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Emission pathways to achieve 2.0°C and 1.5°C climate targets

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Key Points:
- A dynamic optimization model with a full suite of GHGs, pollutants, and aerosols was developed based on DICE-2013R and MAGICC 6.0.
- Addressing individual emissions in an analysis of low stabilization scenarios is important.
- 2.0°C can be efficiently achieved under SSP2; 1.5°C is achieved using an overshoot, tripled carbon price, and doubled mitigation cost.

Supporting Information:
- Supporting Information S1
- Data Set S1

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Abstract We investigated the feasibilities of 2.0°C and 1.5°C climate targets by considering the abatement potentials of a full suite of greenhouse gases, pollutants, and aerosols. We revised the inter-temporal dynamic optimization model DICE-2013R by introducing three features as follows. First, we applied a new marginal abatement cost curve derived under moderate assumptions regarding future socioeconomic development—the Shared Socioeconomic Pathways 2 (SSP2) scenario. Second, we addressed emission abatement for not only industrial CO_2 but also land-use CO_2, CH_4, N_2O, halogenated gases, CO, volatile organic compounds, SO_x, NO_x, black carbon and organic carbon. Third, we improved the treatment of the non-CO_2 components in the climate module based on MAGICC 6.0. We obtained the following findings: (1) It is important to address the individual emissions in an analysis of low stabilization scenarios because abating land-use CO_2, non-CO_2 and aerosol emissions also contributes to maintaining a low level of radiative forcing and substantially affects the climate costs. (2) The 2.0°C target can be efficiently reached under the assumptions of the SSP2 scenario. (3) The 1.5°C target can be met with early deep cuts under the assumption of a temperature overshoot, and it will triple the carbon price and double the mitigation cost compared with the 2.0°C case.

1. Introduction

Industrial CO_2 emissions, which result from fossil fuel combustion and industrial processes, are treated as the only dynamic control variable for climate mitigation in DICE-2013R because CO_2 is the predominant contributor to the warming of the Earth [*Nordhaus*, 2013, 2014; *Nordhaus and Sztorc*, 2013]. Other anthropogenic emissions, e.g., land-use CO_2, methane (CH_4), nitrous oxide (N_2O), halogenated gases, carbon monoxide (CO), nitrogen oxide (NO_x), volatile organic compounds (VOC), sulfate (SO_x), black carbon (BC), and organic carbon (OC), are assumed to follow fixed paths. Cutting non-CO_2 greenhouse gas (GHG) emissions, however, could also significantly affect the climate conditions and lead to substantial changes in mitigation costs [*van Vuuren et al.*, 2006a, 2006b; *Montzka et al.*, 2011; *Gernaat et al.*, 2015]. In addition, it could be feasible to achieve a rapid decrease in radiative forcing (RF) by suppressing the emission of short-lived climate pollutants (SLCPs) [*Bowerman et al.*, 2013; *Shoemaker et al.*, 2013; *Rogelj et al.*, 2014a, 2015a]. Climate change is also influenced by land-use management [*Pielke*, 2005; *Wise et al.*, 2009; *Montzka et al.*, 2011; *Gernaat et al.*, 2015; *Ciais et al.*, 2013a], although with larger uncertainties. To limit the global mean temperature (GMT) increase to below 2.0°C or even 1.5°C, as suggested by the Paris Agreement, abatement efforts that reach beyond industrial CO_2 are also important for climate policy [*Meinshausen et al.*, 2009; *Rogelj et al.*, 2011, 2013, 2015b; *Gernaat et al.*, 2015]. However, such abatements contributed by land-use CO_2, non-CO_2, or aerosols cannot be appropriately exploited by DICE-2013R, since DICE-2013R has relatively less representation of energy, land-use, and other gas emissions. In addition, advances in climate change research, such as new scenarios known as the Shared Socioeconomic Pathways (SSPs) [*Moss et al.*, 2010; *O'Neill et al.*, 2014; *Calvin et al.*, 2017; *Fricko et al.*, 2017; *Fujimori et al.*, 2017], can provide consistent and detailed information with regard to future socioeconomic development, the abatement potentials for individual anthropogenic emissions and the corresponding costs of coping with climate change. This sets the stage for a more comprehensive assessment of the Earth's climate system and socioeconomic development.

As noted above, a major motivation for this study is to introduce into DICE-2013R with richer information regarding energy, land-use, and other gas emissions, which can be provided by more complex integrated assessment models (IAMs) (e.g., Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) [*Fujimori et al.*, 2014a, 2014b, 2017]). Therefore, the objectives of this study are twofold: (1) to revise the DICE-2013R model for the evaluation of low stabilization scenarios by incorporating individual anthropogenic emissions and (2) to demonstrate how this revision is important, particularly for achieving stringent controls, such as the 2.0°C and 1.5°C targets.

2. Methodology

The DICE model is a widely used IAM for finding optimal climate change pathways by weighing the costs and benefits [*Nordhaus*, 2013, 2014; *Nordhaus and Sztorc*, 2013]. Compared to other complicated IAMs such as participating in SSP quantifications (e.g., AIM/CGE [*Fujimori et al.*, 2017] and MESSAGE [*Fricko et al.*, 2017]), the DICE model is simpler and has an advantage that it can easily run numerous scenarios. Based on the DICE framework, we modified DICE-2013R to capture the abatement potentials of a full suite of climate forcers. We first revised the economic module in DICE-2013R to represent a middle-of-the-road scenario — SSP2 [*Fujimori et al.*, 2017; *Fricko et al.*, 2017]. Under the SSP2 assumptions, we utilized the outcomes of the AIM/CGE model [*Fujimori et al.*, 2014a, 2014b, 2017], which contains more detailed information on future projections of socioeconomic development, energy, land-use, and emissions. Then, we expanded the simple climate module in DICE-2013R to represent a full suite of RF agents based on MAGICC 6.0 [*Meinshausen et al.*, 2011a].

In addition, two adjustments were made: (1) The SSP2 reference scenario was extended to the year 2300, with the population stabilizing at 8000.0 million, the Gross Domestic Product (GDP) reaching 2258.7 trillion USD (2005) (purchasing power parity) based on the growth rate circa 2,100, and the anthropogenic emissions roughly maintained at the 2,100 levels (see Table S1 in Appendix S2, Supporting Information). (2) The time step was reduced from 5 to 1 year [*Cai et al.*, 2012] to adequately describe the behaviors of RF agents spanning a wide range of time scales. The modeling period was set to range from 1765 to 2300, with the variables tuned to fit the historical period, i.e., 1765–2004.

2.1. Economic Module

The economic module was revised to represent the outputs of the AIM/CGE model. The population and GDP were adjusted to agree with the SSP2 assumptions [*Dellink et al.*, 2015; *Samir and Lutz*, 2014], with aligned capital stock, consumption, and investment. In addition, we considered the abatement of each climate forcer separately.

The socioeconomic development was parametrized based on a set of sensitivity data generated by the AIM/CGE model [*Fujimori et al.*, 2017]. Eleven artificially defined carbon price paths (Figure S1 in Appendix S2) were used to produce the various economic indicators and corresponding emissions. A new marginal abatement cost (MAC) curve was estimated based on the sensitivity data, as shown in Figure 1. Here, the carbon price is defined as

$$p_c(t) = \theta_1 \mu(t)^{\theta_2} + \theta_1' \mu(t)^{\theta_2'} \quad (1)$$

where $p_c(t)$ is the carbon price in year t, $\mu(t)$ denotes the rate of control of industrial CO_2, and θ_1, θ_2, θ_1' and θ_2' are estimated parameters. $\mu(t)$ is constrained to be nondecreasing, i.e., $\mu(t+1) \geq \mu(t)$, under the assumption that a "lock-in" effect exists in climate change mitigation. The abatement cost as a fraction of the output is therefore given by

$$\Lambda_{abate}(t) = v(t)\,\sigma(t)\left(\frac{\theta_1 \mu(t)^{\theta_2+1}}{\theta_2+1} + \frac{\theta_1' \mu(t)^{\theta_2'+1}}{\theta_2'+1}\right) \quad (2)$$

where $\wedge_{abate}(t)$ is the ratio of the abatement cost to the output, $v(t)$ denotes the carbon price adjustment factor due to technological improvements, and $\sigma(t)$ is the carbon intensity in units of tC per thousand USD (2005).

We used a relatively high carbon price here to reflect the cost of mitigation; this carbon price is higher than that used in DICE-2013R [*Nordhaus*, 2013, 2014; *Nordhaus and Sztorc*, 2013]. This cost was derived directly from the AIM/CGE model, which drives mitigation actions for coping with climate change. We can regard it as a comprehensive cost covering the potential expenses arising from other abatement efforts, which may reach extremely high values when the available reduction potentials are exhausted.

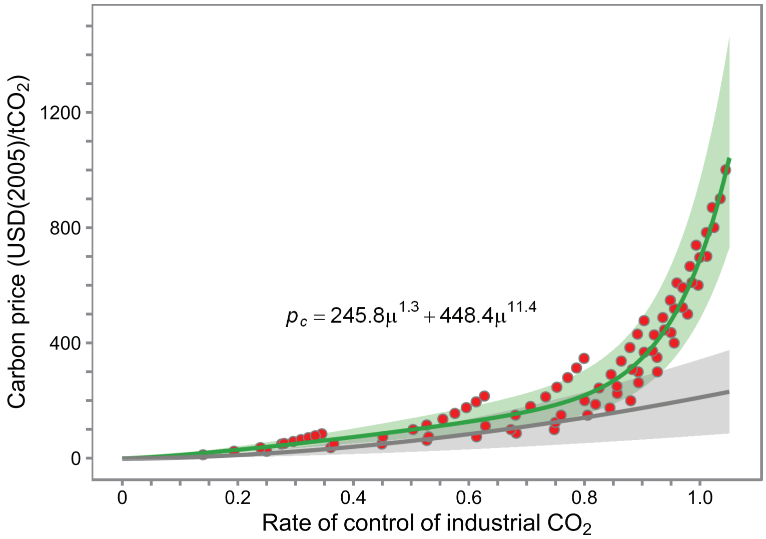

Figure 1. Marginal abatement cost (MAC) curve for the Shared Socioeconomic Pathways 2 scenario. The red points represent sensitivity data relating the rate of control of industrial CO_2 to the carbon price. The green line (equation) and band represent the MAC curve considered in this study, and the gray line and band represent the MAC curve of DICE-2013R. The upper bound is the MAC in 2005, and the lower bound is the MAC in 2300. A two-term power function is introduced to define the relationship between the rate of control of industrial CO_2 emissions and the carbon price. The rate of control is the fraction of CO_2 removed from the total industrial CO_2 emissions, and the carbon price is derived from the AIM/CGE sensitivity data. The curve describes economic behavior such that when the rate of control is relatively low (e.g., $\mu \leq 0.8$), the carbon price behaves as it does in DICE-2013R, whereas when higher control is needed (e.g., $\mu > 0.8$), the carbon price increases rapidly to account for the difficulty in making further cuts. The μ here is allowed to exceed one for considering negative CO_2 emissions.

For CO_2, CH_4, N_2O and fluorinated gases (F-gases), we assumed that the rates of control for these emissions were determined by the carbon prices,

$$\mu_i = a_i p_c^{b_i} \tag{3}$$

where μ_i represents the rate of control of emission *i* and a_i and b_i are parameters that are estimated based on the sensitivity data. Furthermore, the reduction mechanisms of land-use originated CO_2, CH_4, and N_2O are distinguished from those of industrial emissions [*van Vuuren et al.*, 2006a, 2006b; *Wise et al.*, 2009; *Montzka et al.*, 2011; *Ciais et al.*, 2013a; *Ripple et al.*, 2014; *Gernaat et al.*, 2015]. In view of this, we separated the abatement of these land-use emissions and captured the relationship using the same equation 3 for simplification. The estimations are shown in Figure S2 in Appendix S2.

The abatements of climate pollutants and aerosols such as CO, VOC, SO_x, NO_x, BC, and OC were also determined based on the carbon prices. Here, we introduced a simple linear relationship between the reduction of pollutants and aerosols and the carbon prices (see equation (6) in Appendix S2).

We assumed adaptation levels based on the method used in AD-DICE [*de Bruin et al.*, 2009; *de Bruin and Dellink*, 2011]. However, the parameters were re-estimated according to DICE-2013R (Figure S3 in Appendix S2), and the results imply that a 40% reduction in gross damage can lead to a 0.71% loss of total gross output. For climate change damage, we used the damage function in DICE-2013R directly to estimate the losses due to climate change.

2.2. Simple Climate Module

We introduced into DICE-2013R a more detailed representation of the carbon cycle and atmospheric chemistry to describe a variety of GHGs, pollutants, and aerosols based on MAGICC 6.0 [*Meinshausen et al.*, 2011a]. A simplified temperature module was adopted to derive the GMT above the pre-industrial level, thereby avoiding the complexities of the upwelling-diffusion climate model.

The simple climate module simulates the evolution of individual anthropogenic emissions. First, both the terrestrial and oceanic carbon cycles were explicitly considered to derive the atmospheric CO_2 concentration. Compared to MAGICC 6.0, however, we reduced the complexity of the calculations by simplifying some parts of the processes to allow the carbon cycle to be used during the optimization.

Table 1. Scenario Design

Climate Case	Industrial CO_2	Land-use CO_2	Non-CO_2	Climate Policy
Base, DICE-Style	SSP2 reference	Fixed	Fixed	None
Base, Full-Abate	SSP2 reference	SSP2 reference	SSP2 reference	None
Optimal, DICE-Style	Dynamic	Fixed	Fixed	Optimal
Optimal, Full-Abate	Dynamic	Dynamic	Dynamic	Optimal
2.0°C, DICE-Style	Dynamic	Fixed	Fixed	Below 2.0°C after 2100
2.0°C, Full-Abate	Dynamic	Dynamic	Dynamic	Below 2.0°C after 2100
1.5°C, DICE-Style	Dynamic	Fixed	Fixed	Below 1.5°C after 2100
1.5°C, Full-Abate	Dynamic	Dynamic	Dynamic	Below 1.5°C after 2100

SSP2, Shared Socioeconomic Pathways 2.

(1) We chose to treat forest regrowth as varying linearly with respect to the relaxation time in the terrestrial carbon cycle (see equation (35)–(37) and Table S2 in Appendix S2); (2) we re-calibrated the CO_2 fertilization factor using all four Representative Concentration Pathways (RCPs) [*Masui et al.*, 2011; *Riahi et al.*, 2011; *Thomson et al.*, 2011; *Vuuren et al.*, 2011] and the extension [*Meinshausen et al.*, 2011b], based on MAGICC 6.0's calculations using the same inputs (see Figure S4 in Appendix S2 for the calibration of the CO_2 concentrations; the default setting of C4MIP BERN was used). Second, the concentration and RF were calculated separately for various non-CO_2 components, including CH_4, N_2O, halogenated gases (12 addressed under the Kyoto Protocol and 16 addressed under the Montreal Protocol), CO, VOC, SO_x, NO_x, BC, and OC. In addition, contributions from mineral dust, cloud cover, land-use albedo, and natural sources such as volcanic and solar irradiance changes were simply assumed to remain at their respective levels after 2005 based on MAGICC 6.0 (Figure S5 in Appendix S2) [*Meinshausen et al.*, 2011a].

We used the two-box temperature module in DICE instead of the upwelling-diffusion climate model in MAGICC 6.0 to simulate the change in the GMT. The two-box module is simple enough to be involved in the inter-temporal optimizing process on a century time scale while still adequately capturing the characteristics of the temperature evolution derived from more complex climate models [*Glotter et al.*, 2014]. In addition, because the effective radiative forcing (ERF), which is defined as the resulting RF when allowing well-mixed GHSs and aerosols to respond to perturbations with rapid adjustments, is more representative of the GMT response [*Myhre et al.*, 2013], we scaled the standard RF to the ERF by multiplying it by an efficacy factor and then used the ERF in the temperature module to derive the GMT. Here, the climate sensitivity was set to the best-guess level of 3.0°C, and the calibration is shown in Figure S6 in Appendix S2.

2.3. Scenario Design

We designed a set of scenarios to thoroughly investigate the importance of the inclusion of the dynamic abatement of land-use CO_2 and non-CO_2 and their implications for climate policy assessment. Here, we considered two dimensions, as shown in Table 1, namely, (1) climate policy and (2) the running modes. The climate policy dimension consists of the base case, the optimal case and two climate target cases (2.0°C and 1.5°C). The rate of control $\mu(t)$ is equal to zero in the base case, which is the reference case. In the optimal case, future climate emissions are determined using a cost–benefit approach that balances climate costs with climate damages by maximizing the total discounted inter-temporal social welfare. In the 2.0°C and 1.5°C climate target cases, the GMT change after the year 2100 is limited to below 2.0°C and 1.5°C, respectively. In this modeling exercise, we assumed that temperature overshoots were allowed within this century in both climate control cases. In addition, we used best-guess estimates for both the socioeconomic development and climate change, and therefore the results show a best-guess level assessment.

In the base case, the GHGs in 2015 is 57.0 $GtCO_2$-eq yr^{-1} (see Tables S4 and S5 in Appendix S2 for 100-year global warming potential [GWP]), higher than recent baseline estimations [*Rogelj et al.*, 2016a]. However, the Copenhagen Accord was imposed in the optimal case and in the two climate target cases, and a median value of 48.7 $GtCO_2$-eq GHGs by 2020 was adopted based on existing studies [*Rogelj et al.*, 2010; *Stern and Taylor*, 2010; *den Elzen et al.*, 2011; *Höhne et al.*, 2012]. As with the climate pollutants and aerosols, an initial control level was assumed in the base case of SSP2 [*Rao et al.*, 2017], corresponding to the *Rogelj et al.'s*

[2014b] current legislation (CLE) assumption with no new energy access policies. No further air pollution control tightening was imposed in this study, except for those from climate change mitigation.

Two running modes were devised to clarify the effects of addressing land-use CO_2 and non-CO_2 explicitly, i.e., the "DICE-Style" mode and the "Full-Abate" mode. In the DICE-Style mode, the land-use CO_2 emission and non-CO_2 forcing are fixed a priori as in DICE-2013R, with no dynamic abatement of these emissions. However, the Full-Abate mode is the one in which the model improvements described in the previous sections are fully implemented. All the other features of both modes were kept the same.

In the following sections, we first present a comparison between the DICE-Style and Full-Abate modes with regard to various assumptions made concerning land-use CO_2 and non-CO_2 climate forcers as well as their corresponding economic effects; subsequently, the abatement path for anthropogenic emissions and the contributions from individual forcing sources for the 2.0°C target as obtained with the model running in Full-Abate mode are reported. We also examine the 1.5°C target based on the Full-Abate assessment in the discussion, with the caveat that optimistic assumptions are required.

3. Results

3.1. Comparison of the DICE-Style Model and the Fully Revised Model

In the modeling experiments, the Full-Abate mode takes full advantage of the reduction potentials associated with GHGs, pollutants, and aerosols, whereas the DICE-Style mode considers only the abatement that can be realized by controlling industrial CO_2. As a result, a higher industrial CO_2 emission level is found during the current century in the Full-Abate assessment, with a difference of approximately 2.0 $GtCO_2\ yr^{-1}$ compared with the DICE-Style assessment for the 2.0°C target case and a difference of 5.5 $GtCO_2\ yr^{-1}$ for the 1.5°C target case (Figure 2a). However, this is not the case for the optimal case because the emission pathway is optimized with no constraints. The land-use CO_2 level is fixed in the DICE-Style assessment, as shown in Figure 2b. By contrast, in the Full-Abate assessment, the land-use CO_2 level turns negative in the late 2050s and makes its maximum contribution to the abatement efforts in the 2080s, reaching a minimum of −1.2 $GtCO_2\ yr^{-1}$ in the 2.0°C target case. These findings imply that the land-use CO_2 emissions are reduced by more than 2.8 $GtCO_2\ yr^{-1}$ compared with the base case until the 2070s, whereas the relative cuts decrease by the end of the century because of the decreased level of land-use CO_2 in the base assumption at this time. The optimal case is consistent with the DICE-2013R assumption [*Nordhaus and Sztorc*, 2013], which is based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) [*Ciais et al.*, 2013b], with a land-use CO_2 level of approximately −0.1 $GtCO_2\ yr^{-1}$ in 2100. This indicates that the assumption of land-use CO_2 in this study agrees with existing studies. However, because the level of land-use CO_2 in 2020 stipulated by the Copenhagen Accord is higher than the DICE-2013R assumption, a deeper cut for land-use CO_2 is observed since the 2030s for both climate target cases with the Full-Abate assessment.

Similar findings were obtained with respect to the non-CO_2 forcing, for which the optimal case is also consistent with the DICE-2013R fixed assumption (Figure 2c). A reduction of approximately 1.0 $W\ m^{-2}$ in non-CO_2 emissions is found for achieving the 2.0°C target in 2100 according to the Full-Abate assessment. The above findings show that compared with the DICE-2013R assumptions, lower levels of both land-use CO_2 and non-CO_2 emissions can be identified by the end of this century for the 2.0°C and 1.5°C target cases. Therefore, abatement efforts that reach beyond industrial CO_2 are important, especially for low stabilization scenarios.

A greater extent of RF of 0.9 $W\ m^{-2}$ (see Figure 2, forcing effect induced by (1) and forcing in (2) is assumed in the base case of Full-Abate compared to the DICE-Style. However, the climate change costs are smaller in the Full-Abate scenarios even with such additional cuts (see following). Controlling the land-use CO_2 and non-CO_2 emissions provides more abatement options other than reducing the industrial CO_2. If no flexible abatement of land-use CO_2 and non-CO_2 emissions is allowed, then the reduction potentials associated with these emissions cannot be fully exploited.

Abatement efforts that reach beyond industrial CO_2 can be seen to have significant effects on the climate change costs. As shown in Figure 3a, the carbon price in the 2.0°C target case according to the Full-Abate assessment is approximately 20.0% lower than that indicated by the DICE-Style assessment in the middle of the century. Regarding GDP losses (Figure 3b), up to 16.1% of the losses during the current century for the

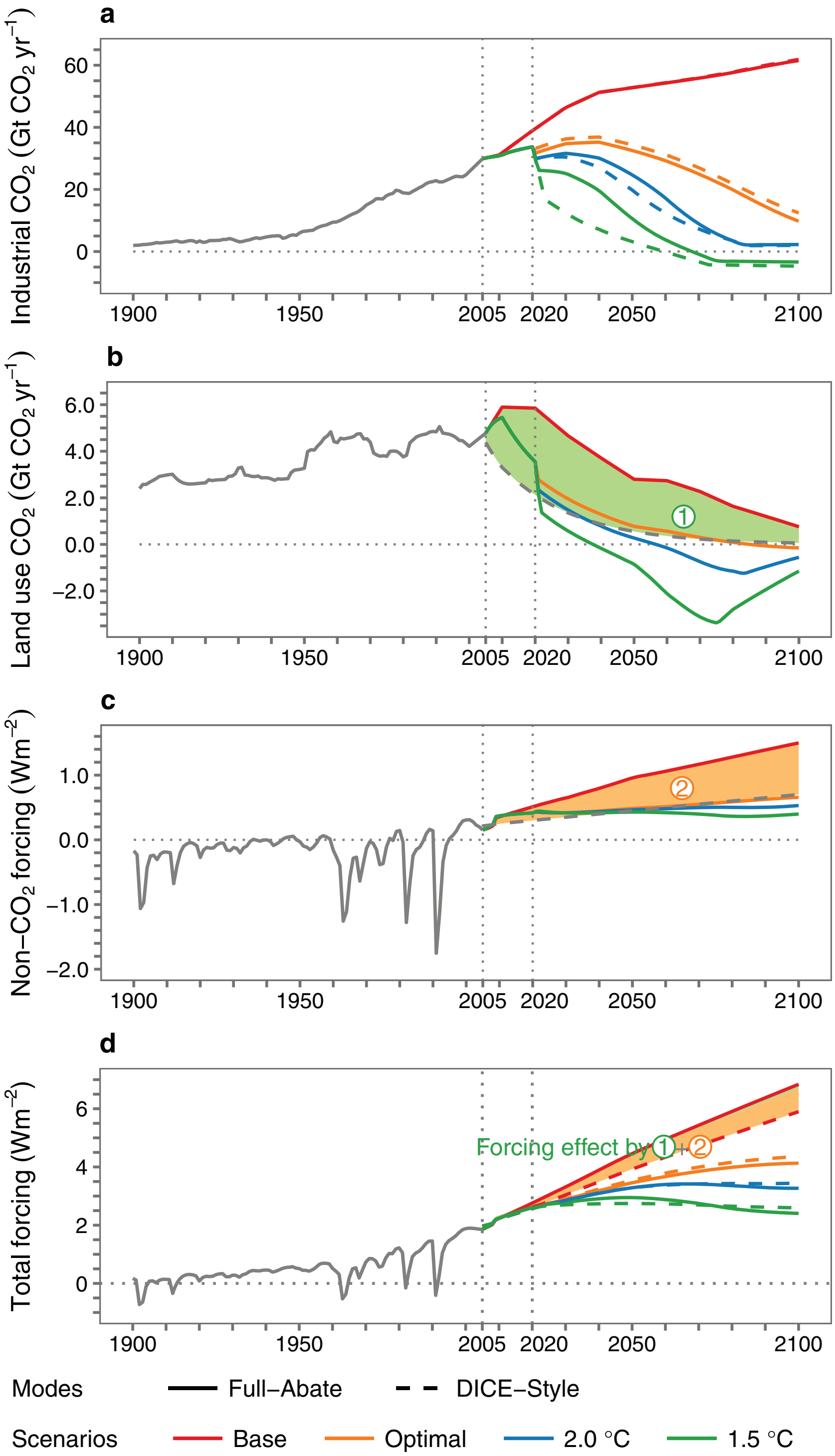

Figure 2. Comparison between the DICE-Style and Full-Abate assessments. (a) Industrial CO_2 emissions. (b) Land-use CO_2 emissions. (c) Non-CO_2 radiative forcing. (d) Total radiative forcing. The gray dashed lines in (b) and (c) represent the DICE-2013R fixed assumptions, scaled from 2005. The colored dashed lines in (a) and (d) are derived from the DICE-Style assessment. The colored region in (d) represents the difference in the base case between the DICE-Style and Full-Abate assessments, which is equivalent to the forcing effect induced by region (1) in (b) plus the forcing in region (2) in (c) since the industrial CO_2 levels are identical in the base case for the two running modes, as shown in (a). The time period covered by the Copenhagen Accord is 2005–2020.

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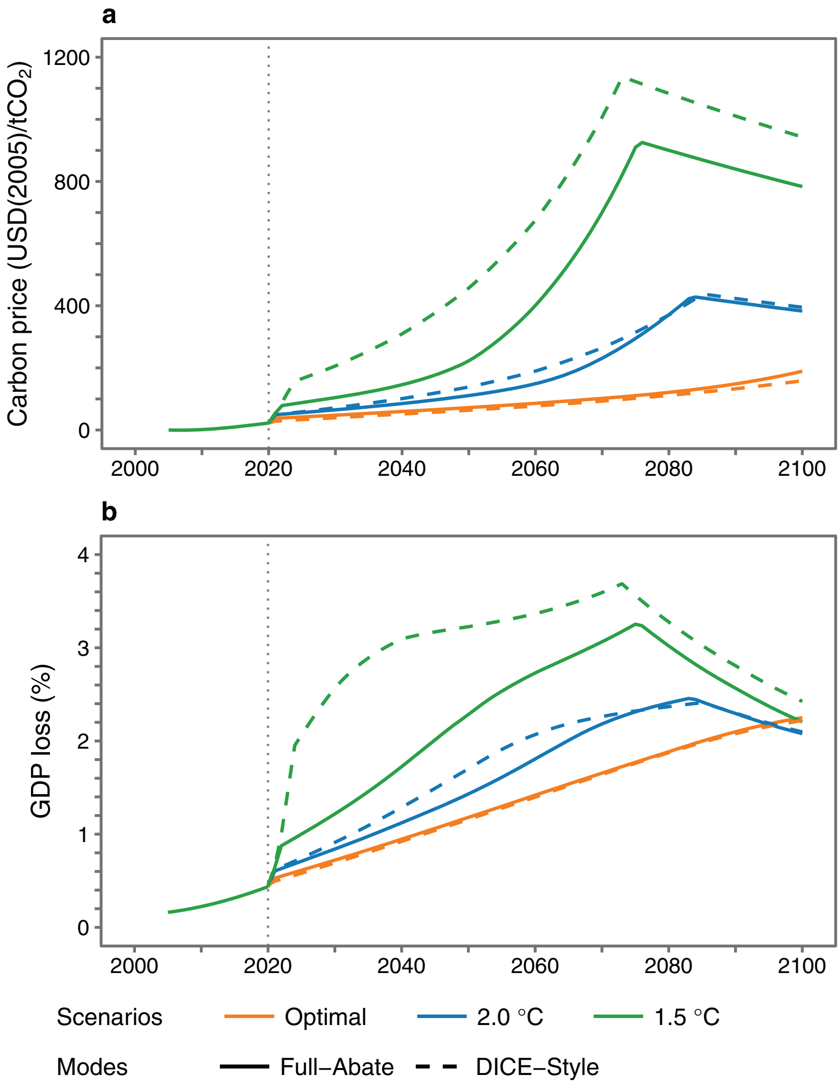

Figure 3. Carbon prices and GDP losses. (a) Carbon prices in USD (2005) (purchasing power parity). (b) GDP losses. The GDP losses include the losses from abatement costs, adaptation costs, and residual climate damages. The time period covered by the Copenhagen Accord is 2005–2020.

2.0°C target case are eliminated in the Full-Abate model compared with the DICE-Style model. The effects are even more remarkable for the 1.5°C target; up to 53.4% of the carbon price in the Full-Abate assessment can be eliminated compared with that in the DICE-Style assessment, and the GDP loss is decreased to approximately half of that in the DICE-Style assessment in the near term. In contrast, for the optimal case, the differences between the DICE-Style and Full-Abate results are not significant because the abatement timing is optimized and no constraints are actually imposed. The results show that in the Full-Abate approach, the climate costs for achieving the 2.0°C and 1.5°C targets are lower, but the forcing is actually reduced to a greater extent. In other words, if the cuts were to be made from the same base levels, then the climate costs indicated by the Full-Abate assessment would dip even lower than those indicated by the DICE-Style assessment. These findings demonstrate that dynamic abatement efforts that reach beyond industrial CO_2 can substantially affect the climate costs, particularly with regard to stringent climate control cases.

3.2. Anthropogenic Emissions for 2.0°C Stabilization

To achieve the 2.0°C target, although most of the emission cuts come from industrial CO_2, reductions in land-use CO_2 and non-CO_2 emissions are also important. The anthropogenic emissions at the end of this century are reduced by approximately 77.6 $GtCO_2$-eq yr^{-1} compared with the base case in the 2.0°C target

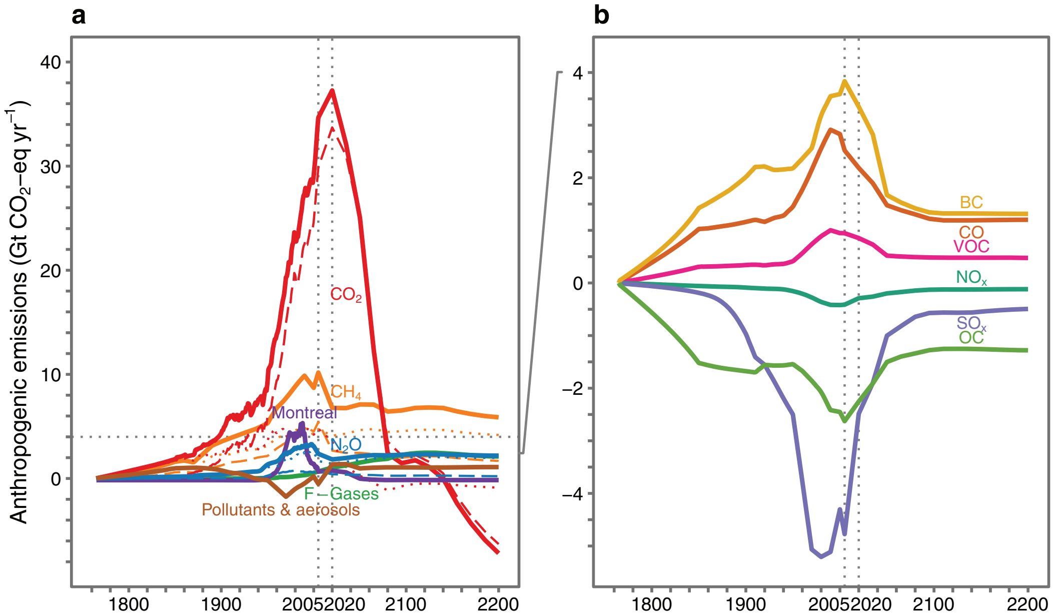

Figure 4. Anthropogenic CO_2-eq emissions for the 2.0°C target. (a) Anthropogenic CO_2-eq emissions. (b) Decomposition of the contributions of pollutants and aerosols. The CO_2-eq values were calculated after the policy path was obtained. The thick solid lines represent anthropogenic emissions, the thin dashed lines represent industrial emissions, and the thin dotted lines represent land-use emissions. For the historical data, the outputs of MAGICC 6.0 for the Representative Concentration Pathways (RCPs) were used. For the Montreal Protocol gases, the output of MAGICC 6.0 for RCP 6.0 was used because (1) there are no separate definitions for these gases in Shared Socioeconomic Pathways 2 and (2) there are no significant differences among the RCPs because these gases are assumed to be under control [*Montzka et al.*, 2011]. The time period covered by the Copenhagen Accord is 2005–2020. The 100-yr Global Warming Potential values listed in Table S4 in Appendix S2 [*Fuglestvedt et al.*, 2010; *Myhre et al.*, 2013] were used in the calculations. The indirect halocarbon effects from ozone depletion are included (Table S5 in Appendix S2) [*Myhre et al.*, 2013]. Negative values indicate that the emissions exert a cooling effect.

case; of this reduction, 76.3% is associated with industrial CO_2, 1.7% with land-use CO_2, and 22.0% with non-CO_2 emissions. As shown in Figure 4a, in the 2.0°C target case, both the industrial and land-use CO_2 emissions are reduced to significantly lower and even negative levels, whereas the CH_4 and N_2O emissions can only be cut down to approximately 6.7 and 2.3 $GtCO_2$-eq yr^{-1}, respectively, in 2100 because of the limited reduction potentials associated with land-use sources. Specifically, CH_4 and N_2O emissions from industrial sources are reduced by 78.9% and 75.1%, respectively, by 2100 in the 2.0°C target case, whereas only half of the CH_4 and less than half of the N_2O emissions from land-use can be eliminated. Regarding halogenated gases, by the end of this century, F-gases are reduced by up to 55.3%, and Montreal Protocol gases are reduced to the level of −0.1 $GtCO_2$-eq yr^{-1}, considering the indirect effects of ozone depletion.

The findings regarding the GHG levels here are consistent with those of *Rogelj et al.* [2011]. However, the Copenhagen Accord level used in this study is assumed to be the median, and a deeper cut is needed from 2020 for a relatively higher emission level. As also reported in *Bowerman et al.* [2013], *Shoemaker et al.* [2013], *Rogelj et al.* [2014a, 2015a], reducing SLCPs, including CH_4, BC, and hydrofluorocarbons, will have instant effects on climate change mitigation in the near term, and it needs to be implemented with the abatement of long-lived GHGs to achieve the low stabilization scenario. Furthermore, we used the AIM/CGE information in which the industrial CO_2 emissions and their air pollutants were explicitly represented. In that sense, the air pollutants would not be over- or under-estimated with respect to the interlinkages with industrial CO_2 emissions, as reported in *Rogelj et al.* [2014a]. Our results also highlight that the potential of reductions in SLCPs is limited for achieving low stabilization targets since their reduction potentials are exhausted in the distant future.

Pollutants and aerosols such as CO, VOC, SO_x, NO_x, BC, and OC are reduced to the level of 1.1 $GtCO_2$-eq yr^{-1} by 2100, considering both cooling and warming effects from these emissions (Figures 4a and 4b). Up to 52.7% of the SO_x and 31.6% of the NO_x are removed by 2100, with no significant changes to the other aerosol levels compared with the base case. As also indicated by *Rogelj et al.* [2014b], the future emissions of air pollutants are very much contingent on assumptions regarding the penetration of clean air policies. The abatement of air pollutants that is assumed in this study represents a combination of reductions under clean air policies of CLE and reduction initiatives based on climate policy. The combined effect of all aerosols does not significantly change by the end of this century because species with both cooling and warming effects are similarly suppressed under climate control efforts.

3.3. Radiative Forcing Agents in 2100 for the 2.0°C Target

In the Full-Abate case, the total forcing is reduced from 6.8 to 3.3 W m^{-2} to meet the 2.0°C target in 2100, as shown in Figure 5. The main contributions to the 2°C target come from well-mixed GHGs, which yield a total RF of 3.5 W m^{-2}, and a small fraction is offset by cooling effects from aerosols, cloud effects, and the land-use albedo. Almost half (49.6%) of the forcing can be cut with respect to the base case based on well-mixed GHG sources. For CH_4 and N_2O, the reductions are 60.7% and 48.1%, respectively. The forcing due to F-gases can be reduced by 50.9% by 2100, whereas the effects from Montreal Protocol gases remain unchanged because of the assumption that these emissions are already constrained by the Montreal Protocol [*Montzka et al.*, 2011].

Regarding aerosols, certain species including sulfate aerosols reflect radiation and cool the atmosphere and Earth' surface. These species are consequently masking warming for climate change but can harm human health and the ecosystem. In the base case, the levels of SO_x and NO_x are assumed to decline within this century. However, large reduction potentials still exist for these two air pollutants, because a considerable portion of these emissions is contributed by fossil fuel consumption and industrial processes [*Rao et al.*, 2017], and climate change mitigation also reduces the two air pollutants. For instance, 58.3% of the negative forcing from SO_x and 47.5% of the negative forcing from NO_x are eliminated by 2100 for the 2.0°C target case. The cooling effect from the total aerosols is decreased by approximately 0.1 W m^{-2} with respect to the base case; therefore, additional efforts regarding GHGs are needed to compensate.

The Full-Abate assessment indicates an optimal GMT above the pre-industrial level of 2.5°C in 2117, in striking contrast to the 3.3°C in 2130 indicated by DICE-2013R [*Nordhaus and Sztorc*, 2013] but close to the 2.0°C target. This finding implies that the 2.0°C target can be efficiently reached in the SSP2 scenario. First, the SSP2 assumptions adopted in the base case involve significant suppression of GHGs [*Fricko et al.*, 2017; *Fujimori et al.*, 2017] compared with the reference projection in DICE-2013R [*Nordhaus*, 2013, 2014; *Nordhaus and Sztorc*, 2013]. Thus, the difficulty of climate control decreases in such a moderate future scenario. Second, the consideration of the dynamic abatement of anthropogenic emissions increases the total reduction potential, allowing greater flexibility in establishing a climate control path. Third, the allowance of overshoot [*Rogelj et al.*, 2016b] also decreases the difficulty of achieving the climate target. However, a reduction of approximately 13.1 $GtCO_2$-eq with respect to the base case in 2020 is needed to comply with the Copenhagen Accord. Thus, short-term reduction is still important for stringent climate control.

4. Discussion

4.1. 1.5°C Target

The 1.5°C target can be met with early deep cuts and high costs under the assumption of a temperature overshoot, as has also been suggested by a previous study [*Rogelj et al.*, 2015b], because the increase in the GMT above the pre-industrial level is already approaching the 1.0°C level at present, and a further increase of 0.5°C is expected by 2028 in the Base case. Figure S8 in Appendix S2 shows that meeting the 1.5°C target requires a deep reduction in CO_2 emissions, and the CO_2 emissions turn negative in the 2060s, with approximately a one-decade delay compared to *Rogelj et al.'s* [2015b] mean results. This is because the total RF for 1.5°C, 2.4 W m^{-2} (Figure S9 in Appendix S2), lies at the upper end of the cited literature. The mitigation floor [*Gasser et al.*, 2015] for land-use emissions occurs in the 2070s, with a value of −3.4 $GtCO_2$. For non-CO_2 emissions, however, most of the necessary cuts are from CH_4 and N_2O, with rates of control of 71.8% and 53.6%, respectively, in 2100. Regarding aerosols, SO_x and NO_x are reduced to low levels of −0.4 and −0.1 $GtCO_2$-eq, respectively, to meet the 1.5°C target. There are almost no additional cuts from other aerosols compared with the 2.0°C target case because the reduction potentials of these emissions are exhausted. Figure S9 in Appendix S2 shows that 83.4% of the total forcing is contributed by CO_2, and the rest is from non-CO_2, with a cooling effect of −0.7 W m^{-2} engendered by aerosols, and effects from the cloud albedo and land-use albedo. In addition, the carbon price increases by a factor of 3 compared with that of the 2.0°C target case

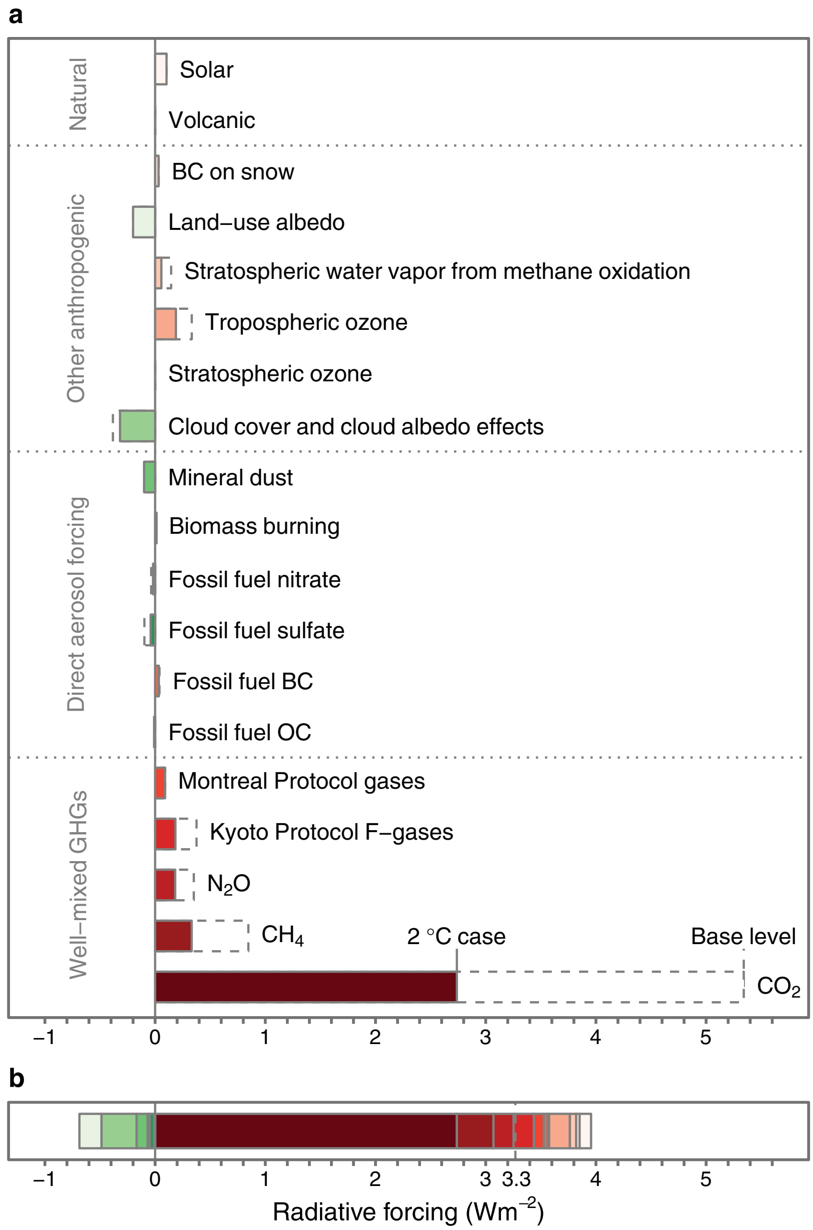

Figure 5. Radiative forcing (RF) agents above pre-industrial levels in 2100 for the 2.0°C target. (a) Forcings from various sources. Each colored bar shows the forcing induced by the corresponding source; the dashed bar indicates the forcing level of the base case. The forcing from biomass burning is calculated by summing the forcings induced by the biomass OC, BC, SO_x, and NO_x. The mineral dust, cloud cover, land-use albedo, volcanic, and solar forcings are assumed to be −0.1, 0.0, −0.2, 0.0, and 0.1 W m^{-2}, respectively, after 2005 [*Meinshausen et al.*, 2011a]. (b) Total RF. The total forcing for the 2.0°C target case is 3.3 W m^{-2}, the sum of the negative forcings on the left and the positive forcings on the right. All values used best-guess levels.

during the 2060s and 2070s because of the need for a high rate of control of greater than 0.8 beginning from the 2050s, which causes the carbon price to significantly increase. The mitigation cost is doubled in the 1.5°C target case compared with the 2.0°C target case during the 2030s–2070s (Figure S7 in Appendix S2). With regard to the aggregated mitigation costs from 2010 to 2100, the 1.5°C target is approximately 1.9-fold costlier than the 2.0°C, slightly lower than the factor of 2.2–3.7 between the 1.5°C-consistent and the medium 2°C scenarios in *Rogelj et al.* [2015b], probably due to the adaptation assumptions in this study.

4.2. Significance of Model Improvements

First, we revised DICE-2013R for dealing with detailed anthropogenic emissions, and it functionally improved the feasibility of performing a long-term time scale optimal assessment considering individual climate forcers. Compared to previous studies [*Meinshausen et al.*, 2009; *Rogelj et al.*, 2015b, 2016a], our results warrant earlier cuts in the GHGs with similar climate control due to the consideration of the climate change feedback to socioeconomic development. In addition, we can use this model for treating uncertainty in both socioeconomic development and climate change through Monte Carlo methods due to the lightweight design, although the results are not shown here and will be presented in our next study.

Second, the mitigation costs substantially increase when deep cuts or even negative emissions are achieved, as is also indicated by the MAC shown in Figure 1, although the adaptation costs and residual damages decrease because of the lower temperatures resulting from stringent climate control measures. However, the climate costs become greater if the abatement efforts are focused solely on industrial CO_2, which will lead to a biased assessment of the economic impacts of climate policy.

Third, in this study, we increased the accuracy of the simple climate module in representing GMT change. As reported by *Glotter et al.* [2014], the highly simplified climate module in DICE-2013R underestimates both the CO_2 concentration and the GMT change. Therefore, the same reduction in CO_2 will result in a smaller change in the CO_2 concentration and a smaller GMT in DICE-2013R as well as a lower level of climate damage. With the advances in climate system modeling that were achieved in this study, these deficiencies are minimized or eliminated through the incorporation of the carbon cycle and the calibrated temperature module.

4.3. Limitations

Three limitations should be noted with regard to this study. First, the simple climate module was calibrated based on MAGICC 6.0 using four RCPs [*Meinshausen et al.,* 2011b], from 2.6 to 8.5 W m^{-2}, extended through the year 2300. The module is not validated for a forcing range that lies outside these RCPs or a time period that extends beyond 2300. However, the findings presented in this study are based on moderate SSP2 assumptions and are optimized for the period from 2005 to 2300, and they lie within the calibrated range of the period, except in the case of the 1.5°C target, for which the forcing is lower than the calibrated RCP 2.6 level. We tested the 1.5°C results with MAGICC 6.0 using the same inputs, and the errors were found to lie within the ranges of [−0.09, +0.09] W m^{-2} for the total RF and [−0.05, +0.07]°C for the GMT during the evaluation period (see Figures S4–S6 in Appendix S2). These results also show a good fit to the outcomes of MAGICC 6.0 for low stabilization scenarios such as the 1.5°C target case. Second, we considered the mitigation costs collectively rather than calculating the costs for the individual emission types [cf. *Johansson*, 2011; *Tanaka et al.*, 2013] because of the data availability for the SSP2 scenario. Thus, the individual costs of the different anthropogenic emissions are not reflected in this assessment. Third, uncertainties existing in the socioeconomic development, future emission mitigation technologies, and climate change impacts, especially those from aerosols, the cloud albedo and the land-use albedo [*Boucher et al.*, 2013; *Ciais et al.*, 2013b; *Hartmann et al.*, 2013; *Myhre et al.*, 2013; *Jones et al.*, 2015], cannot be reflected in this study because only the best-guess levels representing the socioeconomic development and GMT change are used. For example, a relatively large uncertainty range of [−0.85 to +0.15] W m^{-2} was identified for the radiation forcing of the aerosol-radiation interaction in AR5 [*Myhre et al.*, 2013]. Such a high uncertainty will impact the needed amount of GHGs, pollutants or aerosols abated and the resulting climate impacts for reaching 2.0°C or 1.5°C. However, we leave a more elaborate comprehensive uncertainty analysis for future studies.

5. Conclusion

We developed an IAM based on DICE-2013R and MAGICC 6.0 to consider individual anthropogenic emissions dynamically. The results show that the incorporation of individual emissions is important for the consideration of low stabilization scenarios. This is because, in addition to industrial CO_2, land-use CO_2, non-CO_2, and aerosol emissions also contribute to keeping a low level of RF toward the end of this century. Our analysis provides a comprehensive assessment with regard to the reduction potential and the corresponding effect of each emission, which is important for guiding policy-makers in distributing resources to combat climate change. This study also determines the optimal climate policy under the assumption of a moderate future emissions scenario, thereby enriching the literature on climate change assessments to enable the discovery of efficient climate reduction paths.

A flexible climate control path that considers the effects of individual anthropogenic emissions can significantly affect the carbon price and total climate costs, including mitigation costs, adaptation costs, and residual climate change damages, especially in cases of stringent control targets. These effects are further strengthened when more than 0.8 of industrial CO_2 is removed, consistent with the SSP2 assumptions.

The 2.0°C target can be efficiently achieved under the assumptions of the moderate SSP2 scenario. However, for the 1.5°C target, deep cuts are needed starting from the early period under the assumption of a temperature overshoot, and the efforts that are necessary to reach this target can lead to tripling the carbon price and doubling the mitigation cost compared with those in the 2.0°C target case.

For a moderate future emissions scenario, the dynamic assessment approach yields seemingly optimistic results regarding climate control. However, because of the existence of large uncertainties regarding the socioeconomic development and the Earth's climate system, a prudent climate policy is still needed to leave room for uncertainties during the policy-making and implementation stages.

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