 2015.

Sahal, D.: Patterns of Technological Innovations, Addison-Wesley, London, 1981.

Sanderson, J.: An analysis of climate change impact and adaptation for South East Asia, PhD Thesis, Centre for Strategic Economic Studies, Victoria University of Technology, 2002.

Siegenthaler, U. and Oeschger, H.: Predicting future atmospheric carbon dioxide levels, Science, 199, 388–395, 1978

Stanton, E. A., Ackerman, F., and Kartha, S.: Inside the integrated assessment models: four issues in climate economics, Clim. Dev., 1, 166–185, 2009.

Stern, N.: The Economics of Climate Change. The Stern review, Cambridge University Press, 2007.

Stoknes, P. E.: What We Think About When We Try Not To Think About Global Warming: Toward a New Psychology of Climate Action, Chelsea Green Publishing, USA, 2015.

Tol, R. S. J.: The damage costs of climate change towards a dynamic representation, Ecol. Econ., 19, 67–90, 1996.

Tol, R. S. J.: Estimates of the damage costs of climate change – Part 2: dynamic estimates, Environ. Resource Econ., 21, 35–160, 2002.

Traeger, C. P.: A 4-Stated DICE: quantitatively addressing uncertainty effects in climate change, Environ. Resource Econ., 59:1–37, 2014.

UN – United Nations: United Nations Framework Convention on Climate Change, United Nations, Bonn, Germany, 1992.

UN – United Nations: Copenhagen Accord, United Nations, New York, 2009.

Van Vuuren, D P. and Carter, T. R..: Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old, Climatic Change, 122, 415– 429, doi:10.1007/s10584-013-0974-2, 2014.

Van Vuuren, D. P., Eickhout, B., Lucas, P. L., and den Elzen, M. G. J.: Long-term multi-gas scenarios to stabilize radiative forcing – exploring costs and benefits within an integrated assessment framework, Energ. J., 27, 201–233, 2006.

Weinstein, M. P., Turner, R. E., and Ibáñez, C.: The global sustainability transition: it is more than changing light bulbs, Sustainability: Science, Practice, and Policy, 9, 4–15, 2013.

Wesselink, A., Challinor, A. J., Watson, J., Beven, K., Allen, I., Hanlon, H., Lopez, A., Lorenz, S., Otto, F., Morse, A., Rye, C., Saux-Picard, S., Stainforth, D., and Suckling, E.: Equipped to deal with uncertainty in climate and impacts predictions: lessons from internal peer review, Climatic Change, 132:1–14, 2015.

Yakovets, Yu. V., Kuzyk, B. N., Bekturganov, N, S. (Eds.): Global Forecast "Future of Civilizations" for 2050: Part 9 – The Future of Civilizations and Strategy of Civilizational Partnership (abridged version), Pitirim Sorokin/Nikolai Kondratieff International Institute, Moscow, SKII, 600 pp., 2009.

Earth Syst. Dynam. Discuss., 6, 819–863, 2015
www.earth-syst-dynam-discuss.net/6/819/2015/
doi:10.5194/esdd-6-819-2015

Earth System Dynamics Discussions
Open Access

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1: Abatement share and investment in low-carbon technologies

K. B. Z. Ogutu[1,2,3], **F. D'Andrea**[2], **M. Ghil**[2,4,5], **C. Nyandwi**[3], **M. M. Manene**[6], **and J. N. Muthama**[7]

[1]Department of Statistics and Actuarial Science, School of Science, Dedan Kimathi University of Technology, Nyeri, Kenya
[2]Laboratoire de Météorologie Dynamique (CNRS and IPSL), Ecole Normale Supérieure, Paris, France
[3]Department of Applied and Industrial Mathematics, School of Mathematics, University of Nairobi, Nairobi, Kenya
[4]Environmental Research & Teaching Institute, Ecole Normale Supérieure, Paris, France
[5]Department of Atmospheric & Oceanic Sciences and Institute of Geophysics & Planetary Physics, University of California, Los Angeles, USA
[6]Department of Statistics and Operations Research, School of Mathematics, University of Nairobi, Nairobi, Kenya

[7]Department of Meteorology, School of Physical Sciences, University of Nairobi, Nairobi, Kenya

Received: 2 March 2015 – Accepted: 31 March 2015 – Published: 20 April 2015

Correspondence to: K. B. Z. Ogutu (okeroboto@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

ESDD

6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Abstract

The Coupled Climate–Economy–Biosphere (CoCEB) model described herein takes an integrated assessment approach to simulating global change. By using an endogenous economic growth module with physical and human capital accumulation, this paper considers the sustainability of economic growth, as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change. Different types of fossil fuels and different technologies produce different volumes of carbon dioxide in combustion. The shares of different fuels and their future evolution are not known. We assume that the dynamics of hydrocarbon-based energy share and their replacement with renewable energy sources in the global energy balance can be modeled into the 21st century by use of logistic functions. Various climate change mitigation policy measures are considered. While many integrated assessment models treat abatement costs merely as an unproductive loss of income, we consider abatement activities also as an investment in overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system. The paper shows that these efforts help to reduce the volume of industrial carbon dioxide emissions, lower temperature deviations, and lead to positive effects in economic growth.

1 Introduction and motivation

The vast evidence that the climate of the Earth is changing due to the anthropogenic increase in greenhouse gases (GHGs) is compiled in the successive reports of the Intergovernmental Panel on Climate Change (IPCC, 1996a, 2001, 2007, 2013), carbon dioxide (CO_2) being the largest contributor (Stott et al., 2000; Stern, 2008; Mokhov et al., 2012; Farmer and Cook, 2013, p. 4). Typically, the effect of global warming on the economic system is modeled using integrated assessment models (IAMs); see also Meyers (2012, 5399–5428) and Rasch (2012, Ch. 8) for a further discussion. IAMs are motivated by the need to balance the dynamics of carbon accumulation in the at-

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

mosphere and the dynamics of de-carbonization of the economy (Nordhaus, 1994a). A specific goal of these studies is to evaluate different abatement scenarios as to economic welfare and their effects on GHG emissions.

In this paper, we study the interaction between global warming and economic growth, along the lines of the Dynamic Integrated model of Climate and the Economy (DICE) of Nordhaus (1994a), with subsequent updates in Nordhaus and Boyer (2000) and Nordhaus (2007, 2008, 2010, 2013). Greiner (2004) (see also, Greiner and Semmler, 2008) extended the DICE framework by including endogenous growth, to account for the fact that environmental policy affects not only the level of economic variables but also the long-run growth rate. Using the extended DICE model, Greiner argues that higher abatement activities reduce GHG emissions and may lead to a rise or decline in growth. The net effect on growth depends on the specification of the function between the economic damage and climate change.

Since anthropogenic GHGs are the result of economic activities, the main shortcoming in Greiner's (2004) approach is that of treating industrial CO_2 emissions as constant over time. Another problematic aspect of Greiner's emissions formulation is its inability to allow for zero abatement activities. In fact, his formulation only holds for a minimum level of abatement.

We address these issues in the present Part 1 of a two-part paper by using a novel approach to formulating emissions that depend on economic growth and vary over time; in this approach, abatement equal to zero corresponds to Business As Usual (BAU).

We further use the extended DICE modeling framework by considering both human and physical capital accumulation, in addition to the GHG emissions, as well as a ratio of abatement spending to the tax revenue or abatement share (see also, Greiner, 2004; Greiner and Semmler, 2008). Our methodology can analytically clarify the mutual causality between economic growth and the climate change-related damages and show how to alter this relationship by the use of various mitigation measures geared toward reduction of CO_2 emissions (Metz et al., 2007; Hannart et al., 2013). We will use the abatement share to invest in the increase of overall energy efficiency of the

ESDD
6, 819–863, 2015

economy (Diesendorf, 2014, p. 143) and decrease of overall carbon intensity of the energy system. It will be shown below that over the next few decades, up to the mid-21st century, mitigation costs do hinder economic growth, but that this growth reduction is compensated later on by the having avoided negative impacts of climate change on the economy; see also Kovalevsky and Hasselmann (2014, Fig. 2).

The companion paper, Part 2, complements the model by introducing carbon capturing and storing (CCS) technologies and control of deforestation, as well as increasing photosynthetic biomass sinks as a method of controlling atmospheric CO_2 and consequently the intensity and frequency of climate change related damages.

Our Coupled Climate–Economy–Biosphere (CoCEB) model is not intended to give a detailed quantitative description of all the processes involved, nor to make specific predictions for the latter part of this century. It is a reduced-complexity model that tries to incorporate the climate–economy–biosphere interactions and feedbacks with the minimum amount of variables and equations needed. We merely wish to trade realism for greater flexibility and transparency of the dynamical interactions between the different variables. The need for a hierarchy of models of increasing complexity is an idea that dates back – in the climate sciences – to the beginnings of numerical modeling (e.g. Schneider and Dickinson, 1974), and has been broadly developed and applied since (Ghil, 2001, and references therein). There is an equivalent need for such model hierarchy to deal with the higher-complexity problems at the interface of the biogeophysical-biogeochemical climate sciences and of socio-economic policy.

The CoCEB model lies toward the highly idealized end of such a hierarchy: it takes an integrated assessment approach to simulating global change. By using an endogenous economic growth module with physical and human capital accumulation, this paper considers the sustainability of economic growth, as economic activity intensifies greenhouse gas emissions that in turn cause economic damage due to climate change (Stern, 2007; Nordhaus, 2008; Dell et al., 2014 and the references therein).

As different types of fossil fuels produce different volumes of CO_2 in combustion, the dynamics of fossil fuel consumption – that is, the relative shares of coal, oil, and nat-

ESDD
6, 819–863, 2015

K. B. Z. Ogutu et al.

ural gas – has to be taken into account when calculating the future dynamics of CO_2 emission (see also, Akaev, 2012). These shares are not known at this time (Akaev, 2012), nor is it easy to predict their evolution. In order to describe the dynamics of hydrocarbon-based energy share into the global energy balance of the 21st century and their replacement with renewable energy sources we use, following Sahal (1981), logistic functions (see also, Probert et al., 2004, p. 108, and references therein). This is a novel approach with respect to most other integrated assessment modeling studies in the climate change mitigation literature, which often assume an unrealistic approach of fixed, predictable technological change, independent of public policy, as well as the treatment of investment in abatement as a pure loss (Stanton et al., 2009). Technology change in these IAMs is modeled in a simple way by using an autonomous energy efficiency improvement (AEEI) parameter that improves the energy efficiency of the economy by some exogenous amount overtime: see, for instance, Bosetti et al.'s (2006, 2009) World Induced Technical Change Hybrid (WITCH) model and van Vuuren et al.'s (2006) Integrated Model for the Assessment of the Global Environment (IMAGE) model. However, the use of AEEI ignores the causes that influence the evolution of technologies (Lucas, 1976; Popp et al., 2010 and references therein). Even though this shortcoming can be remedied by including endogenous technological change in IAMs either through direct price-induced, research and development-induced, or learning-induced approaches (see Popp et al., 2010 for details), there is no accord in the climate change mitigation literature regarding a single best approach (Grubb et al., 2002; Popp et al., 2010).

Various climate change mitigation policy measures are considered. While many integrated assessment models treat abatement costs merely as an unproductive loss of income (e.g. Nordhaus and Boyer, 2000; Nordhaus, 2007, 2008, 2010, 2013), we consider abatement activities also as an investment in overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system. The paper shows that these efforts help to reduce the volume of industrial carbon dioxide emissions, lower temperature deviations, and lead to positive effects in economic growth.

ESDD
6, 819–863, 2015

The model is, of course sensitive, to the choice of key parameters. We do carry out a sensitivity study, but do not intend to make precise calibrations; rather, we want to provide a tool for studying qualitatively how various climate policies affect the economy.

The next section describes the theoretical model, detailing the additions with respect to Nordhaus (2013), Greiner (2004) and Greiner and Semmler (2008). Section 3 discusses the numerical simulations and results, while Sect. 4 tests the sensitivity of the results to key parameters. Section 5 concludes with caveats and avenues for future research.

2 Model description

2.1 Climate module

The time evolution of the average surface temperature T (SAT) on Earth is given by

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{(1-\alpha_\mathrm{T})Q}{4c_\mathrm{h}} - \frac{\varepsilon\sigma_\mathrm{T}\tau_\mathrm{a}}{c_\mathrm{h}}T^4 + \frac{6.3\beta_1(1-\xi)}{c_\mathrm{h}}\ln\left(\frac{C}{\hat{C}}\right), \tag{1}$$

see, for instance, Ghil and Childress (1987, Ch. 10), McGuffie and Henderson-Sellers (2005, p. 81–85; 2014) or Hans and Hans (2013, Ch. 2). Here the first and second terms on the right-hand side are incoming and outgoing radiative fluxes respectively, while the third term is radiative forcing due to increase in GHGs (Kemfert, 2002; Greiner and Semmler, 2008); σ_T is the Stefan–Boltzmann constant, τ_a the infrared (long-wave) transmissivity of the atmosphere, ε the emissivity that gives the ratio of actual emission to blackbody emission, α_T the mean planetary albedo, Q is the average solar constant. The specific heat capacity c_h of Earth is largely determined by the oceans (Levitus et al., 2005) and it is taken equal to $16.7\,\mathrm{W\,m^{-2}\,K^{-1}}$ (Schwartz, 2007, 2008), which corresponds to an ocean fractional area of 0.71 and a depth of 150 m of the ocean mixed layer. The current CO_2 concentration C is given in gigatons of carbon (Gt C, $1\,\mathrm{Gt} = 10^{15}\,\mathrm{g}$) and $\hat{C}$ is the pre-industrial CO_2 concentration. All the feedbacks,

ESDD
6, 819–863, 2015
Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1
K. B. Z. Ogutu et al.

are represented in this highly idealized model by the factor β_1, which is assumed to take values between 1.1 and 3.4 (Greiner and Semmler, 2008, p. 62); in this study, it was assumed that $\beta_1 = 3.3$. The parameter $\xi = 0.23$ captures the fact that part of the warmth generated by the greenhouse effect is absorbed by the oceans and transported from their upper layers to the deep sea (Greiner and Semmler, 2008). The other parameters have standard values that are listed in Table 1.

At equilibrium, that is for $dT/dt = 0$, Eq. (1) gives an average SAT of 14 °C for the pre-industrial GHG concentration, i.e. for $C = \hat{C}$. Doubling the CO_2 concentration in Eq. (1) yields an increase of about 3.3 °C in equilibrium temperature, to 17 °C. This increase lies within the range of IPCC estimates, between 1.5 and 4.5 °C (Charney et al., 1979; IPCC, 2001, p. 67, 2013) with a best estimate of about 3.0 °C (IPCC, 2007, p. 12).

We represent the evolution C of the concentration of CO_2 in the atmosphere, following Uzawa (2003) and Greiner and Semmler (2008), as

$$\frac{dC}{dt} = \beta_2 E_Y - \mu_o (C - \hat{C}), \tag{2}$$

where E_Y is industrial CO_2 emissions. The excess C above pre-industrial level is reduced by the combined effect of land and ocean sinks. The inverse μ_o of the atmospheric lifetime of CO_2 is estimated in the literature to lie within an uncertainty range that spans 0.005–0.2 (IPCC, 2001, p. 38); we take it here to equal $\mu_o = 1/120 = 0.0083$, i.e. closer to the lower end of the range (Nordhaus, 1994a, p. 21; IPCC, 2001, p. 38). The fact that a certain part of GHG emissions is taken up by the oceans and does not remain in the atmosphere is reflected in Eq. (2) by the parameter β_2.

2.2 Economy module

In Greiner (2004) and Greiner and Semmler (2008) the per capita gross domestic product (GDP), Y, is given by a modified version of a constant-return-to scale Cobb–Douglas production function (Cobb and Douglas, 1928),

$$Y = AK^{\alpha} H^{1-\alpha} D(T - \hat{T}). \tag{3}$$

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Here K is the per capita physical capital, H is the per capita human capital, $A > 0$ the total factor of productivity, $0 < \alpha < 1$ is the capital share, $D(T - \hat{T})$ is the damage, expressed as a function of the temperature difference due to climate change. The damage function is described in Section "Damage function" below.

The economy income identity in per capita variables is given by

$$Y - X = I + M_E + G_E, \quad (4)$$

with $X = \tau Y$ the (per capita) tax revenue, $0 < \tau < 1$ the per annum tax rate, I investment, M_E consumption, and G_E abatement activities. This means that national income after tax is used for investment, consumption, and abatement. We assume that G_E is expressed as a fraction of X,

$$G_E = \tau_b X = \tau_b \tau Y, \quad (5)$$

with $0 \le \tau_b < 1$ the ratio of per annum abatement share, used as a policy tool. Consumption is also expressed as a fraction of Y after tax, that is,

$$M_E = c(1 - \tau)Y, \quad (6)$$

with $0 < c < 1$ the global annual consumption share.

The accumulation of per capita physical capital K is assumed to obey

$$\frac{dK}{dt} = Y - X - M_E - G_E - (\delta_K + n)K, \quad (7)$$

the logistic-type human population growth rate $0 < n < 1$ is given, in turn, by

$$\frac{dn}{dt} = \left(\frac{1}{1 - \delta_n} - 1\right) n, \quad (8)$$

with δ_n being the per year decline rate of n, and δ_K the per year depreciation rate of physical capital. Substituting the definitions of Y, X, M_E, and G_E into Eq. (7) we get

$$\frac{dK}{dt} = AK^{\alpha}H^{1-\alpha}D(T - \hat{T})[1 - \tau(1 + \tau_b) - c(1 - \tau)] - (\delta_K + n)K. \quad (9)$$

ESDD
6, 819–863, 2015

For physical capital to increase, $\mathrm{d}K/\mathrm{d}t > 0$, the parameters must satisfy the inequality $0 < [\tau(1+\tau_\mathrm{b}) + c(1-\tau)] < 1$. Now, proceeding as above for K, we assume that the per capita human capital H evolves over time as

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \varphi \left\{ AK^{\alpha}H^{1-\alpha}D(T-\hat{T})[1-\tau(1+\tau_\mathrm{b})-c(1-\tau)] \right\} - (\delta_H + n)H, \quad (10)$$

here $\varphi > 0$ is a coefficient that determines how much any unit of investment contributes to the formation of the stock of knowledge and δ_H gives the depreciation of knowledge.

Note that we take, as a starting point, the Solow–Swan approach (Solow, 1956; Swan, 1956; Greiner and Semmler, 2008), in which the share of consumption and saving 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 resulting from different preferences.

Our formulation assumes, furthermore, that government spending, except for abatement, does not affect production possibilities. Emissions of CO_2 are a byproduct of production and hence are a function of per capita output relative to per capita abatement activities. This implies that a higher production goes along with higher emissions for a given level of abatement spending. This assumption is frequently encountered in environmental economics (e.g. Smulders, 1995). It should also be mentioned that the emission of CO_2 affect production indirectly by affecting the climate of the Earth, which leads to a higher SAT and to an increase in the number and intensity of climate-related disasters (see, e.g. Emanuel, 2005; Min et al., 2011).

2.3 Industrial CO_2 emissions

In Greiner (2004) and Greiner and Semmler (2008), emissions E_Y are formally described, as a function of the production Y, by

$$\left(\frac{aY}{G_\mathrm{E}}\right)^{\gamma} = \left(\frac{aY}{\tau_\mathrm{b}\tau Y}\right)^{\gamma} = \left(\frac{a}{\tau_\mathrm{b}\tau}\right)^{\gamma}, \quad (11)$$

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

here $\gamma > 0$ is a constant and $a > 0$ a technology index that describes how polluting a given technology is. Note that Eq. (11) is defined only for τ_b different from zero; hence, it does not consider a no-abatement or BAU scenario. Moreover, Eq. (11) also gives constant emissions over time even when the economic activity is changing, which is unrealistic. Here, we use instead a formulation of emissions E_Y that vary over time and in which we can let abatement be zero.

Specifically, we use the Kaya–Bauer identity (Kaya, 1990; Bauer, 2005) that breaks down CO_2 emissions E_Y (in $\mathrm{Gt\,C\,yr^{-1}}$) into a product of five components: emissions per unit of energy consumed (carbon intensity of energy), energy use per unit of aggregate GDP (energy intensity), per capita GDP, human population, and carbon emission intensity, as shown below:

$$\begin{aligned} E_Y &= \left(\frac{E_{\mathrm{tot}}}{\mathrm{energy}}\right)\left(\frac{\mathrm{energy}}{\overline{Y}}\right)\left(\frac{\overline{Y}}{L}\right)L\left(\frac{E_Y}{E_{\mathrm{tot}}}\right) \\ &= c_{\mathrm{c}}e_{\mathrm{c}}YL\kappa_{\mathrm{ccs}} \\ &= \sigma YL\kappa_{\mathrm{ccs}}. \end{aligned}$$

Here $\overline{Y}$ is aggregate GDP, $Y = (\overline{Y}/L)$ is per capita GDP, L is the human population, $c_{\mathrm{c}} = E_{\mathrm{tot}}/\mathrm{energy}$ is the carbon intensity of energy, $e_{\mathrm{c}} = \mathrm{energy}/\overline{Y}$ is the energy intensity, $c_{\mathrm{c}}e_{\mathrm{c}} = E_{\mathrm{tot}}/\overline{Y} = \sigma$ is the ratio of industrial carbon emissions to aggregate GDP or the economy carbon intensity, $E_Y/E_{\mathrm{tot}} = \kappa_{\mathrm{ccs}}$ is the fraction of emissions that is vented to the atmosphere and involves CCS.

The E_Y level also depends on abatement activities, as invested in the increase of overall energy efficiency in the economy and decrease of overall carbon intensity of the energy system. The case of $\tau_b = 0$ in Eq. (5) corresponds to unabated emissions, i.e. BAU. Emissions are reduced as the abatement share increases. Taking the natural logarithms and differentiating both sides of the Kaya–Bauer identity yields

$$\frac{\mathrm{d}E_Y}{\mathrm{d}t} = [g_\sigma + g_Y + n + g_{\mathrm{ccs}}]E_Y, \tag{12}$$

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

where g_σ is the growth rate of σ, g_Y is the growth rate of Y, n is the population growth rate and g_{ccs} is the CCS growth rate. If CCS is applied, then $E_Y < E_{tot}$. There are many concerns and uncertainties about the CCS approach and it is usually not taken as a real sustainable and environmental friendly mitigation option to reduce emissions over a longer period (Tol, 2010). We will not consider it in this part of the paper, that is, we take $E_Y = E_{tot}$ or $\kappa_{ccs} = 1$.

We now formulate the technology-dependent carbon intensity σ. We follow the approach of Sahal (1981), who models the replacement of one technology by another using a logistic law. The energy intensity e_c, in tons of reference fuel (TRF)/USD 1000 of $\overline{Y}$, is the share of hydrocarbon-based energy (coal, oil, and natural gas) in the global energy balance (GEB) of the twenty-first century. Its dynamics are described by a descending logistic function (Akaev, 2012),

$$e_c = f_c\left(1 - \frac{r\exp(\psi t)}{1 + r(\exp(\psi t) - 1)}\right), \tag{13}$$

here we take 1990 as the time when the use of renewable energy sources (biomass and wastes, hydropower, geothermal energy, wind energy, and solar energy) and biofuels became significant in the GEB. The multiplier $f_c = 0.881$ corresponds to 1.0107×10^{10} TRF as the share of fossil fuels in the GEB (1.1472×10^{10} TRF) in 1990 (Akaev, 2012, Table 2). The parameters r and ψ are derived by assuming a level of 95 % fossil fuels used for year 2020 and of 5 % for year 2160. They are $r = 0.05$ and $\psi = \psi_0[1/(1 - \alpha_\tau \tau_b)]$, with $\psi_0 = 0.042$; $\alpha_\tau > 0$ here is an abatement efficiency parameter, chosen such that for the path corresponding to $\tau_b = 0.075$, carbon emissions reduction from baseline is about 50 % by year 2050; see Sect. 2.5 for details. Calculations based on Eq. (13) using these values indicate that the share of fossil fuels will be significant throughout the whole twenty-first century and, when $\tau_b = 0$, this share decreases to 35 % only by its end (Akaev, 2012).

As different types of fossil fuels produce different volumes of CO_2 in combustion, the dynamics of fossil fuel consumption – i.e. the relative shares of coal, oil, and natural

ESDD
6, 819–863, 2015
Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1
K. B. Z. Ogutu et al.

gas – should be taken into account when calculating the future dynamics of CO_2 emission. Since these shares are not known at this time, we assume a logistic function for describing a reduction of the carbon intensity of energy c_c, in tons of carbon/tons of reference fuel ($\mathrm{t\,C\,TRF^{-1}}$), throughout the 21st century (Akaev, 2012),

$$c_c = c_{-\infty} + \frac{a_c}{1 + r\exp(-\psi t)}, \tag{14}$$

with $a_c > 0$ a constant.

Thus the carbon intensity σ, which is technology-dependent and represents the trend in the CO_2-output ratio, can now be given by the product of the energy intensity e_c in Eq. (13) and the carbon intensity of energy c_c in Eq. (14), thus:

$$\sigma = f_c \left[1 - \frac{r\exp(\psi t)}{1 + r(\exp(\psi t) - 1)}\right] \left[c_{-\infty} + \frac{a_c}{1 + r\exp(-\psi t)}\right]. \tag{15}$$

We can now calculate the de-carbonization of the economy, i.e. the declining growth rate of σ, by taking the natural logarithms of Eq. (15) and getting the derivative with respect to time:

ESDD
6, 819–863, 2015

$$g_\sigma = \frac{f_c}{e_c}\left[\frac{[\psi r \exp(\psi t)][1+r(\exp(\psi t)-1)]-[\psi r^2 \exp(\psi t)]}{[1+r(\exp(\psi t)-1)]^2}\right] + \frac{1}{c_c}\left[\frac{a_c \psi r \exp(-\psi t)}{[1+r\exp(-\psi t)]^2}\right]. \quad (16)$$

In a similar way as Eq. (16) was derived from Eq. (15), the growth rate g_Y of per capita output is obtained from Eq. (3) as

$$\frac{1}{Y}\frac{dY}{dt} = \frac{\alpha}{K}\frac{dK}{dt} + \frac{(1-\alpha)}{H}\frac{dH}{dt} + \frac{1}{D}\frac{dD}{dT}\frac{dT}{dt},$$

or,

$$g_Y = \alpha g_K + (1-\alpha) g_H + \frac{1}{D}\frac{dD}{dT}\frac{dT}{dt}, \quad (17)$$

with g_K the per capita physical capital growth and g_H the per capita human capital growth.

Human population evolves; cf. Golosovsky (2010), as

$$\frac{dL}{dt} = nL\{1-\exp[-(L/L(1990))]\}, \quad (18)$$

where n is the population growth rate as given in Eq. (8). Equation (18) yields $L = 9 \times 10^9$ people in the year $t = 2100$. This value is consistent with the 2100 population projections of scenarios in the literature (e.g. van Vuuren et al., 2012, Table 3).

Damage function

The damage function D gives the decline in Y, the global GDP, which results from an increase of the temperature T above the pre-industrial temperature $\hat{T}$. Nordhaus (1994a) formulates it as

ESDD
6, 819–863, 2015

K. B. Z. Ogutu et al.

$$D(T-\hat{T}) = \left[1 + m_1(T-\hat{T})^{\chi}\right]^{-1}, \tag{19}$$

with $m_1 > 0$ and $\chi > 0$, and the damage is defined as $Y - DY = (1-D)Y$. The greater $T - \hat{T}$, the smaller the value of $D(T-\hat{T})$, and accordingly the smaller the value DY of the remaining GDP, after the damage.

The representation of climate change damages is both a key part and one of the weakest points of IAMs (Tol and Fankhauser, 1998). Temperature was used originally by Nordhaus (1994a) as a proxy for overall climate change. This may have taken the research community's focus off from potentially dangerous changes in climate apart from temperature (Toth, 1995). However, without using a detailed climate model, temperature remains the best option available. We assume, in choosing this option, that physical and human capitals are distributed across infinitely many areas in the economy, and that the damages by natural disasters are uncorrelated across areas. With such an assumption, some version of the law of large numbers can justify a result like Eq. (19) above; see Dell et al. (2014) for an insightful discussion about the damage function.

Nordhaus (1994a) first estimated the damage from CO_2 doubling – which, in his calculations was equivalent to a 3 °C warming – to be 1.33 % of global GDP (Nordhaus, 1992). Additionally, he argued that damage would increase sharply as temperature increases; hence he used a quadratic function, in which $\chi = 2$, and m_1 is chosen to have 1.33 % loss of GDP for a 3 °C warming.

Roughgarden and Schneider (1999), using the same functional form (Eq. 19), derived damage functions for each of the disciplines represented in an expert opinion solicited by a climate change survey (Nordhaus, 1994b). Taking an average of their values, we get $m_1 = 0.0067$; see, for instance, Table 1 in Labriet and Loulou (2003). On the other hand, we calibrated the nonlinearity parameter $\chi = 2.43$ so that our model's BAU emissions of $CO_2\,yr^{-1}$ and concentrations by 2100 mimic the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2007; IPCC, 2013). In fact, our projected climate change damages before and after abatement, as given by the damage function D in Eq. (19), are consistent with the damages projected in Stern (2007); see also Creedy and Guest (2008) as well as Chen et al. (2012, p. 5).

2.4 Climate change abatement measures

A key part of the mitigation literature concentrates on the feasibility of different climate targets, often defined by GHG concentrations or by radiative forcing levels, and the associated costs; see van Vuuren et al. (2012) and the citations therein. The broad range of options available for mitigating climate change includes the reduction of CO_2 emissions (increasing energy efficiency, increasing non-fossil fuel-based energy production, and the use of CCS), and CO_2 removal (Edenhofer et al., 2012; Steckel et al., 2013).

2.5 Abatement policies

For reasons of political feasibility as well as of efficiency, the focus of climate policy has been on energy intensity and carbon intensity of energy, and not on population and wealth (Tol, 2010). All the popular policies point to increased de-carbonization efforts, i.e. to an increase in g_σ. The historical record, however, shows quite clearly that global and regional rate of de-carbonization have seen no acceleration during the recent decade and in some cases even show evidence of re-carbonization (Canadell et al., 2007; Prins et al., 2009).

Among the various market-based (or economic) instruments adopted to reduce CO_2 emissions, *carbon taxes* and *tradable permits* are the most widely discussed *cost-efficient* policies, both at a national and international level (Weitzman, 1974; Fiddaman, 1997; Pizer, 1999, 2002, 2006; Fischer et al., 2003; Uzawa, 2003; IPCC, 2007; Mankiw, 2007; Nordhaus, 2008). *Forestry policies*, particularly deforestation control, also emerge as additional low cost measures for the reduction of CO_2 emissions. Deforestation control would cut CO_2 emissions and increased afforestation would sequester CO_2 from the atmosphere (see, e.g. Tavoni et al., 2007; Bosetti et al., 2011).

ESDD
6, 819–863, 2015

2.6 Abatement share

The abatement costs of several IAMs tend to cluster in the range of about 1–2 % of GDP as the cost of cutting carbon emissions from baseline by 50 % in the period 2025–2050, and about 2.5–3.5 % of GDP as the cost of reducing emissions from baseline by about 70 % by 2075–2100 (Boero et al., 1991; Cline, 1992, p. 184; Boero, 1995; Clarke et al., 1996; Tol, 2010, p. 87, Fig. 2.2) with an increasing dispersion of results as higher emission reduction targets are set (Boero et al., 1991).

Using the definition of abatement in Eq. (5) and the GDP evolution in Eq. (3), we obtain an abatement share that gives an abatement cost equivalent to 1 % of GDP by 2050 to be

$$\frac{G_E}{Y} = \tau_b \tau = 0.01 \Rightarrow \tau_b = 0.05. \tag{20}$$

Similarly, the abatement share giving an abatement cost equivalent to 2 % of GDP by 2050 is $\tau_b = 0.1$. We take, as our lower abatement share, the average $\tau_b = 0.075$ of the two abatement shares that give an abatement cost equivalent to 1.5 % of GDP by 2050.

Next, we choose the abatement efficiency parameter $\alpha_\tau = 1.8$ such that, for the path corresponding to $\tau_b = 0.075$, carbon emissions reduction from baseline is about 50 % by 2050. Our scenario corresponding to $\tau_b = 0.075$ also happens to mimic the RCP6.0 by 2100 (Fujino et al., 2006; Hijioka et al., 2008; IPCC, 2013). For the other non-BAU scenarios, we choose abatement shares of $\tau_b = 0.11$ and 0.145, such that an emissions reduction of 50 % or more from baseline by 2050 and beyond gives a reduction in GDP of 2.2 and 2.9 %, respectively; the scenario given by $\tau_b = 0.11$ also mimics RCP4.5 (Clerke et al., 2007; Wise et al., 2009; IPCC, 2013). Note that the abatement shares in Greiner (2004) and Greiner and Semmler (2008), which use Eq. (11), are about 10 times lower than the ones chosen here.

ESDD
6, 819–863, 2015

2.7 Summary formulation of CoCEB

Our coupled CoCEB model is described by Eqs. (1), (2), (9), (10) and (12). The model describes the temporal dynamics of five variables: per capita physical capital K, per capita human capital H, the average global surface air temperature T, the CO_2 concentration in the atmosphere C, and industrial CO_2 emissions E_Y. The other variables are connected to these five independent variables by algebraic equations. In Part 2, a supplementary equation will be added for the biomass. The equations are grouped for the reader's convenience below:

$$\frac{dK}{dt} = A\left[1-\tau(1+\tau_b)-c(1-\tau)\right]K^{\alpha}H^{1-\alpha}D(T-\hat{T})-(\lambda_K+n)K, \tag{21a}$$

$$\frac{dH}{dt} = \varphi\left\{A[1-\tau(1+\tau_b)-c(1-\tau)]K^{\alpha}H^{1-\alpha}D(T-\hat{T})\right\}-(\lambda_H+n)H, \tag{21b}$$

$$\frac{dT}{dt} = \frac{(1-\alpha_T)Q}{4c_h}-\frac{\varepsilon\sigma_T\tau_a}{c_h}T^4+\frac{\beta_1(1-\xi)}{c_h}6.3\ln\left(\frac{C}{\hat{C}}\right), \tag{21c}$$

$$\frac{dC}{dt} = \beta_2 E_Y-\mu_o(C-\hat{C}), \tag{21d}$$

$$\frac{dE_Y}{dt} = [g_\sigma+g_Y+n]E_Y. \tag{21e}$$

The parameter values used in the model are as described in the text above and in Table 1 below. They have been chosen according to standard tables and previous papers.

3 Numerical simulations and abatement results

In the following, we confine our investigations to the transition path for the 110 years from the baseline year 1990 to the end of this century. We consider four scenarios with an aggregate CO_2 concentration larger than or equal to the pre-industrial

ESDD
6, 819–863, 2015

K. B. Z. Ogutu et al.

level: (i) a baseline or BAU scenario, with no abatement activities, i.e. $\tau_b = 0$; and (ii)–(iv) three scenarios with abatement measures, corresponding to $\tau_b = 0.075$, 0.11 and 0.145, as chosen in Sect. 2.6.

The CoCEB model is integrated in time starting from the initial values at year 1990, as listed in Table 1. The damage function exponent χ in Eq. (19) is taken to be super-quadratic, $\chi = 2.43$; all other parameter values are as in Table 1. The time step is 1 year and the integration is stopped at year 2100. The values of CO_2 emissions and concentration, temperature, damage and GDP growth at the end of the integrations are shown in Table 2 for the four scenarios.

From the table, it is clear that, if no action is taken to reduce baseline CO_2 emissions, these will attain 29.3 Gt C yr^{-1} by 2100, leading to an atmospheric CO_2 concentration of 1842 Gt C, i.e. about 3.1 times the pre-industrial level at that time. As a consequence, global average SAT will rise by 5.2 °C from the pre-industrial level with a corresponding damage to the per capita GDP of 26.9 %. This compares well with the IPCC results for their RCP8.5 scenario, cf. Table 4 below.

The year-2100 changes in our three non-BAU scenarios' global mean SAT from the pre-industrial level are 3.4, 2.6, and 2 °C. The RCP6.0, RCP4.5, and RCP2.6 give a similar range of change in global SAT of 1.4–3.1 °C with a mean of 2.2 °C, 1.1–2.6 °C with a mean of 1.8 °C, and 0.3–1.7 °C with a mean of 1 °C, respectively (IPCC, 2013). We note that our scenarios' change in temperature compare well with the IPCC ones.

The cumulative CO_2 emissions for the 1990–2100 period in this study's non-BAU scenarios are 1231, 1037, and 904 Gt C. On the other hand, for the 2012–2100 period, RCP6.0 gives cumulative CO_2 emissions in the range of 840–1250 Gt C with a mean of 1060 Gt C; RCP4.5 gives a range of 595–1005 Gt C with a mean of 780 Gt C, while RCP2.6 gives a range of 140–410 Gt C with a mean of 270 Gt C. The two former RCPs agree rather well with our results, while RCP2.6 is less pessimistic.

In Fig. 1, the time-dependent evolution of the CoCEB output is shown, from 1990 to 2100. The figure shows that an increase in the abatement share τ_b from 0 to 0.145 leads to lower CO_2 emissions per year (Fig. 1a) as well as to lower atmospheric

ESDD
6, 819–863, 2015

CO_2 concentrations (Fig. 1b) and, as a consequence, to a lower average global SAT (Fig. 1c), compared to the baseline value. This physical result reduces the economic damages (Fig. 1d) and hence the GDP growth decrease is strongly modified (Fig. 1e).

Figure 1e is the key result of our study: it shows that abatement policies do pay off in the long run. From the figure, we see that – because of mitigation costs – per capita GDP growth on the paths with nonzero abatement share, $\tau_b \neq 0$, lies below growth on the BAU path for the earlier time period, approximately between 1990 and 2060. Later though, as the damages from climate change accumulate on the BAU path (Fig. 1d), GDP growth on the BAU slows and falls below the level on the other paths (Fig. 1e), i.e. the paths cross.

This crossing of the paths means that mitigation allows GDP growth to continue on its upward path in the long run, while carrying on BAU leads to great long-term losses. As will be shown in Table 3 below, the losses from mitigation in the near future are outweighed by the later gains in averted damage. The cross-over time after which abatement activities pay off occurs around year 2060; its exact timing depends on the definition of damage and on the efficiency of the modeled abatement measures in reducing emissions.

The average annual growth rates (AAGRs) of per capita GDP between 1990 and 2100, are given in our model by $(1/110)\sum_{t=1990}^{t=2100} g_Y(t)$ and their values, starting from the BAU scenario, are 2.6, 2.4, 2.1 % yr^{-1}, and 1.8 % yr^{-1}, respectively. Relative to 1990, these correspond to approximate per capita GDP increase of 5.5–14.5 times, that is USD_{1990} 34×10^3–90×10^3 in year 2100, up from an approximate of USD 6×10^3 in 1990. Our scenarios' AAGRs and the 2100-to-1990 per capita GDP ratio agree well with scenarios from other studies, which give AAGRs of 0.4–2.7 % yr^{-1} and a per capita GDP increase of 3–21 fold, corresponding to USD_{1990} 15×10^3–106×10^3 (Leggett et al., 1992; Holtz-Eakin and Selden, 1995; Rabl, 1996; Chakravorty et al., 1997; Grübler et al., 1999; Nakićenović and Swart, 2000; Schrattenholzer et al., 2005, p. 59; Nordhaus, 2007; Stern, 2007; van Vuuren et al., 2012; Krakauer, 2014).

ESDD
6, 819–863, 2015

Now, according to the United Nations Framework Convention on Climate Change (UNFCCC, 1992), the average global SAT should not exceed its pre-industrial level by more than 2 °C. This SAT target means that global efforts to restrict or reduce CO_2 emissions must aim at an atmospheric CO_2 concentration of no more than 1171.5 Gt C. This CO_2 target can be achieved if carbon emissions are reduced to no more than 3.3 Gt C yr^{-1}, or nearly half relative to the 1990 level of 6 Gt C yr^{-1} (Akaev, 2012). This goal is met, in our highly simplified model, by the path with the highest abatement share of the four, $\tau_b = 0.145$. From Table 2 and Fig. 1, we notice that this level of investment in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system enable emissions to decrease to 2.5 Gt C yr^{-1} by year 2100 (Fig. 1a), about a 58 % drop below the 1990 emissions level. This emissions drop enables the deviation from pre-industrial SAT to reach no higher than 2 °C by year 2100 (Fig. 1c).

The per capita abatement costs $G_E = \tau_b X = \tau_b \tau Y$ from Eq. (5) and the damage costs $(1 - D)Y$ from Eq. (19) for the various emission reduction paths are given in Table 3 for the year 2100. From the table we notice that, generally, the more one invests in abatement, the more emissions are reduced relative to baseline and the less the cost of damages from climate change. From Tables 2 and 3, we notice that limiting global average SAT to about 2 °C over pre-industrial levels would require an emissions reduction of 92 % from baseline by 2100, at a per capita cost of USD_{1990} 990, which translates to 2.9 % of per capita GDP. Although attaining the 2 °C goal comes at a price, the damages will be lower all along and the GDP growth better than for BAU starting from the cross-over year 2058.

Recall, moreover, that the benefits of GHG abatement are not limited to the reduction of climate change costs alone. A reduction in CO_2 emissions will often also reduce other environmental problems related to the combustion of fossil fuels. The size of these so-called secondary benefits is site-dependent (IPCC, 1996b, p. 183), and it is not taken into consideration as yet in the CoCEB model.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ESDD

6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 4 gives a comparative summary of our CoCEB model's results and those from other studies that used more detailed IAM models and specific IPCC (2013) RCPs. We notice that the CO_2 emissions per year and the concentrations in the transition path up to year 2100 agree fairly well with those of RCP8.5, RCP6.0 and RCP4.5.

4 Sensitivity analysis

We conducted an analysis to ascertain the robustness of the CoCEB model's results and to clarify the degree to which they depend on three key parameters: the damage function parameters m_1 and χ and the abatement efficiency parameter α_τ. The values of these parameters are varied below in order to gain insight into the extent to which particular model assumptions affect our results in Sect. 3 above.

4.1 Damage function parameters m_1 and χ

We modify the values of the parameters m_1 and χ by +50 and –50 % from their respective values $m_1 = 0.0067$ and $\chi = 2.43$ in Tables 1–4 above, and examine how that affects model results for year 2100. In Table 5 are listed the per annum CO_2 emissions, CO_2 concentrations, SAT, damages, and growth rate of per capita GDP. All parameter values are as in Table 1, including $\alpha_\tau = 1.8$.

From the table we notice that reducing m_1 by 50 % lowers the damages to per capita GDP from 26.9 to 20.3 %, i.e. a 24.5 % decrease on the BAU ($\tau_b = 0$) path. This depresses the economy less and contributes to higher CO_2 emissions of 50.8 $GtC\,yr^{-1}$. On the other hand, increasing m_1 by 50 % increases the damages from 26.9 to 30.3 %, i.e. a 12.6 % increase on the BAU path. This depresses the economy more and lowers CO_2 emissions in 2100 to 20.4 $GtC\,yr^{-1}$.

The sensitivity to the nonlinearity parameter χ is considerably higher. Decreasing it by 50 % reduces the damages to per capita GDP from 26.9 to about 6.3 %, i.e. a 76.6 % reduction on the BAU path. This contributes to higher economic growth and higher

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

emissions of 99.6 Gt C yr^{-1}. Conversely, increasing χ by 50 % increases the damages to per capita GDP from 26.9 to about 41.6 %, i.e. a 54.6 % increase on the BAU path. This contributes to a decrease in economic growth and to lower emissions of 6 Gt C yr^{-1} in the year 2100.

In Fig. 2 are plotted the GDP growth curves with time for the experiments summarized in Table 5. It is clear from the figure that the growth rate of per capita GDP is more sensitive to the nonlinearity parameter χ than to m_1. A decrease of m_1 by 50 % pushes the crossover point further into the future, from year 2058 to 2070 (Fig. 2a), while an increase by 50 % pulls the crossover point closer to the present, to about 2053 (Fig. 2b). Decreasing χ by 50 %, on the other hand, pushes the crossover point even further away, past the end of the century (Fig. 2c), while an increase of χ by 50 % pulls it from year 2058 to about 2037 (Fig. 2d).

4.2 Abatement efficiency parameter α_τ

Next, we modify the value of the parameter α_τ by +50 and −50 % from the standard value of $\alpha_\tau = 1.8$ used in Tables 1–5 above, and examine in Table 6 how that affects the model emissions reduction from baseline by the year 2100, as well as the per capita abatement costs and the per capita damage costs.

A 50 % decrease of the abatement efficiency gives $\alpha_\tau = 0.9$ in the upper half of the table. There is a substantial decrease in emissions reduction for all three scenarios with $\tau_b > 0$, compared to Table 3, and hence more damages for the same abatement costs. Furthermore, the increased damages increase the depression of the economy and contribute to low economic growth.

On the other hand, a 50 % increase in the abatement efficiency, to $\alpha_\tau = 2.7$, leads to an increase in the emissions reduction from baseline by 2100. This reduces the damages and hence lessens the depression to the economy, enabling economic growth to increase.

ESDD
6, 819–863, 2015

5 Conclusions and way forward

5.1 Summary

In this paper, we introduced a simple coupled climate–economy (CoCEB) model with the goal of understanding the various feedbacks involved in the system and also for use by policy makers in addressing the climate change challenge. In this Part 1 of our study, economic activities are represented through a Cobb–Douglas output function with constant returns to scale of the two factors of production: per capita physical capital and per capita human capital. The income after tax is used for investment, consumption, and abatement. Climate change enters the model through the emission of GHGs arising in proportion to economic activity. These emissions accumulate in the atmosphere and lead to a higher global mean surface air temperature (SAT). This higher temperature then causes damages by reducing output according to a damage function. The CoCEB model, as formulated here, was summarized as Eqs. (21a)–(21e) in Sect. 2.7.

Using this model, we investigated in Sect. 3 the relationship between investing in the increase of overall energy efficiency of the economy and decrease of overall carbon intensity of the energy system through abatement activities, as well as the time evolution, from 1990 to 2100, of the growth rate of the economy under threat from climate change–related damages. The CoCEB model shows that taking no abatement measures to reduce GHGs leads eventually to a slowdown in economic growth; see also Kovalevsky and Hasselmann (2014, Fig. 2).

This slowdown implies that future generations will be less able to invest in emissions control or adapt to the detrimental impacts of climate change (Krakauer, 2014). Therefore, the possibility of a long-term economic slowdown due to lack of abating climate change (Kovalevsky and Hasselmann, 2014) heightens the urgency of reducing GHGs by investing in low-carbon technologies, such as electric cars, biofuels, CO_2 capturing and storing (CCS), renewable energy sources (Rozenberg et al., 2014), and technology for growing crops (Wise et al., 2009). Even if this incurs short-term economic costs, the transformation to a de-carbonized economy is both feasible and affordable accord-

ESDD
6, 819–863, 2015

ing to Azur and Schneider (2002), Weber et al. (2005), Stern (2007), Schneider (2008), and would, in the long term, enhance the quality of life for all (Hasselmann, 2010). The great flexibility and transparency of the CoCEB model has helped us demonstrate that an increase in the abatement share of investments yields a win-win situation: higher annual economic growth rates, on average, of per capita GDP can go hand-in-hand with a decrease in GHG emissions and, as a consequence, to a decrease in average global SATs and the ensuing damages. These results hold when considering the entire transition path from 1990 to 2100, as a whole.

5.2 Discussion

The CoCEB model builds upon previous work on coupled models of global climate–economy interactions, starting from the pioneering work of Nordhaus (1994a), as extended in Greiner (2004) by the inclusion of endogenous growth. Greiner (2004) treated industrial CO_2 emissions as constant over time, while excluding the particular case of zero abatement activities (BAU); in fact, his model only applied for a minimum level of abatement. The present paper takes into account, more generally, emissions that depend on economic growth and vary over time, while including the case of abatement equal to zero, i.e. BAU. This was done by using logistic functions (Sahal, 1981; Akaev, 2012) in formulating equations for the evolution of energy intensity and carbon intensity of energy throughout the whole 21st century (Akaev, 2012).

The CoCEB model, as developed in this paper, analyzes the carbon policy problem in a single-region global model with the aim to understand theoretically the dynamic effects of using the abatement share as a climate change mitigation strategy. To be able to draw more concrete, quantitative policy recommendations is it important to account for regional disparities, an essential development left to future research.

A finite-horizon optimal climate change control solution can be gotten by assuming that the government takes per capita consumption and the annual tax rate as given and sets abatement such that welfare is maximized. As to welfare, one can assume that it is given by the discounted stream of per capita utility times the number of individ-

ESDD
6, 819–863, 2015

uals over a finite time horizon. The Pontryagin Maximum Principle (Pontryagin et al., 1964; Hestenes, 1966; Sethi and Thompson, 2000) is used to find the necessary optimality conditions for the *finite-horizon* control problem. The Maximum Principle for *infinite-horizon* control problems is presented in Michel (1982), Seierstadt and Sydsaeter (1987), Aseev and Kryazhimskiy (2004, 2007), and Maurer et al. (2013). For a modern theory of infinite–horizon control problems the reader is referred to Lykina et al. (2008). The determination of an optimal abatement path along the lines above will be the object of future work.

Concerning the damage function, Stern (2007) states that “Most existing IAMs also omit other potentially important factors – such as social and political instability and cross-sector impacts. And they have not yet incorporated the newest evidence on damaging warming effects,” and he continues “A new generation of models is needed in climate science, impact studies and economics with a stronger focus on lives and livelihoods, including the risks of large-scale migration and conflicts” (Stern, 2013). Nordhaus (2013) suggests, more specifically, that the damage function needs to be reexamined carefully and possibly reformulated in cases of higher warming or catastrophic damages. In our CoCEB model, an increase in climate-related damages has the effect of anticipating the crossover time, starting from which the abatement-related costs start paying off in terms of increased per capita GDP growth.

A major drawback of current IAMs is that they mainly focus on mitigation in the energy sector. For example, the RICE (Regional Dynamic Integrated model of Climate and the Economy) and DICE (Nordhaus and Boyer, 2000) models consider emissions from deforestation as exogenous. Nevertheless, GHG emissions from deforestation and current terrestrial uptake are significant, so including GHG mitigation in the biota sinks has to be considered within IAMs. Several studies provide evidence that forest carbon sequestration can help reduce atmospheric CO_2 concentration significantly and could be a cost-efficient way for curbing climate change (e.g. Tavoni et al., 2007; Bosetti et al., 2011).

ESDD
6, 819–863, 2015

In Part 2 of this paper, we report on work along these lines, by studying relevant economic aspects of deforestation control and carbon sequestration in forests, as well as the widespread application of CCS technologies as alternative policy measures for climate change mitigation.

Finally, even though there are several truly coupled IAMs (e.g. Nordhaus and Boyer, 1998; Ambrosi et al., 2003; Stern, 2007), these IAMs disregard variability and represent both climate and the economy as a succession of equilibrium states without endogenous dynamics. This can be overcome by introducing business cycles into the economic module (e.g. Akaev, 2007; Hallegatte et al., 2008) and by taking them into account in considering the impact of both natural, climate-related and purely economic shocks (Hallegatte and Ghil, 2008; Groth et al., 2014).

Acknowledgements. This work was supported by Dedan Kimathi University of Technology (DeKUT) and the Embassy of France in Kenya, whose views it does not claim to represent.

References

Akaev, A. A.: Derivation of the general macroeconomic dynamics equation describing the joint interaction of long-term growth and business cycles, Dokl. Math., 76, 879–881, doi:10.1134/S1064562407060191, 2007.

Akaev, A. A.: Stabilization of the planetary climate in the twenty first century by transition to a new paradigm of energy consumption, Dokl. Earth Sci., 446, 1180–1184, 2012.

Ambrosi, P., Hourcade, J. C., Hallegatte, S., Lecocq, F., Dumas, P., and Duong, M. H.: Optimal control models and elicitation of attitudes towards climate change, Environ. Model. Assess., 8, 135–147, doi:10.1023/A:1025586922143, 2003.

Aral, M. M.: Climate change and human population dynamics, J. Water Qual. Expo. Health, 6, 53–62, doi:10.1007/s12403-013-0091-5, 2013.

Aseev, S. M. and Kryazhimskiy, A. V.: The Pontryagin maximum principle and transversality condition for a class of optimal control problems with infinite time horizons, SIAM J. Control Optim., 43, 1094–1119, 2004.

Aseev, S. M. and Kryazhimskiy, A. V.: The Pontryagin maximum principle and economic growth, P. Steklov Inst. Math., 257, 1–255, 2007.
Azur, C. and Schneider, S. H.: Are the economic costs of stabilizing the atmosphere prohibitive?, Ecol. Econ., 42, 73–80, doi:10.1016/S0921-8009(02)00042-3, 2002.
Bauer, N.: Carbon capturing and sequestration – an option to buy time, PhD thesis, Faculty of Economics and Social Sciences, University Potsdam, Potsdam, 2005.
Boero, G.: Global warming – some economic aspects, Scot. J. Polit. Econ., 42, 99–112, 1995.
Boero, G., Clarke, R., and Winters, L. A.: The Macroeconomic Consequences of Controlling Greenhouse Gases: a Survey, DOE Environmental Economics Research Series, HMSO, London, 1991.
Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M.: WITCH: a world induced technical change hybrid model, Energ. J., 27, 13–38, 2006.
Bosetti, V., De Cian, E., Sgobbi, A., and Tavoni, M.: The 2008 WITCH Model: new model features and baseline, Working Paper No. 85, Fondazione Eni Enrico Mattei, Milan, 2009.
Bosetti, V., Lubowski, R., Golub, A., and Markandya, A.: Linking reduced deforestation and global carbon market: implications for clean energy technology and policy flexibility, Environ. Dev. Econ., 16, 479–505, 2011.
Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks, P. Natl. Acad. Sci. USA, 104, 18866–18870, 2007.
Chakravorty, U., Roumasset, J., and Tse, K.: Endogenous substitution among energy resources and global warming, J. Polit. Econ., 105, 1201–1234, 1997.
Charney, J. G., Arakawa, A., Baker, D. J., Bolin, B., Dickinson, R. E., Goody, R. M., Leith, C. E., Stommel, H. M., and Wunsch, C. I.: Carbon Dioxide and Climate: a Scientific Assessment, National Academic Press, Washington, D.C., 1979.
Chen, W.-Y., Seiner, J., Suzuki, T., and Lackner, M. (Eds.): Handbook of Climate Change Mitigation, Springer, New York, p. 5, doi:10.1007/978-1-4419-7991-9, 2012.
Clarke, L. E., Edmonds, J. A., Jacoby, H. D., Pitcher, H. M., Reilly, J. M., and Richels, R. G.: Scenarios of greenhouse gas emissions and atmospheric concentrations, Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological & Environmnetal Research, Washington, D.C., USA, 154 pp., 2007.

Clarke, R., Boero, G., and Winters, A. L.: Controlling greenhouse gases – a survey of global macroeconomic studies, B. Econ. Res., 48, 269–308, 1996.
Cline, W. R.: Energy efficiency and greenhouse abatement costs (Comment on Lovins and Lovins), Climatic Change, 22, 95–97, doi:10.1007_bf00142960, 1992.
Cobb, C. W. and Douglas, P. H.: A theory of production, Am. Econ. Rev., 18, 139–165, 1928.
Creedy, J. and Guest, R.: Sustainable preferences and damage abatement: value judgments and implications for consumption streams, Research Paper 1026, Department of Economics, The University of Melbourne, Melbourne, Australia, 2008.
Dell, M., Jones, B. F., and Olken, B. A.: What do we learn from the weather? The new climate–economy literature, J. Econ. Lit., 52, 740–798, doi:10.1257/jel.52.3.740, 2014.
Diesendorf, M.: Sustainable energy solutions for climate change mitigation, University of New South Wales Press Ltd, Sydney, Australia, 142–143, 2014.
Edenhofer, O., Carraro, C., and Hourcade, J. C.: On the economics of de-carbonization in an imperfect world, Climatic Change, 114, 1–8, doi:10.1007/s10584-012-0549-7, 2012.
Emanuel, K.: Increasing destructiveness of tropical cyclones over the past 30 years, Nature, 436, 686–688, 2005.
Erk, N., Çabuk, A., and Ateş, S.: Long-run growth and physical capital-human capital concentration, METU International Economic Conference II, 9–12 September 1998, Ankara, 1998.
Farmer, G. T. and Cook, J.: Climate Change Science: a Modern Synthesis, vol. 1, The Physical Climate, Springer, Dordrecht, p. 4, 2013.
Fiddaman, T. S.: Feedback complexity in integrated climate–economy models, PhD thesis, MIT Sloan School of Management, Cambridge, MA, 1997.
Fischer, C., Parry, I. W. H., and Pizer, W. A.: Instrument choice for environmental protection when technological innovation is endogenous, J. Environ. Econ. Manage., 45, 523–45, 2003.
Fujino, J., Nair, R., Kainuma, M., Masui, T., and Matsuoka, Y.: Multi-gas mitigation analysis on stabilization scenarios using aim global model, Energy J., 0, 343–353, 2006.
Ghil, M.: Hilbert problems for the geosciences in the 21st century, Nonlin. Processes Geophys., 8, 211–211, doi:10.5194/npg-8-211-2001, 2001.
Ghil, M. and Childress, S.: Topics in Geophysical Fluid Dynamics: Atmospheric Dynamics, Dynamo Theory and Climate Dynamics, Springer-Verlag, New York, Berlin, Tokyo, 485 pp., 1987.
Gollin, D.: Getting income shares right, J. Polit. Econ., 110, 458–474, 2002.

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Golosovsky, M.: Hyperbolic growth of the human population of the Earth: analysis of existing models, in: History and Mathematics: Processes and Models of Global Dynamics, edited by: Grinin, L., Herrmann, P., Korotayev, A., and Tausch, A., Uchitel, Volgograd, 188–204, 2010.

Greiner, A.: Anthropogenic climate change in a descriptive growth model, Environ. Dev. Econ., 9, 645–662, 2004.

Greiner, A. and Semmler, W.: The Global Environment, Natural Resources and Economic Growth, Oxford University Press, NY, 60–68, 2008.

Groth, A., Dumas, P., Ghil, M., and Hallegatte, S.: Impacts of natural disasters on a dynamic economy, in: Extreme Events: Observations, Modeling and Economics, edited by: Chavez, M., Ghil, M., and Urrutia-Fucugauchi, J., AGU Monograph, Washington, D.C., in press, 2014.

Grubb, M., Kohler, J., and Anderson, D.: Induced technical change in energy and environmental modeling: analytic approaches and policy implications, Annu. Rev. Energ. Env., 27, 271–308, 2002.

Grübler, A., Nakićenović, N., and Victor, D. G.: Dynamics of energy technologies and global change, Energ. Policy, 27, 247–280, 1999.

Gueymard, C.: The Sun's total and spectral irradiance for solar energy applications and solar radiation models, Sol. Energy, 76, 423–452, 2004.

Hallegatte, S. and Ghil, M.: Natural disasters impacting a macroeconomic model with endogenous dynamics, Ecol. Econ., 68, 582–592, doi:10.1016/j.ecolecon.2008.05.022, 2008.

Hallegatte, S., Ghil, M., Dumas, P., and Hourcade, J. C.: Business cycles, bifurcations and chaos in a neoclassical model with investment dynamics, J. Econ. Behav. Organ., 67, 57–77, 2008.

Hannart, A., Ghil, M., Dufresne, J.-L., and Naveau, P.: Disconcerting learning on climate sensitivity and the uncertain future of uncertainty, Climatic Change, 119, 585–601, doi:10.1007/s10584-013-0770-z, 2013.

Hans, G. K. and Hans, E.: Mathematics and Climate, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, Pennsylvania, 2013.

Hasselmann, K.: The climate change game, Nat. Geosci., 3, 511–512, 2010.

Hestenes, M. R.: Calculus of Variations and Optimal Control Theory, Wiley, New York, 1966.

Hijioka, Y., Matsuoka, Y., Nishomoto, H., Masui, M., and Kainuma, M.: Global GHG emission scenarios under GHG concentration stabilization targets, J. Global Environ. Eng., 13, 97–108, 2008.

ESDD

6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Holtz-Eakin, D. and Selden, T. M.: Stoking the fires? CO_2 emissions and economic growth, J. Public Econ., 57, 85–101, 1995.

IPCC: Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the IPCC, Cambridge University Press, 1996a.

IPCC: Climate Change 1995: Economic and Social Dimensions of Climate Change, Contribution of Working Group III to the Second Assessment Report of the IPCC, Cambridge University Press, p. 183, 1996b.

IPCC: Climate Change 2001: the Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Cambridge University Press, 881 pp., 2001.

IPCC: Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, 996 pp., 2007.

IPCC: Climate Change 2013: the Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, 1535 pp., 2013.

Kaya, Y.: Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, 1990.

Kemfert, C.: An integrated assessment model of economy–energy–climate – the model Wiagem, Integrat. Ass., 3, 281–298, 2002.

Kovalevsky, D. V. and Hasselmann, K.: Assessing the transition to a low-carbon economy using actor-based system-dynamic models, in: Proceedings of the 7th International Congress on Environmental Modeling and Software (iEMSs), edited by: Ames, D. P., Quinn, N. W. T., and Rizzoli, A. E., 15–19 June 2014, San Diego, California, USA, 1865–1872, available at: http://www.iemss.org/society/index.php/iemss-2014-proceedings, last access: 5 October 2014.

Krakauer, N. Y.: Economic growth assumptions in climate and energy policy, Sustainability, 6, 1448–1461, doi:10.3390/su6031448, 2014.

Labriet, M. and Loulou, R.: Coupling climate damages and GHG abatement costs in a linear programming framework, Environ. Model. Assess., 8, 261–274, 2003.

Leggett, J., Pepper, W. J., and Swart, R. J.: Emissions scenarios for IPCC: an update, in: Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment, Ch. A3, edited by: Houghton, J. T., Callander, B. A., and Varney, S. K., Cambridge University Press, 69–95, 1992.
Lenton, T. M.: Land and ocean carbon cycle feedback effects on global warming in a simple Earth system model, Tellus B, 52, 1159–1188, 2000.
Levitus, S., Antonov, J., and Boyer, T.: Warming of the World Ocean, 1955–2003, Geophys. Res. Lett., 32, L02604, doi:10.1029/2004GL021592, 2005.
Lucas Jr., R. E.: On the mechanics of economic development, J. Monetary Econ., 22, 3–42, 1988.
Lykina, V., Pickenhain, S., and Wagner, M.: Different interpretations of the improper integral objective in an infinite horizon control problem, J. Math. Anal. Appl., 340, 498–510, 2008.
Mankiw, N. G.: One answer to global warming: a new tax, The New York Times, 07/16/09, 2007.
Maurer, H., Preuß, J. J., and Semmler, W.: Optimal control of growth and climate change-exploration of scenarios, in: Green Growth and Sustainable Development, Dynamic Modeling and Econometrics in Economics and Finance, edited by: Cuaresma, J. C. and Palokangas, T., 14, doi:10.1007/978-3-642-34354-4_6, Springer-Verlag, Berlin, Heidelberg, 113–139, 2013.
McGuffie, K. and Henderson-Sellers, A.: A Climate Modeling Primer, 3rd edn., John Wiley, Chichester, 81–85, 2005.
McGuffie, K. and Henderson-Sellers, A.: A climate modeling primer, 4th Edn., John Wiley Sons Inc, USA, 456 pp., 2014.
Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A. (Eds.): Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the IPCC, Cambridge University Press, 2007.
Meyers, R. A. (Ed.): Encyclopedia of Sustainability Science and Technology, Springer, New York, 12678 pp., doi:10.1007/978-1-4419-0851-3, 2012.
Michel, P.: On the transversality conditions in infinite horizon optimal control problems, Econometrica, 50, 975–985, 1982.
Min, S. K., Zhang, X., Zwiers, F. W., and Hegerl, G. C.: Human contribution to more intense precipitation extremes, Nature, 470, 378–381, 2011.

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Mokhov, I. I., Smirnov, D. A., and Karpenko, A. A.: Assessments of the relationship of changes of the global surface air temperature with different natural and anthropogenic factors based on observations, Dokl. Earth Sci., 443, 381–387, 2012.

Nakićenović, N. and Swart, R. J. (Eds.): IPCC Special Report on Emissions Scenarios, Cambrigde University Press, 2000.

Nordhaus, W. D.: An optimal transition path for controlling greenhouse gases, Science, 258, 1315–1319, 1992.

Nordhaus, W. D.: Rolling the "DICE" – an optimal transition path for controlling greenhouse gases, Resour. Energy Econ., 15, 27–50, 1993.

Nordhaus, W. D.: Managing the Global Commons: the Economics of Climate Change, MIT Press, Cambridge, 1994a.

Nordhaus, W. D.: Expert opinion on climatic change, Am. Sci., 82, 45–51, 1994b.

Nordhaus, W. D.: The challenge of global warming: economic models and environmental policy, Yale University, New Haven, CT, USA, 2007.

Nordhaus, W. D.: A Question of Balance, Princeton University Press, Princeton, 2008.

Nordhaus, W. D.: RICE-2010 model, Yale University, New Haven, CT, USA, 2010.

Nordhaus, W. D.: Integrated Economic and Climate Modeling, in: Handbook of Computable General Equilibrium Modeling, edited by: Dixon, P. B. and Jorgenson, D. W., Elsevier B. V., Oxford, UK, 1069–1131, 2013.

Nordhaus, W. D. and Boyer, J.: Roll the DICE Again: the Economics of Global Warming, Yale University, Yale, 1998.

Nordhaus, W. D. and Boyer, J.: Warming the World: Economic Models of Global Warming, MIT Press, Cambridge, MA, 2000.

Pizer, W. A.: Optimal choice of policy instrument and stringency under uncertainty, Resour. Energy Econ., 21, 255–287, 1999.

Pizer, W. A.: Combining price and quantity controls to mitigate global climate change, J. Public Econ., 85, 409–434, 2002.

Pizer, W. A.: Choosing price or quantity controls for greenhouse gases, in: The RFF Reader in Environmental and Resource Policy, 2nd Edn., edited by: Oates, W. E., Resources for the Future Press, Washington, D.C., USA, 225–234, 2006.

Pontryagin, L. S., Boltyanski, V. G., Gramkrelidze, R. V., and Miscenko, E. F.: The Mathematical Theory of Optimal Processes, Moscow, Fitzmatgiz, English translation, Pergamon, New York, 1964.

ESDD
6, 819–863, 2015

Popp, D., Newell, R. G., and Jaffe, A. B.: Energy, the environment and technological change, in: Handbook of the Economics of Innovation, vol. 2, edited by: Hall, B. and Rosenberg, N., Elsevier B. V., Oxford, UK, 873–937, doi:10.1016/S0169-7218(10)02001-0, 2010.
Prins, G., Cook, M., Green, C., Hulme, M., Korhola, A., Korhola, E.-R., Pielke, Jr. R., Rayner, S., Sawa, A., Sarewitz, D., Stehr, N., and von Storch, H.: How to get climate policy back on course, Institute for Science, Innovation and Society, University of Oxford, Oxford, 2009.
Probert, D., Granstrand, O., Nagel, A., Tomlin, B., Herstatt, C., Tschirky, H., and Durand, T. (Eds.): Bringing technology and innovation into the boardroom: strategy, innovation and competences for business value, European Institute for Technology and Innovation Management, Basingstoke, Palgrave MacMillan, 2004.
Rabl, A.: Discounting of long-term costs: what would future generations prefer us to do?, Ecol. Econ., 17, 137–145, 1996.
Rao, S. and Riahi, K.: The role of non-CO_2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st century, multi-gas mitigation and climate policy, Energ. J., 3, 177–200, 2006.
Rasch, P. J. (Ed.): Climate Change Modeling Methodology: Selected Entries from the Encyclopedia of Sustainability Science and Technology, Springer Science + Business Media, New York, doi:10.1007/978-1-4614-5767-1_8, 2012.
Riahi, K., Gruebler, A., and Nakićenović, N.: Scenarios of long-term socio-economic and environmental development under climate stabilization, Technol. Forecast. Soc., 74, 887–935, 2007.
Roughgarden, T. and Schneider, S. H.: Climate change policy: quantifying uncertainties for damages and optimal carbon taxes, Energ. Policy, 27, 415–429, 1999.
Rozenberg, J., Guivarch, C., Lempert, R., and Hallegatte, S.: Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation, Climatic Change, 122, 509–522, doi:10.1007/s10584-013-0904-3, 2014.
Sahal, D.: Patterns of Technological Innovations, Addison-Wesley, London, 1981.
Schneider, S. H.: Geoengineering: could we or should we make it work?, Philos. T. Roy. Soc. A, 366, 3843–3862, 2008.
Schneider, S. H. and Dickinson, R. E.: Climate modeling, Rev. Geophys. Space Ge., 12, 447–493, 1974.

ESDD
6, 819–863, 2015
Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1
K. B. Z. Ogutu et al.

Schrattenholzer, L., Miketa, A., Riahi, K., and Roehrl, R. A.: Achieving a Sustainable Global Energy System Identifying Possibilities Using Long-Term Energy Scenarios, ESRI Studies Series on the Environment, Edward Elgar, Cheltenham, UK, Northampton, MA, USA, 2005.

Schwartz, S. E.: Heat capacity, time constant, and sensitivity of Earth's climate system, J. Geophys. Res., 112, D24S05, doi:10.1029/2007JD008746, 2007.

Schwartz, S. E.: Reply to comments by Foster, G. et al., Knutti, R. et al., and Scafetta, N. on "Heat capacity, time constant, and sensitivity of Earth's climate system", J. Geophys. Res., 113, D15105, doi:10.1029/2008JD009872, 2008.

Seierstadt, A. and Sydsaeter, K.: Optimal Control Theory with Economic Applications, Elsevier B. V., Amsterdam, North-Holland, the Netherlands, 1987.

Sethi, S. P. and Thompson, G. L.: Optimal Control Theory: Applications to Management Science and Economics, 2nd Edn., Kluwer Academic, Norwell, 2000.

Smith, S. J. and Wigley, T. M. L.: Mult-gas forcing stabilization with the MiniCAM, Energ. J., SI3, 373–391, 2006.

Smulders, S.: Entropy, environment, and endogenous growth, Int. Tax Public Finan., 2, 319–340, 1995.

Solow, R. M.: A contribution to the theory of economic growth, Q. J. Econ., 70, 65–94, 1956.

Stanton, E. A., Ackerman, F., and Kartha, S.: Inside the integrated assessment models: four issues in climate economics, Clim. Dev., 1, 166–185, 2009.

Steckel, J. C., Brecha, R. J., Jakob, M., Strefler, J., and Luderer, G.: Development without energy? Assessing future scenarios of energy consumption in developing countries, Ecol. Econ., 90, 53–67, 2013.

Stern, N.: The Economics of Climate Change. The Stern review, Cambridge University Press, 2007.

Stern, N.: The economics of climate change, Am. Econ. Rev., 98, 1–37, 2008.

Stern, N.: 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, doi:10.1257/jel.51.3.838, 2013.

Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B., and Jenkins, G. J.: External control of 20th century temperature by natural and anthropogenic forcings, Science, 290, 2133–2137, doi:10.1126/science.290.5499.2133, 2000.

Swan, T. W.: Economic growth and capital accumulation, Econ. Rec., 32, 334–361, 1956.

ESDD
6, 819–863, 2015

Tavoni, M., Sohngen, B., and Bosetti, V.: Forestry and the carbon market response to stabilize climate, Energ. Policy, 35, 5346–5353, 2007.
Tol, S. J. R.: Carbon dioxide mitigation, in: Smart Solutions to Climate Change – Comparing Costs and Benefits, edited by: Lomborg, B., Cambridge University Press, 2010.
Tol, S. J. R. and Fankhauser, S.: On the representation of impact in integrated assessment models of climate change, Environ. Model. Assess., 3, 63–74, 1998.
Toth, F. L.: Practise and progress in integrated assessments of climate change: a workshop overview, Energ. Policy, 239, 253–267, 1995.
UN – United Nations: United Nations Framework Convention on Climate Change, United Nations, Bonn, Germany, 1992.
Uzawa, H.: Economic Theory and Global Warming, Cambridge University Press, 2003.
van Vuuren, D. P., Eickhout, B., Lucas, P. L., and den Elzen, M. G. J.: Long-term multi-gas scenarios to stabilize radiative forcing – exploring costs and benefits within an integrated assessment framework, Energ. J., 27, 201–233, 2006.
van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakićenović, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S. K., and Arnell, N.: A proposal for a new scenario framework to support research and assessment in different climate research communities, Global Environ. Change, 22, 21–35, doi:10.1016/j.gloenvcha.2011.08.002, 2012.
Weber, M., Barth, V., and Hasselmann, K.: A multi-actor dynamic integrated assessment model (MADIAM) of induced technological change and sustainable economic growth, Ecol. Econ., 54, 306–327, 2005.
Weitzman, M. L.: Prices vs. quantities, Rev. Econ. Stud., 41, 477–491, 1974.
Wigley, T. M. L.: A simple inverse carbon cycle model, Global Biogeochem. Cy., 5, 373–382, 1991.
Wilkerson, J. T., Leibowicz, B. D., Turner, D. D., and Weyant, J. P.: Comparison of integrated assessment models: carbon price impacts on U.S. energy, Energ. Policy, 76, 18–31, 2015.
Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S. J., Janetos, A., and Edmonds, J.: Implications of limiting CO_2 concentrations for land use and energy, Science, 324, 1183–1186, doi:10.1126/science.1168475, 2009.

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 1. List of variables and parameters and their values used.

Symbol	Meaning	Value	Units	Source
Independent variables				
K	Per capita physical capital		Trillions USD_{1990}	
H	Per capita human capital		Trillions USD_{1990}	
T	Average global surface temperatures		Kelvin (K)	
C	Atmospheric CO_2 concentration		Gt C	
E_Y	Industrial CO_2 emissions		Gt C yr^{-1}	
Initial (1990) values for independent variables				
k_0	Per capita physical capital-human capital ratio K_0/H_0	8.1	Ratio	Erk et al. (1998)
K_0		0.8344	USD_{1990} 10^4	Nordhaus and Boyer (2000)
H_0		0.1039	USD_{1990} 10^4	K_0/k_0
T_0		287.77	Kelvin (K)	
C_0		735	Gt C	Nordhaus and Boyer (2000)
E_{Y0}		6	Gt C yr^{-1}	Lenton (2000)
Parameters and other symbols				
Economy module				
n	Population growth rate		% yr^{-1}	Nordhaus (2013)
L	Human population		Millions	
L_0	1990 world population	5632.7	Millions	Nordhaus and Boyer (2000)
n_0	1990 population growth rate	1.57	% yr^{-1}	Nordhaus and Boyer (2000)
Λ_L	Population carrying capacity	11 360	Millions	Aral (2013)
A	Total factor productivity	2.9		Greiner and Semmler (2008)
c	Consumption share	80	% yr^{-1}	Greiner and Semmler (2008)
φ	External effect coefficient	0.1235		
δ_K	Depreciation rate of K	7.5	% yr^{-1}	Greiner and Semmler (2008)
δ_H	Depreciation rate of H	7.2	% yr^{-1}	
δ_n	Decline rate of n	2.22	% yr^{-1}	Nordhaus and Boyer (2000)
α	Capital share	0.35		Gollin (2002)
τ	Tax rate	20	% yr^{-1}	Greiner and Semmler (2008)
τ_b	Abatement share	0; 0.075; 0.11; 0.145	Ratio	
Damage function				
m_1		0.0067		Roughgarden and Schneider (1999)
χ		2.43		

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 1. Continued.

Symbol	Meaning	Value	Units	Source
Climate module (carbon cycle and surface temperature)				
β_2	Part of CO_2 emissions taken up by oceans and do not enter the atmosphere	0.49		IPCC (2001, p. 39)
μ_o	Rate of CO_2 absorption from the atmosphere into the ocean	0.0083		Nordhaus (1994a)
$\hat{C}$	Pre-industrial CO_2 concentration	596.4	Gt C	Wigley (1991)
e_c	Energy intensity		TRF/USD 10^3 of $\overline{Y}$	Akaev (2012)
c_c	Carbon intensity of energy		t C TRF^{-1}	Akaev (2012)
g_{ec}	Growth rate of e_c			
g_{cc}	Growth rate of c_c			
σ	Carbon intensity		t C/USD 10^3 of $\overline{Y}$ (Ratio)	Nordhaus and Boyer (2000)
g_σ	Rate of decline ofσ			
σ_0	1990 levelσ	0.274	t C/USD 10^3 of $\overline{Y}$ (Ratio)	Nordhaus and Boyer (2000)
ψ_0		0.042		Akaev (2012)
α_τ	Abatement efficiency	1.8		
r		0.05		Akaev (2012)
$c_{-\infty}$	c_c used before 1990	0.1671	t C TRF^{-1}	
a_c		0.169		Akaev (2012)
c_h	Earth specific heat capacity	16.7	W m^{-2} K^{-1}	Schwartz (2008)
α_T	Planetary/Surface albedo	0.3		McGuffie and Henderson-Sellers (2005)
ε	Emissivity	0.95		McGuffie and Henderson-Sellers (2005)
σ_T	Stefan–Boltzmann constant	5.67×10^{-8}	W m^{-2} K^{-4}	McGuffie and Henderson-Sellers (2005)
τ_a	Infrared transmissivity	0.6526		McGuffie and Henderson-Sellers (2005)
Q	Solar flux	1366	W m^{-2}	Gueymard (2004)
ξ	T rise absorbed by the oceans	0.23		Greiner and Semmler (2008)
β_1	Feedback effect	3.3		Greiner and Semmler (2008)
$\hat{T}$	Pre-industrial T	287.17	K	

Table 2. Target values of key variables for our policy scenarios at year 2100, with $\chi = 2.43$.

τ_b	Emissions E_Y ($GtC\,yr^{-1}$)	CO_2 $C/\hat{C}$	Deviation from pre-industrial $T-\hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\%\,yr^{-1}$)
0	29.3	3.1	5.2	26.9	1.1
0.075	11.8	2.1	3.4	11.6	2.1
0.11	5.9	1.7	2.6	6.6	2.2
0.145	2.5	1.5	2.0	3.5	2.0

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 3. Per capita abatement costs and damage costs at year 2100, with $\chi = 2.43$.

Abatement share τ_b	% emissions (E_Y) reduction from baseline	Per capita abatement costs (% Y)	Per capita damage costs (% Y)
0	0	0	26.9
0.075	60	1.5	11.6
0.11	80	2.2	6.6
0.145	92	2.9	3.5

ESDD
6, 819–863, 2015

Table 4. Comparison between global results of alternative policies.

Global industrial CO_2 emissions ($GtC\,yr^{-1}$) Policy Scenario	1995	2005	2010	2020	2030	2050	2100
CoCEB model: $\tau_b = 0$	7.1	10.8	13.2	19.3	27.0	43.4	29.3
CoCEB model: $\tau_b = 0.075$	6.8	9.2	10.6	13.8	17.0	21.6	11.8
CoCEB model: $\tau_b = 0.11$	6.7	8.6	9.6	11.7	13.5	14.7	5.9
RCP8.5 (Rao and Riahi, 2006; Riahi et al., 2007)	–	8	8.9	11.5	13.8	20.2	28.7
RCP6.0 (Fujino et al., 2006; Hijioka et al., 2008)	–	8	8.5	9	10	13	13.8
RCP4.5 (Smith and Wigley, 2006; Clerke et al., 2007; Wise et al., 2009)	–	8	8.6	9.9	11	11	4.2

Global atmospheric CO_2 concentration (GtC)	1995	2010	2020	2030	2050	2075	2100
CoCEB model: $\tau_b = 0$	743	793	852	939	1206	1612	1842
CoCEB model: $\tau_b = 0.075$	743	785	826	880	1014	1168	1231
CoCEB model: $\tau_b = 0.11$	743	781	816	858	948	1027	1037
RCP8.5 (Riahi et al., 2007)	–	829	886	956	1151	1529	1993
RCP6.0 (Fujino et al., 2006; Hijioka et al., 2008)	–	829	872	914	1017	1218	1427
RCP4.5 (Clerke et al., 2007; Wise et al., 2009)	–	829	875	927	1036	1124	1147

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 5. Policy scenario values at year 2100 with $\alpha_\tau = 1.8$, varying m_1, and χ.

		τ_b	Emissions E_Y ($GtC\,yr^{-1}$)	CO_2, $C/\hat{C}$	Deviation from pre-industrial, $T-\hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\%\,yr^{-1}$)
$m_1 = 0.0034$ (−50 %)	$\chi = 2.34$	0	50.8	3.7	5.9	20.3	1.8
		0.075	16.0	2.2	3.7	7.3	2.5
		0.11	7.3	1.8	2.8	3.8	2.4
		0.145	2.8	1.5	2.1	1.9	2.1
$m_1 = 0.01$ (+50 %)		0	20.4	2.8	4.7	30.3	0.7
		0.0175	9.3	2.0	3.2	14.4	1.8
		0.11	5.0	1.7	2.5	8.6	2
		0.145	2.2	1.5	1.9	4.8	1.9
$\chi = 1.215$ (−50 %)	$m_1 = 0.0067$	0	99.6	4.5	6.7	6.3	3.6
		0.075	19.1	2.3	3.8	3.3	3.0
		0.11	7.8	1.8	2.8	2.3	2.6
		0.145	2.9	1.5	2.1	1.6	2.2
$\chi = 3.645$ (+50 %)		0	6.0	2.1	3.6	41.6	−0.2
		0.075	4.9	1.8	2.8	22.9	1.0
		0.11	3.5	1.6	2.4	13.5	1.6
		0.145	1.9	1.5	1.9	6.6	1.8

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

Table 6. Effect of varying α_τ by year 2100; all other parameter values as in Table 1.

	Abatement share τ_b	% reduction of emissions (E_Y) from baseline	Per capita abatement costs (% Y)	Per capita damage costs (% Y)	GDP growth g_Y (% yr^{-1})
Abatement efficiency = 0.9 (−50 %)	0	0	0	26.9	1.1
	0.075	48	1.5	13.6	1.8
	0.11	67	2.2	8.8	1.9
	0.145	81	2.9	5.5	1.8
Abatement efficiency = 2.7 (+50 %)	0	0	0	26.9	1.1
	0.075	71	1.5	9.4	2.3
	0.11	90	2.2	4.4	2.4
	0.145	98	2.9	1.9	2.1

ESDD
6, 819–863, 2015

Coupled Climate–Economy–Biosphere (CoCEB) model – Part 1

K. B. Z. Ogutu et al.

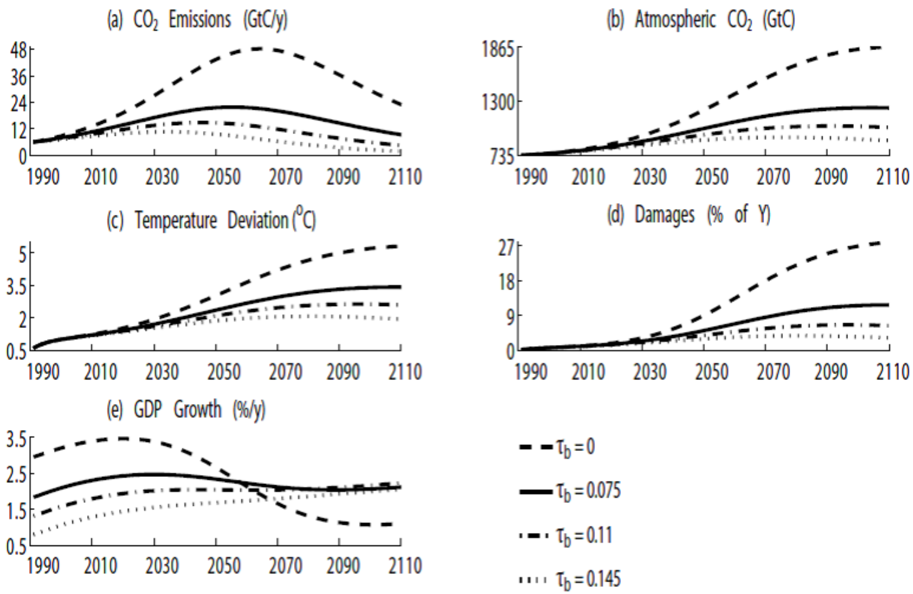

Figure 1. Evolution of several CoCEB model variables in time, for abatement shares τ_b that range from 0.0 (no abatement) to 0.145; see legend for curves, with $\tau_b = 0$ – dashed, $\tau_b = 0.075$ – solid, $\tau_b = 0.11$ – dash-dotted, and $\tau_b = 0.145$ – dotted.

ESDD
6, 819–863, 2015

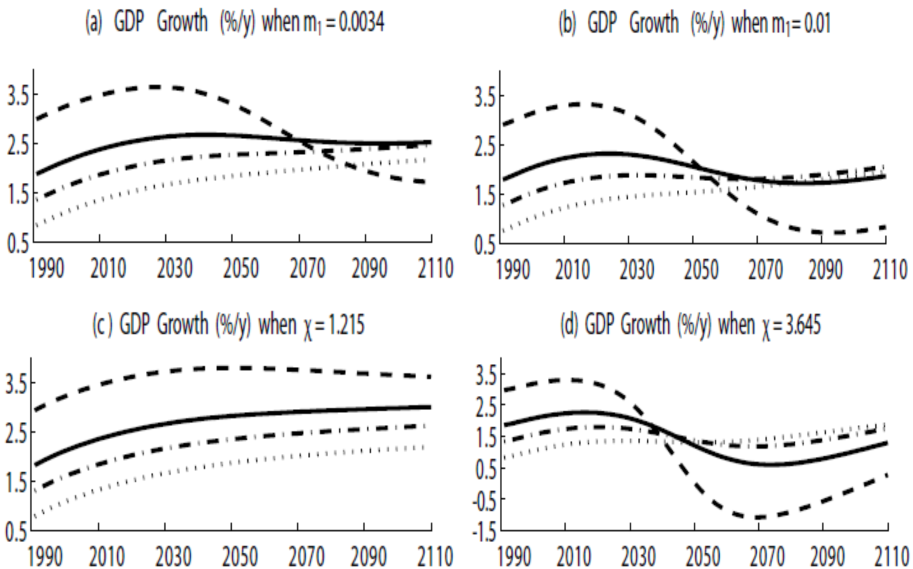

Figure 2. GDP growth over time as a function of abatement share values τ_b between 0.0 and 0.145; see legend for curve identification, while $\alpha_\tau = 1.8$. **(a, b)** m_1 is larger or smaller by 50 % than the value in Tables 1–4; **(c, d)** same for the nonlinearity parameter χ.

ESDD
6, 819–863, 2015