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

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

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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 relies on recent versions of the Dynamic Integrated model of Climate and the Economy (DICE) model but innovates by taking into account the mutual feedback effects between climate and economic growth. CoCEB is composed of a physical climate module, 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. More broadly, the simplicity, transparency and flexibility of the model provides the corner stone for a whole new area in integrated assessment modeling, an area that engages in the evaluation of non-equilibrium climate–economy and climate–economy–biosphere models. Such non-equilibrium coupled models, along with the analysis methodology introduced in this paper, will provide novel tools for studying intrinsic and endogenous variability in one or more of their constituent modules.

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., 2015). 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 global 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.

Global climate–economy 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 simplicity, transparency and flexibility of the dynamical interactions between the different variables.

Forceful arguments have been made in favor of the need for a fuller understanding of intrinsic climate variability (Ghil, 2001, 2015) and of endogenous macroeconomic variability (Hallegatte and Ghil, 2008; Hallegatte et al., 2008; Groth et al., 2015) in the context of global change studies. Simplicity, transparency and flexibility are key ingredients in opening the door to the evaluation of non-equilibrium climate–economy and climate–economy–biosphere models. Such models, along with the analysis methodology introduced in this paper, will provide novel tools for studying intrinsic and endogenous variability in one or more constituent modules of future non-equilibrium IAMs.

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) putting in evidence the feedbacks between economy and climate via the interactive emissions; 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 well as allowing for parameter stability analysis.

Our study also points 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 21st 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); α_{T} is the mean planetary albedo, Q the average solar constant, ε the emissivity that gives the ratio of actual emission to blackbody emission, σ_{T} the Stefan-Boltzmann constant, τ_{a} is the infrared (long-wave) transmissivity of the atmosphere.

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 $\mu_{\mathrm{o}} = 1/120 = 0.0083$, 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),

$$Y = \mathrm{A}K^{\alpha}H^{1-\alpha}D\left(T - \hat{T}\right). \tag{3}$$

Here $A > 0$ is the total factor of productivity, K is the per capita physical capital, H is the per capita human capital, $0 < \alpha < 1$ 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

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

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,

$$G_{\mathrm{E}} = \tau_{\mathrm{b}} X = \tau_{\mathrm{b}}\tau Y, \tag{5}$$

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,

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

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

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

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

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

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

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

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

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

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

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 both of the right-hand-sides of equations (9) and (10) are given by gross investment minus replacement investments — these negative terms on the right-hand-sides of the two equations are also called break-even investments. The latter consists of replacement of worn out capital, furnishing of newborns with capital, and an adjustment due to the continuous upgrading of productivity; see also Eriksson (2013, p. 38). Note, furthermore, that the growth model presented in this study is not an optimizing model in the generalized-equilibrium sense and we take, as a starting point, the Solow–Swan approach (Solow, 1956; Swan, 1956; Greiner and Semmler, 2008), in which the shares of consumption and savings are given. We do this because we want to focus on effects resulting from climate change, which affect production as modeled in Eqs. (3)–(10) and, therefore, neglect effects that result from different preferences. The consequences of this assumption may be addressed by models with overlapping generations of individuals, each of which lives a finite number of years (e.g., McCandless, 2008, and references therein). Including such savings decisions, however, is beyond the scope of this study and is left as a worthwhile line of future work; see also Fankhauser and Tol (2005) and Kalkuhl and Edenhofer (2016), who discuss the role of an endogenous savings rate for assessing climate damages. Our model's macroeconomic production function only considers per capita 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 paper's main focus is on how the fraction $\tau_{\mathrm{b}}X = \tau_{\mathrm{b}}\tau Y$ of the tax revenue is used for abatement activities, and not on how the government uses its total tax revenue $X = \tau Y$ to generally macro-manage the economy; see, for instance, Blanchard and Perotti (2002). In fact, our formulation assumes, furthermore, that government spending, except for abatement, is held constant throughout this work, so that only changes in abatement affect the size of per capita GDP (see also Greiner and Semmler, 2008, p. 64). On the one hand, an increase in abatement activities, leads to a higher value of the abatement share $\tau_{\mathrm{b}} > 0$, and it makes the difference $1-\left[\tau\left(1+\tau_{\mathrm{b}}\right)+c\left(1-\tau\right)\right]$ 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.

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:

$$
\begin{aligned}
E_{\mathrm{Y}} &= \left(\frac{E_{\mathrm{tot}}}{\mathrm{energy}}\right)\left(\frac{\mathrm{energy}}{\bar{Y}}\right)\left(\frac{\bar{Y}}{L}\right)L\left(\frac{E_{\mathrm{Y}}}{E_{\mathrm{tot}}}\right) \\
&= c_{\mathrm{c}}e_{\mathrm{c}}YL\kappa_{\mathrm{ccs}} \\
&= \sigma YL\kappa_{\mathrm{ccs}}.
\end{aligned}
\tag{11}
$$

Here $\bar{Y}$ is aggregate GDP, $Y=\left(\bar{Y}/L\right)$ is per capita GDP, L is the human population, $c_{\mathrm{c}}=E_{\mathrm{tot}}/\mathrm{energy}$ is the carbon intensity of energy, $e_{\mathrm{c}}=\mathrm{energy}/\bar{Y}$ is the energy intensity, $c_{\mathrm{c}}e_{\mathrm{c}}=E_{\mathrm{tot}}/\bar{Y}=\sigma$ is the ratio of industrial carbon emissions to aggregate GDP or the economy carbon intensity, $E_{\mathrm{Y}}/E_{\mathrm{tot}}=\kappa_{\mathrm{ccs}}$ 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 $\tau_{\mathrm{b}}=0$ 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

$$
\frac{\mathrm{d}E_{\mathrm{Y}}}{\mathrm{d}t}=\left[g_{\sigma}+g_{\mathrm{Y}}+n+g_{\mathrm{ccs}}\right]E_{\mathrm{Y}}, \tag{12}
$$

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 $E_{\mathrm{Y}}<E_{\mathrm{tot}}$. 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 by following the approach of Sahal (1985), who models the replacement of one technology by another using a logistic law. We believe that this approach is more reasonable than the one used in DICE, which uses an exponential law. Our approach is consistent with the point made by Costanza et al. (2007), who argue that the economic growth in DICE is not limited by the availability or non-availability of different energy sources. 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

$$\frac{1}{Y}\frac{\mathrm{d}Y}{\mathrm{d}t} = \frac{\alpha}{K}\frac{\mathrm{d}K}{\mathrm{d}t} + \frac{(1-\alpha)}{H}\frac{\mathrm{d}H}{\mathrm{d}t} + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t},$$

or,

$$g_{\mathrm{Y}} = \alpha g_{\mathrm{K}} + (1-\alpha)g_{\mathrm{H}} + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t}, \tag{18}$$

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

$$\frac{\mathrm{d}L}{\mathrm{d}t} = nL\left\{1 - \exp\left[-\left(L/L(1990)\right)\right]\right\}, \tag{19}$$

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

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

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 $D\left(T - \hat{T}\right)$ 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 calibrating χ. Our approach is motivated by Burke et al.'s (2015, Fig. 5a and Extended Data Table 3) study, in which unmitigated warming is expected to reshape the global economy by reducing average global per capita incomes roughly 26 %, or even more, by 2100. In fact, our projected climate change damages before and after abatement, 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). Moreover, recent studies argue that the DICE framework supports strong controls on emissions if its restrictive assumptions about growth, damage and climate risk are relaxed. These assumptions arguably lead to gross underestimation of the overall scale of the risks from unmanaged climate change in DICE and other IAMs (Stern, 2013); see also the further discussion in Sect. 5.2 below. This paper basically considers a so-called *AK* model (Aghion and Howitt, 1999, Ch. 1), with *K* being "broad capital": privately held machines, human capital, public infrastructure, and possibly energy use. It is an endogenous growth model, in which the damage from climate change affects the long-run growth, not just current output; see also Barro and Salai-Martin (2004, Ch. 4), and Dietz and Stern (2015). In fact, the study relaxes the assumption that the underlying drivers of economic growth — notably human capital — are exogenous or implicit and unaffected by climate change; see also Greiner and Semmler (2008). Actually, as will be demonstrated in Sect. 4.1 below and in Ogutu et al. (2017), the efficiency of abatement measures in reducing climate-related damage is highly sensitive to the values of the damage function parameters and of the energy share in the economy, respectively.

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). In fact, there are several IAMs that aim to better represent mitigation options and the benefits of increased energy efficiency or the use of backstop technologies. Examples include Popp (2004; 2006), Edenhofer et al. (2005), Kverndokk and Rosendahl (2007), Grimaud et al. (2011), and Kalkuhl et al. (2012; 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 $\psi = \psi_0 \left[1/\left(1-\alpha_\tau \tau_\mathrm{b}\right) \right]$; 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

$$\frac{G_\mathrm{E}}{Y} = \tau_\mathrm{b}\tau = 0.01 \Rightarrow \tau_\mathrm{b} = 0.05 . \tag{21}$$

Similarly, the abatement share giving an abatement cost equivalent to 2 % of GDP by 2050 is $\tau_\mathrm{b} = 0.1$. We take, as our lower abatement share, the average $\tau_\mathrm{b} = 0.075$ 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 a reduction of 50 % in carbon emissions from BAU — for the scenario corresponding to $\tau_\mathrm{b} = 0.075$ — costs 1.5 % of GDP by 2050. This abatement cost is in the range used by recent IAMs in the literature; see, for instance, Tol (2010) and Den Bergh (2015). Our scenario corresponding to $\tau_\mathrm{b} = 0.075$ also happens to mimic the RCP6.0 by 2100 (Hijioka et al., 2008). For the other non-BAU scenarios, we choose abatement shares of $\tau_\mathrm{b} = 0.11$ 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 $\tau_\mathrm{b} = 0.11$ 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:

$$\frac{\mathrm{d}K}{\mathrm{d}t} = \mathrm{A}\left[1-\tau(1+\tau_{\mathrm{b}})-c(1-\tau)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)-\left(\delta_{\mathrm{K}}+n\right)K \,, \tag{22a}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \varphi\left\{\mathrm{A}\left[1-\tau(1+\tau_{\mathrm{b}})-c(1-\tau)\right]K^{\alpha}H^{1-\alpha}D\left(T-\hat{T}\right)\right\}-\left(\delta_{\mathrm{H}}+n\right)H \,, \tag{22b}$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{(1-\alpha_{\mathrm{T}})\mathrm{Q}}{4c_{\mathrm{h}}} - \frac{\varepsilon\tau_{\mathrm{a}}\sigma_{\mathrm{T}}}{c_{\mathrm{h}}}T^4 + \frac{(6.3)\beta_1(1-\xi)}{c_{\mathrm{h}}}\mathrm{In}\left(\frac{C}{\hat{C}}\right), \tag{22c}$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2 E_{\mathrm{Y}} - \mu_{\mathrm{o}}\left(C-\hat{C}\right), \tag{22d}$$

$$\frac{\mathrm{d}E_{\mathrm{Y}}}{\mathrm{d}t} = \left[g_{\sigma}+g_{\mathrm{Y}}+n\right]E_{\mathrm{Y}} \,. \tag{22e}$$

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., $\tau_{\mathrm{b}} = 0$; 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.

Since the CoCEB model is not designed for a cost–benefit analysis, it cannot help compare costs and benefits that may occur at different points in time. Doing so would require specifying a social discount rate, as in DICE (Nordhaus, 2007) and PAGE2002 (Stern, 2007). While this is certainly a worthwhile line of future research, it is fraught with considerable danger: the serious divergence between the values assigned to this rate in the work of W. Nordhaus (Nordhaus, 2007) and of N. Stern (Stern, 2007) has led to an acrimonious debate in the IAM literature (Ackerman et al., 2009a). Instead, CoCEB does show that the crossover time after which abatement activities start paying off in terms of growth occurs around year 2060. The exact timing of this crossover 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., 2009b), 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).

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, 2015, 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., 2015).

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.

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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 with $\chi = 2.43$ and the RCP scenarios, at year 2100**

Policy Scenario	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})
$\tau_b = 0$	29.3	3.1	5.2	26.9	1.1
$\tau_b = 0.075$	11.8	2.1	3.4	11.6	2.1
$\tau_b = 0.11$	5.9	1.7	2.6	6.6	2.2
$\tau_b = 0.145$	2.5	1.5	2.0	3.5	2.0
RCP8.5	28.7	3.3	3.7	–	–
RCP6.0	13.8	2.4	2.2	–	–
RCP4.5	4.2	1.9	1.8	–	–
RCP2.6	−0.21	0.7	1.0	–	–

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
CoCEB model: $\tau_b = 0.145$	6.5	7.9	8.6	9.8	10.6	9.6	2.5
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
RCP2.6 (Van Vuuren et al., 2012)	–	7.5	8.5	9.5	7.4	3.0	−0.21
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
CoCEB model: $\tau_b = 0.145$	742	777	806	838	894	923	904
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
RCP2.6 (Van Vuuren and Carter, 2014)	–	389	412	431	443	435	421

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

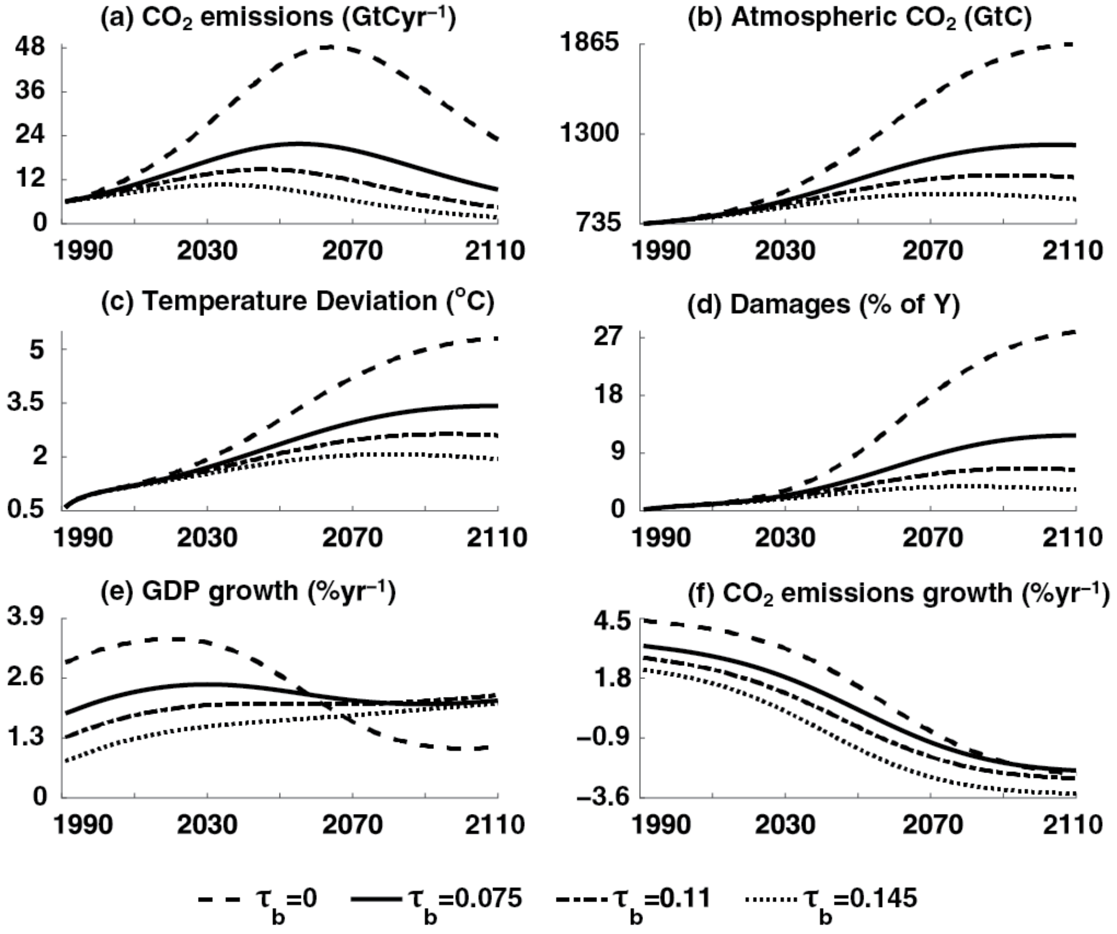

Figure 1. Evolution of several CoCEB model variables in time, for abatement shares τ_b that range from 0.0 (no abatement) to 0.145; see legend for curves, with $\tau_b = 0$ — dashed, $\tau_b = 0.075$ — solid, $\tau_b = 0.11$ — dash-dotted, and $\tau_b = 0.145$— dotted.

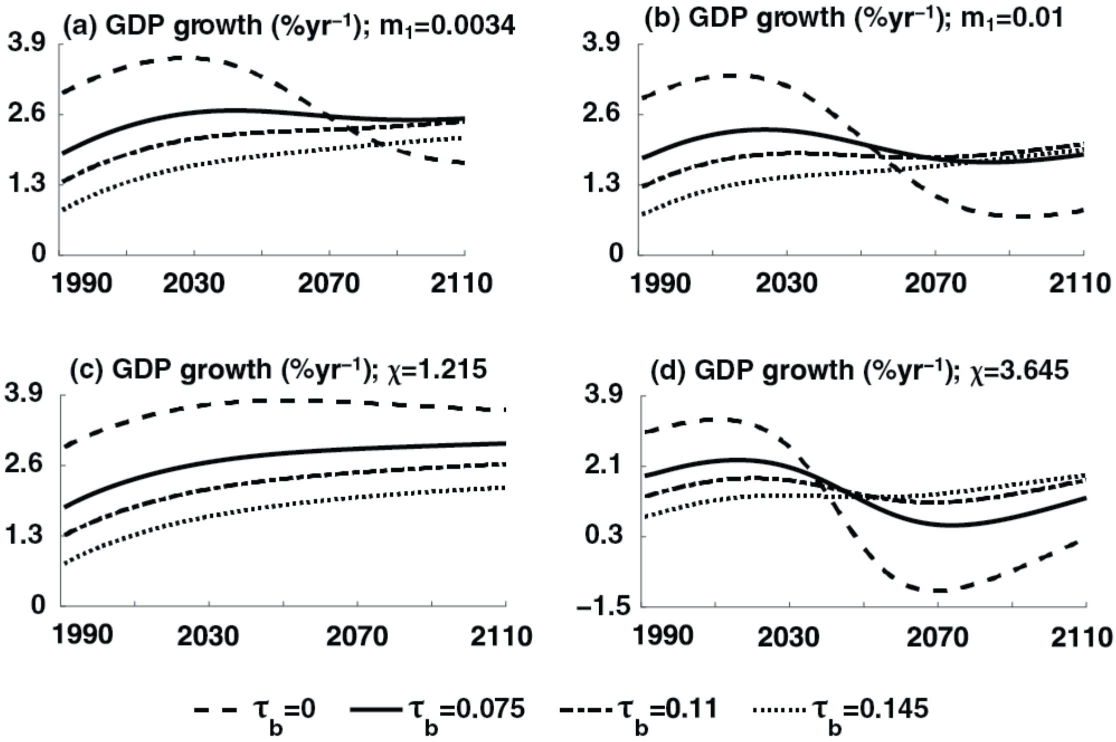

Figure 2. Per capita GDP growth over time as a function of abatement share values τ_b between 0.0 and 0.145; see legend for curve identification, while $\alpha_\tau = 1.8$. Panels (a, b) the coefficient m_1 is larger or smaller by 50 % than the value in Tables 1–4; (c, d) same for the exponent χ.