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

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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 atmosphere 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 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 natural 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.

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 Gt = 10^{15} g) and $\hat{C}$ is the pre-industrial CO_2 concentration. All the feedbacks, 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 $\mathrm{d}T/\mathrm{d}t = 0$, Eq. (1) gives an average SAT of 14 °C for the pre-industrial GHG concentration, i.e. for $C = \hat{C}$. Doubling the $\mathrm{CO_2}$ 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 $\mathrm{CO_2}$ in the atmosphere, following Uzawa (2003) and Greiner and Semmler (2008), as

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \beta_2 E_Y - \mu_\mathrm{o}(C - \hat{C}), \tag{2}$$

where E_Y is industrial $\mathrm{CO_2}$ 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 $\mathrm{CO_2}$ 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 $\mu_\mathrm{o} = 1/120 = 0.0083$, 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),

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

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

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

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

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

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

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

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

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

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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

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

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 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

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

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 $\mathrm{CO_2}$ 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 $\tau_\mathrm{b} = 0$ 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

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

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 $E_Y < E_{\text{tot}}$. 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 $E_Y = E_{\text{tot}}$ or $\kappa_{\text{ccs}} = 1$.

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 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:

$$g_\sigma = \frac{f_\mathrm{c}}{e_\mathrm{c}}\left[\frac{[\psi r\exp(\psi t)][1+r(\exp(\psi t)-1)]-[\psi r^2\exp(\psi t)]}{[1+r(\exp(\psi t)-1)]^2}\right] + \frac{1}{c_\mathrm{c}}\left[\frac{a_\mathrm{c}\psi r\exp(-\psi t)}{[1+r\exp(-\psi t)]^2}\right]. \tag{16}$$

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

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

or,

$$g_Y = \alpha g_K + (1-\alpha)g_H + \frac{1}{D}\frac{\mathrm{d}D}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}t}, \tag{17}$$

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

$$\frac{\mathrm{d}L}{\mathrm{d}t} = nL\{1-\exp[-(L/L(1990))]\}, \tag{18}$$

where n is the population growth rate as given in Eq. (8). Equation (18) 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).

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

$$D(T-\hat{T}) = \left[1 + m_1(T-\hat{T})^{\chi}\right]^{-1}, \tag{19}$$

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 $CO_2\,\mathrm{yr}^{-1}$ 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).

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

$$\frac{G_\mathrm{E}}{Y} = \tau_\mathrm{b}\tau = 0.01 \Rightarrow \tau_\mathrm{b} = 0.05. \tag{20}$$

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 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 $\tau_\mathrm{b} = 0.075$, carbon emissions reduction from baseline is about 50 % by 2050. Our scenario corresponding to $\tau_\mathrm{b} = 0.075$ 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 $\tau_\mathrm{b} = 0.11$ 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 $\tau_\mathrm{b} = 0.11$ 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.

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 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

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 $\%\,\mathrm{yr}^{-1}$, and 1.8 $\%\,\mathrm{yr}^{-1}$, 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 $\%\,\mathrm{yr}^{-1}$ 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).

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.

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 $\mathrm{Gt\,C\,yr^{-1}}$. 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 $\mathrm{Gt\,C\,yr^{-1}}$.

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 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.

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 according 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 individuals 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).

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).

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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		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	$\text{USD}_{1990}\ 10^4$	Nordhaus and Boyer (2000)
H_0		0.1039	$\text{USD}_{1990}\ 10^4$	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		$\%\ \text{yr}^{-1}$	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	$\%\ \text{yr}^{-1}$	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	$\%\ \text{yr}^{-1}$	Greiner and Semmler (2008)
φ	External effect coefficient	0.1235		
δ_K	Depreciation rate of K	7.5	$\%\ \text{yr}^{-1}$	Greiner and Semmler (2008)
δ_H	Depreciation rate of H	7.2	$\%\ \text{yr}^{-1}$	
δ_n	Decline rate of n	2.22	$\%\ \text{yr}^{-1}$	Nordhaus and Boyer (2000)
α	Capital share	0.35		Gollin (2002)
τ	Tax rate	20	$\%\ \text{yr}^{-1}$	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		

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	

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

τ_b	Emissions E_Y ($\mathrm{Gt\,C\,yr^{-1}}$)	CO_2 $C/\hat{C}$	Deviation from pre-industrial $T-\hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\mathrm{\%\,yr^{-1}}$)
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 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

Table 4. Comparison between global results of alternative policies.

Global industrial CO_2 emissions ($\mathrm{Gt\,C\,yr^{-1}}$) Policy Scenario	1995	2005	2010	2020	2030	2050	2100
CoCEB model: $\tau_{\mathrm{b}} = 0$	7.1	10.8	13.2	19.3	27.0	43.4	29.3
CoCEB model: $\tau_{\mathrm{b}} = 0.075$	6.8	9.2	10.6	13.8	17.0	21.6	11.8
CoCEB model: $\tau_{\mathrm{b}} = 0.11$	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 ($\mathrm{Gt\,C}$)	1995	2010	2020	2030	2050	2075	2100
CoCEB model: $\tau_{\mathrm{b}} = 0$	743	793	852	939	1206	1612	1842
CoCEB model: $\tau_{\mathrm{b}} = 0.075$	743	785	826	880	1014	1168	1231
CoCEB model: $\tau_{\mathrm{b}} = 0.11$	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

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

		τ_b	Emissions E_Y ($\mathrm{Gt\,C\,yr^{-1}}$)	$\mathrm{CO_2}$, $C/\hat{C}$	Deviation from pre-industrial, $T-\hat{T}$ (°C)	Damages (% GDP)	GDP growth g_Y ($\mathrm{\%\,yr^{-1}}$)
$m_1 = 0.0034$ (−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

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

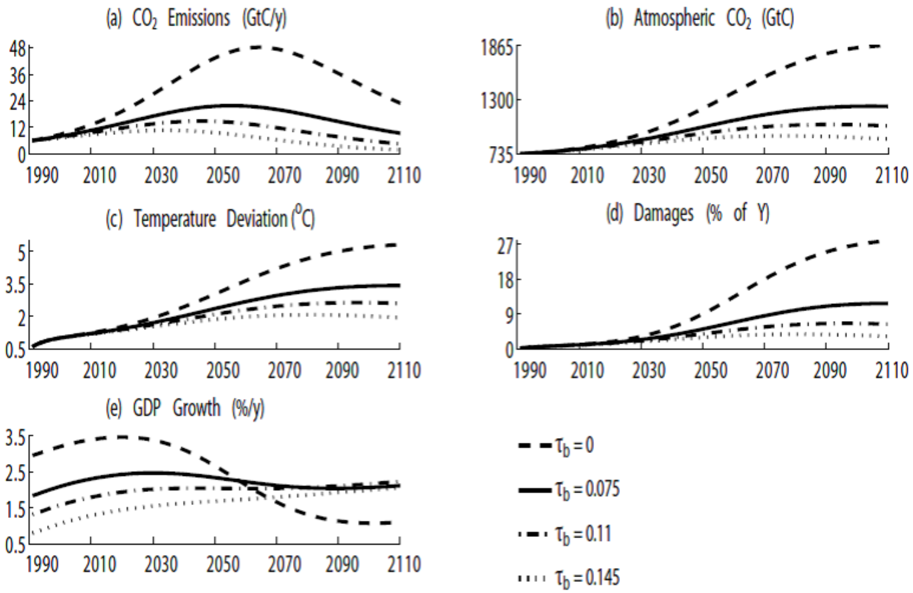

Figure 1. Evolution of several CoCEB model variables in time, for abatement shares τ_b that range from 0.0 (no abatement) to 0.145; see legend for curves, with $\tau_b = 0$ – dashed, $\tau_b = 0.075$ – solid, $\tau_b = 0.11$ – dash-dotted, and $\tau_b = 0.145$ – dotted.

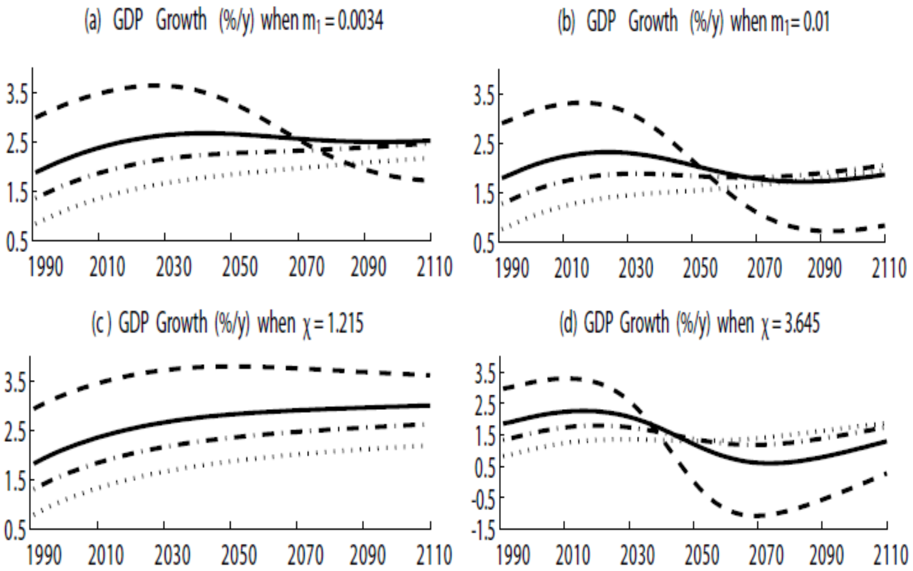

Figure 2. GDP growth over time as a function of abatement share values τ_b between 0.0 and 0.145; see legend for curve identification, while $\alpha_\tau = 1.8$. **(a, b)** m_1 is larger or smaller by 50 % than the value in Tables 1–4; **(c, d)** same for the nonlinearity parameter χ.