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Implications of temperature overshoot dynamics for climate and carbon dioxide removal policies in the DICE model

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Implications of temperature overshoot dynamics for climate
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E-mail: wilfried.rickels@ifw-kiel.de**Keywords:** temperature overshoot, integrated assessment modelling, DICE, FaIRSupplementary material for this article is available [online](#)

Abstract

Assessing climate policies that involve temporary overshoot of temperature targets requires an accurate representation of carbon cycle and climate dynamics. Here, we compare temperature overshoot climate policies obtained with the dynamic integrated climate–economy (DICE) integrated assessment model using two different climate–carbon cycle sub-models: first, the original DICE implementation, and second an implementation of the finite amplitude impulse response (FaIR) simple climate model. We analyze in a cost-effectiveness framework the minimum abatement and carbon dioxide removal costs for compliance against a (future) ceiling on temperatures. In our setup, the magnitude of the overshoot is not limited by temperature impacts, but simply by the temperature dynamics such that from a certain compliance date onwards a temperature ceiling cannot be exceeded anymore. We show that the rather sluggish temperature response and underestimation of carbon sinks in the most recent version of DICE implies that the additional future temperature change after a cessation of a given CO₂ emission scenario is significantly overestimated compared to the zero emission commitments obtained with FaIR and complex earth system models. However, investigating climate policies which allow for a temporary temperature overshoot, this inertia translates into more than twice as high optimal carbon prices compared to FaIR and consequently in rather strict climate policies. For compliance with the 1.5 °C target from 2100 onward and non-CO₂-warming of 0.2 °C, the mean optimal carbon prices in the year 2030 are 173USD/tCO₂ and 56USD/tCO₂ for DICE and FaIR, respectively. Still, the dynamics towards the target suggest that improved understanding of and accounting for (limited) reversibility of vulnerable Earth system components is required to derive appropriate overshoot climate policies.

1. Introduction

The dynamic integrated climate–economy (DICE) model (Nordhaus 1992, 2008, 2014, 2017, 2019) has been criticized for underestimating the economic impacts of climate change (Stern 2007, Burke *et al* 2015, Hänsel *et al* 2020). At the same time the simplified carbon cycle and climate dynamics of DICE are subject to criticism, mainly due to their sluggish temperature response to increased atmospheric greenhouse gas (GHG) concentrations and over- or underestimation of carbon sinks (e.g. Rickels *et al* 2018,

Dietz and Vernmans 2019, Dietz *et al* 2021, Johannsson *et al* 2020, Azar and Johannsson 2021).

In the most recent calibration of DICE these two deficits partly balance each other as the following illustrative calculations in a cost-benefit framework demonstrate. The optimal cost-benefit climate policy results in emissions pathways leading to modelled DICE-temperature increases of 3.44 °C and 3.18 °C relative to preindustrial levels by the year 2100, under exogenous forcing as specified in DICE and under RCP2.6, respectively. In the simple climate carbon cycle model FaIR (Millar *et al* 2017,

Smith *et al* 2018) with climate dynamics following Geoffroy *et al* (2013), these optimal emission pathways obtained with DICE result in modelled temperature increases of only 2.85 °C and 2.58 °C in 2100, respectively. FaIR has been calibrated to recent generation Earth system models (ESMs) and is able to skillfully simulate the carbon and climate dynamics of these models over a wide range of scenarios, making it plausible to consider the temperatures modelled by FaIR as current best estimates for anthropogenic climate change. Accounting for a larger carbon sink and a less sluggish reaction of temperature, by deriving optimal climate policies with a version of DICE that employs the FaIR-Geoffroy climate-carbon cycle sub-model, optimal temperature increases in 2100 to 2.98 °C and 2.71 °C, again for both non-CO₂-forcing specifications (see section 2). These still high optimal temperatures indicate that estimates for climate change damages in DICE are low. Yet, the smaller carbon sink and sluggish temperature response in DICE compared to FaIR-Geoffroy translate into increased CO₂ prices, e.g. in the year 2030 from 41 to 48 USD/tCO₂ in optimal cost-benefit climate policies (for non-CO₂-forcing as specified in DICE). These limitations of the carbon and climate system in DICE are in particular relevant in the context of ambitious temperature targets which are potentially achieved after a temporary temperature overshoot.

Among the 90 IPCC SR15 scenarios compatible with limiting temperature increase to 1.5 °C by 2100, only nine achieved the temperature target with no temperature overshoot (Huppmann *et al* 2018). For the IPCC sixth assessment report (AR6) scenarios based on ‘shared socioeconomic pathways’ (O’Neill *et al* 2014) have been analyzed. Among the main SSP scenarios, i.e. those that have been selected to be included in the Coupled Model Intercomparison Project Phase 6 (CMIP6) (O’Neill *et al* 2016) only the SSP1-1.9 complies in its central estimate for global surface air temperature with the 1.5 °C target by the year 2100, but involves a temporary overshoot of 0.1 °C which is estimated for the middle of the century (IPCC 2021). The scenario SSP1-1.9 assumes that GHG emissions decline from the year 2020 onward and accordingly, scenarios with delayed reductions in net emissions and in turn with a stronger overshoot are gaining attention in the mitigation context. In SSP5-3.4-OS emissions follow until the year 2040 the high emission scenario SSP5-8.5 before assuming a deep cut in emissions, supplemented with substantial carbon dioxide removal (CDR) which is assumed to reach about 20 GtCO₂ by the year 2100 (O’Neill *et al* 2016). The atmospheric CO₂ concentration in this scenario is estimated to peak at 571 ppm in the year 2062 and is then projected to decline to 497 ppm by the year 2100 (Lee *et al* 2021). The decline in atmospheric carbon concentration successfully lowers global mean surface temperatures, but still ‘changes in climate

have not fully reversed by 2100 under this reversal of CO₂ concentrations’ (Lee *et al* 2021). In addition to various climate feedbacks and possible irreversibility involved in temporary temperature overshoots, the linear relationship between cumulative net CO₂ emissions and temperature response (transient response to cumulative CO₂ emissions, TCRE) weakens because ocean heat and carbon uptake show increasing path dependencies for levels of overshoots above 300 GtC (Zickfeld *et al* 2016, Tokarska *et al* 2019, Lee *et al* 2021). These results are based on exogenously defined climate policies, i.e. prescribed paths for net CO₂ and other GHG emissions, raising in turn the question of how far carbon cycle and climate feedbacks affect endogenous climate policies.

Following Johannson *et al* (2020) we analyze climate policies involving temporary overshoot of temperature targets. While they consider either a radiative forcing target for year 2100 or a permanent temperature ceiling, we focus on temperature ceilings, i.e. temperature targets which are not supposed to be exceeded. We analyze the sensitivity of climate policies and CDR with respect to the compliance date, i.e. the year from which onward the ceiling is binding. Furthermore, we deliberately neglect non-CO₂-forcings and temperature-related impacts to investigate the implications of carbon cycle dynamics in isolation. Instead of cost-benefit analysis (CBA) we consider a cost-effectiveness framework to achieve compliance against a (future) ceiling on temperatures with minimum abatement and CDR costs. Accordingly, in our analysis, the magnitude of the overshoot is not limited by temperature impacts, but only by the carbon cycle and climate dynamics constraining the paths in a way that after a certain compliance date a temperature ceiling cannot be exceeded anymore.

The article is structured as follows. Section 2 explains how we compare different vintages of the DICE carbon cycle and climate model with each other and with FaIR-Geoffroy, by implementing all these models in the economic model of the most recent DICE version. The different calibrations are used first to assess exogenous zero-emission commitment scenarios and second to investigate endogenous temperature overshoot scenarios in dependence of the compliance date. Sections 3 and 4 present and discuss the results, respectively, before the article ends with a summary and conclusions.

2. Methods

The analysis is based on the integrated assessment model DICE2016R2 (Nordhaus 2017) which is augmented such that the carbon cycle and climate dynamics are either described by DICE2016R2, DICE2013 (Nordhaus 2014), DICE2007 (Nordhaus 2008) or FaIR-Geoffroy (Geoffroy *et al* 2013, Millar *et al* 2017, Smith *et al* 2018). FaIR is capable of

reproducing results of recent generation ESMs and we use it as a benchmark to assess the results obtained with the simpler carbon and climate models in DICE. We focus our analysis on the comparison between the carbon cycle and climate dynamics as described by DICE2016R2 and FaIR-Geoffroy. The FaIR carbon cycle model is discretized following a similar approach as suggested by Faulwasser *et al* (2018). The adjustment of the DICE carbon cycle model from 5 to 1 year timesteps has been carried out by recalculating or recalibrating the parameters (see SI1 in the supplementary material, available online at stacks.iop.org/ERL/16/104042/mmedia). The former provides an identical solution for initial value or pulse emissions, the latter is sensitive to the emissions scenario (i.e. calibrating against a business-as-usual scenario results in different parameters compared to a calibration against an optimal climate policy). We focus on the recalculated parameter values as these are more appropriate in examining low emission scenarios since the recalibration was done as in the original DICE calibration against a business-as-usual emissions path. The indicative example of CBA derived climate policies as presented in the introduction is based on the recalculated parameter values. The full results of the CBA climate policies, on recalculated and recalibrated parametrizations, can be found in SI3.

To ensure comparability, we carried out an historical spin-up, starting in the year 1765, with and without non-CO₂-forcing (see SI2), using this information (a) to calibrate the initial values for FaIR-Geoffroy in 2015 to match the initial values of DICE when implementing the CBA emissions paths and (b) to determine the initial values for 2015 in the CO₂-only analysis for all specifications of carbon cycle and climate dynamics. Accordingly, in all investigated scenarios, the different carbon and climate models have identical initial values for atmospheric carbon concentration and mixed- and deep layer temperature.

Before calculating optimal overshoot scenarios, we demonstrate the different characteristics of the carbon cycle and climate dynamics by comparing zero emission commitments (ZECs) for different scenarios. ZEC is defined as the simulated temperature change after cessation of CO₂ emissions. We use three versions of DICE, DICE2016R2 (D16), DICE2013 (D13), DICE2007 (D07), and the FaIR-Geoffroy model to perform two types of simulations: (a) abrupt cessation of emissions following the consumption of the 1.5 °C CO₂ budget and (b) emissions following the bell-shaped scenario B1 from the zero-emission commitment model intercomparison project (ZECMIP, Jones *et al* 2019). In the first type of simulations, CO₂ emissions follow RPC8.5 emissions from 2015 onward, until cumulative emissions since 2018 have reached 420 GtCO₂ in 2026. Then, CO₂ emissions are abruptly stopped. Cumulative CO₂-emissions of 420 GtCO₂ correspond to the IPCC

SR15 estimate for limiting global mean surface temperature increase to 1.5 °C with a 66% probability (2018). We do not include other forcings than CO₂ in these simulations. In the second type of simulations, the ZECMIP B1 experiment prescribes a bell-shaped emissions pathway with cumulative emissions of 1000 GtC over 100 years, followed by 100 years of zero emissions, starting at preindustrial conditions. SI4 lists the results for other ZECMIP scenarios (i.e. B2 and B3).

For the analysis of overshoot scenarios, we include CDR as an additional control variable. Our implementation can be thought of as representing direct air capture of CO₂ with permanent geological storage, implying that carbon sinks are not manipulated as would be the case for many proposed ocean or terrestrial CDR methods (Keller *et al* 2018). Following Rickels *et al* (2018), we assume that annual operational costs for CDR, $C(\text{CDR})$, measured in trillion USD, are described by a linear-quadratic function:

$$C(\text{CDR}) = c_1 * \text{CDR} + c_2 * \text{CDR}^2, \quad (1)$$

where CDR is measured in GtCO₂yr⁻¹ with $c_1 = 50 \times 10^{-3}$ trillion USD/GtCO₂ and c_2 is either 6.5×10^{-3} , 12×10^{-3} , or 17.5×10^{-3} trillion USD/(GtCO₂)². The parameter c_2 has been calibrated such that marginal cost, i.e. $c_1 + 2c_2 * \text{CDR}$, are either 180, 290, or 400 USD/tCO₂ at an annual removal of 10 GtCO₂, reflecting a low, medium, and high cost scenario, following the marginal cost curve estimates in Goldman Sachs Research (2020). The CDR costs reduce gross output in the DICE model. The abatement cost function in DICE is augmented so that maximum abatement is 100% (i.e. $\mu \leq 1$) while the original DICE specification allows beyond 2100 abatement to become larger than 100% (net negative emissions) which we model by including CDR explicitly. For further details see SI6.

The optimization is carried out under the standard DICE assumptions with respect to the exogenous change in carbon intensity, total factor productivity, costs of backstop technologies, and population growth, except that we exclude external non-CO₂-forcing and external land-use emissions to focus on industrial CO₂ emissions, which is a control variable. We impose a ceiling on global mean surface temperature of 1.3 °C and increase the first year from which this ceiling becomes binding (ranging from 2015 to 2150) while the entire modelling horizon extends until 2300. One can interpret the analysis in the context of the 1.5 °C target, implicitly assuming a rather strong contribution of non-CO₂ warming since the temperature increase is calculated against the reference year 1765 and not against the average temperature between 1850 until 1900. Note that reference non-CO₂ temperature contribution in the calculations for the remaining carbon budgets with FaIR in IPCC SR15 is only 0.13 °C.

Finally, we demonstrate the implications of the rather unrealistic temperature response in DICE2016R by implementing the overshoot emissions pathways obtained in DICE into FaIR-Geoffroy. More specifically, the emissions pathways are derived under a climate policy with a temperature ceiling of 1.3 °C from 2100 onward with parameter uncertainty about the CDR costs (uniform distribution over the range from low to high CDR cost). We increased the marginal cost at 10GtCO₂ stepwise by 2 USD (from 180 to 400 USD) having 110 scenarios overall for which we calculate the optimal climate policies in terms of gross emissions and CDR. However, we implement only the CO₂ emissions into FaIR-Geoffroy and ignore the optimal amount of CDR deployment (as it is part of optimal overshoot climate policy in DICE2016). We obtained from these 110 scenarios the outcome in FaIR-DICE by implementing the gross emissions only (i.e. CDR = 0) via bootstrapping with replacement and $N = 10\,000$. The probability estimate has been obtained via the empirical distribution.

3. Results

The effect of the rather sluggish temperature response and underestimation of carbon sinks in the most recent version of DICE is demonstrated in figure 1: In the simulation where emissions abruptly cease following the consumption of the 1.5 °C CO₂ budget (figure 1, upper panels), all DICE calibrations underestimate the initial carbon uptake by sinks before emissions cease compared to FaIR as a reference. While the calibrations in D07 and D13 imply that the carbon sink in the long run during the zero-emission phase is overestimated, the D16 calibration implies that it is underestimated. According to D07 and D13, atmospheric carbon concentration falls below 2015 levels 25 and 33 years after cessation of emissions, respectively. According to FaIR-Geoffroy, falling below 2015 levels does not happen before 50 years after emissions cessation, and according to D16 it does not happen at all until 2200 (panel a). The underestimation of the carbon sink in D16 is aggravated by a sluggish temperature response and temperature increase exceeds 1.5 °C even without non-CO₂ GHG forcing.

In the second type of simulations, where emissions follow the bell-shaped curves B1 from ZECMIP (figure 1, lower panels), the temperature changes 50 years after emissions ceased (ZEC50) is 0.42 °C, −0.13 °C, −0.27 °C, and −0.03 °C for D16, D13, D07, and FaIR-Geoffroy, respectively (figure 1, panel d). In comparison, the multi-model mean for ZEC50 is −0.07 °C with a median of −0.05 °C and an overall range from −0.36 °C to 0.29 °C (albeit obtained from a slightly different simulation, MacDougall *et al* 2020). Results for ZECMIP simulations with emissions of

750 GtC (B2) and 2000 GtC (B3) can be found in SI4.

The FaIR-Geoffroy transient climate response to emissions (TCRE) is approximately constant across the four ZEC scenarios, ranging from 0.42 °C to 0.47 °C per 1000 GtCO₂ (lower TCRE values for higher cumulative emissions). This is well in line with the recent central estimate of Matthew *et al* (2021) who estimated a median TCRE of 0.44 °C (and range of 0.32–0.62 °C for the 0.05 and 0.95 percentiles) and the estimate in AR6 which report a best estimate of 0.45 °C and a likely range of 0.27 °C to 0.63 °C (IPCC 2021). The approximate constancy of TCRE in FaIR-Geoffroy is in line with the behavior of complex ESMs and supports our premise that the FaIR-Geoffroy model can be used as a benchmark for assessing overshoot climate policies obtained in DICE. The central TCRE of the different DICE vintages is higher and sensitive to cumulative emissions: D16: 0.53 °C–0.72 °C, D13: 0.48 °C–0.65 °C, and D07: 0.47 °C–0.62 °C (see SI4).

Focusing on a carbon-only-emission scenario with initial conditions for the year 2015 obtained from a historical spin-up with FaIR-Geoffroy, we analyze overshoot dynamics for a 1.3 °C global temperature ceiling (i.e. temperature target). Figure 2 shows in the upper panel (a1) the CO₂ price in the year 2030 (left axis) and the peak increase in temperature relative to the ceiling (right axis), both in dependence of the year in which the ceiling becomes binding (see SI6.F1 and SI6.F2 for corresponding information regarding DICE2013 and DICE2007). Enforcing early compliance dates, i.e. before 2050 (FaIR-Geoffroy) and 2054 (DICE2016), is equivalent to prescribing a permanent ceiling since temperature overshoot is not part of efficient climate policies in these cases. If compliance dates are postponed beyond these dates, delaying emission abatement and temporarily overshooting the temperature ceiling become efficient in both model versions. For compliance from year 2100 and later, (a) the peak temperature increase above the ceiling ranges from 0.29 °C to 0.44 °C and from 0.31 °C to 0.44 °C for high to low CDR costs and for DICE2016 and FaIR-Geoffroy, respectively (see table SI6.T1).

Underlying these seemingly very similar temperature overshoots are very different climate policies as can be seen from the differences in carbon prices. These reflect the difference in the remaining net carbon budget (middle panel, b1–b3, counted from the year 2015). Delaying compliance from year 2050 to 2100 implies that the 2030 CO₂ price decreases from 291 to 141 on average, and from 139 to 69 USD/tCO₂ on average for DICE2016 and FaIR-Geoffroy, respectively (see table SI6.T2). Accordingly, gross emissions in the first half of the century (2015 until 2049) increase by 114 and 97 GtC and CDR decreases by 64 and 37 GtC for DICE2016 and FaIR-Geoffroy, respectively. In turn, higher abatement and CDR

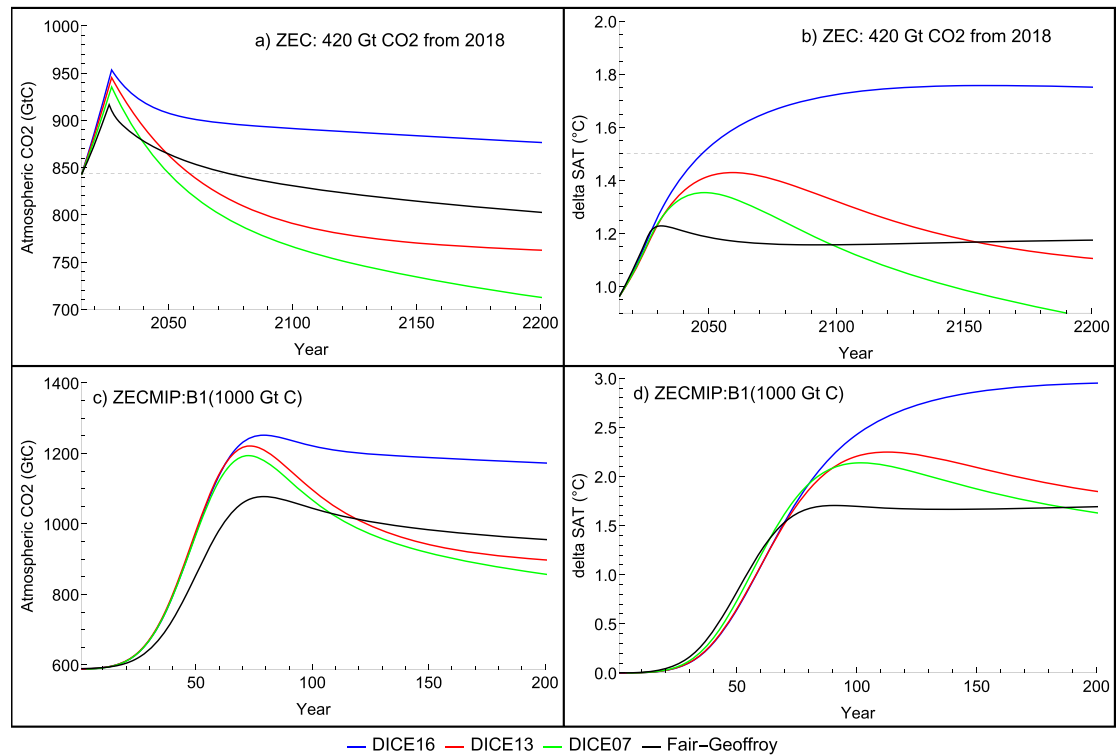


Figure 1. Zero emission commitments for different versions of DICE in comparison to FaIR-Geoffroy. The upper panel shows atmospheric carbon (a) and SAT increase (b) for cessation of emissions in 2026 after cumulative emissions of 420 Gt CO₂ since 2018 have been reached. The lower panel shows the corresponding information for a bell-shaped emission path with cumulative emissions of 1000 Gt C, starting at preindustrial conditions (ZECMIP:B1). Both panels show the CO₂-only responses, forcing of other non-CO₂-gases is not included.

deployment after 2049 is required. Gross emissions in the second half of the century decline on average by 119 GtC and 35 GtC and CDR increases by 174 and 87 GtC for DICE2016 and FaIR-Geoffroy, respectively (see figures 2, panel (b1)–(b3) and tables SI6.T3(a)–(f)).

However, allowing for a temperature overshoot (i.e. ceiling becomes binding after 2050), carbon prices in efficient climate policies do not monotonically increase towards compliance date. For example, with compliance from 2100 onward, DICE2016 results in average CO₂ prices of 141 USD/tCO₂ in 2030 which increase to 320 USD/tCO₂ in 2050, but then decreases to 133 USD/tCO₂ in 2100 (see table SI6.T2). The reason is the inertia of carbon cycle and climate dynamics in DICE2016 (figure 1), requiring sooner a deep reduction in net emissions to achieve temperature compliance by the year 2100 and hence the high CO₂ prices in 2050. The lower panel of figure 2 shows for medium CDR costs that in the DICE carbon and climate model, the temperature overshoot before compliance is followed by a temperature undershoot after compliance (figure 2, c1). Obviously, the effect is more pronounced for a ceiling becoming binding in the year 2150 compared to 2100 while there is no overshoot and in turn undershoot if the ceiling is binding from the year 2050 onward. These effects are less pronounced in FaIR-Geoffroy (which shows in contrast to DICE2016 a

declining long-term atmospheric carbon concentration because of saturation effects). These overshoot-undershoot dynamics are quantified in the upper panel of figures 2(a2) and (a3), which shows temperatures 10 years before and 10 years after the ceiling has become binding in dependence of compliance date, here for the low CDR cost scenario. We have coined these dynamics as the ‘Dive’. With DICE2016, the ‘Dive’, amounts to -0.31 °C and up to -0.79 °C for the temperature ceiling becoming binding in year 2100 and 2150, respectively. FaIR-Geoffroy results in smoother landing (-0.24 °C and -0.47 °C for compliance to be reached from 2100 and 2150 onward, respectively) with almost no undershoot (see table SI6.T1, figures SI6.F3 and SI6.F4).

These dynamics towards compliance date reflect that the ceiling is imposed as a simple constraint and no (economic) impacts follow from the level of overshoot or the pace at which temperatures increase or decrease. Accordingly, social welfare (i.e. discounted sum of the population-weighted utility of per capita consumption) is unambiguously increasing with later compliance date in our analysis irrespective of the specification of the carbon cycle and climate dynamics (see figure SI6.F5).

The underestimation of the carbon sink capacity in DICE2016 compared to FaIR-Geoffroy (net emissions until 2200 for compliance in 2100 are -8 and 202 GtC, respectively) implies that DICE2016

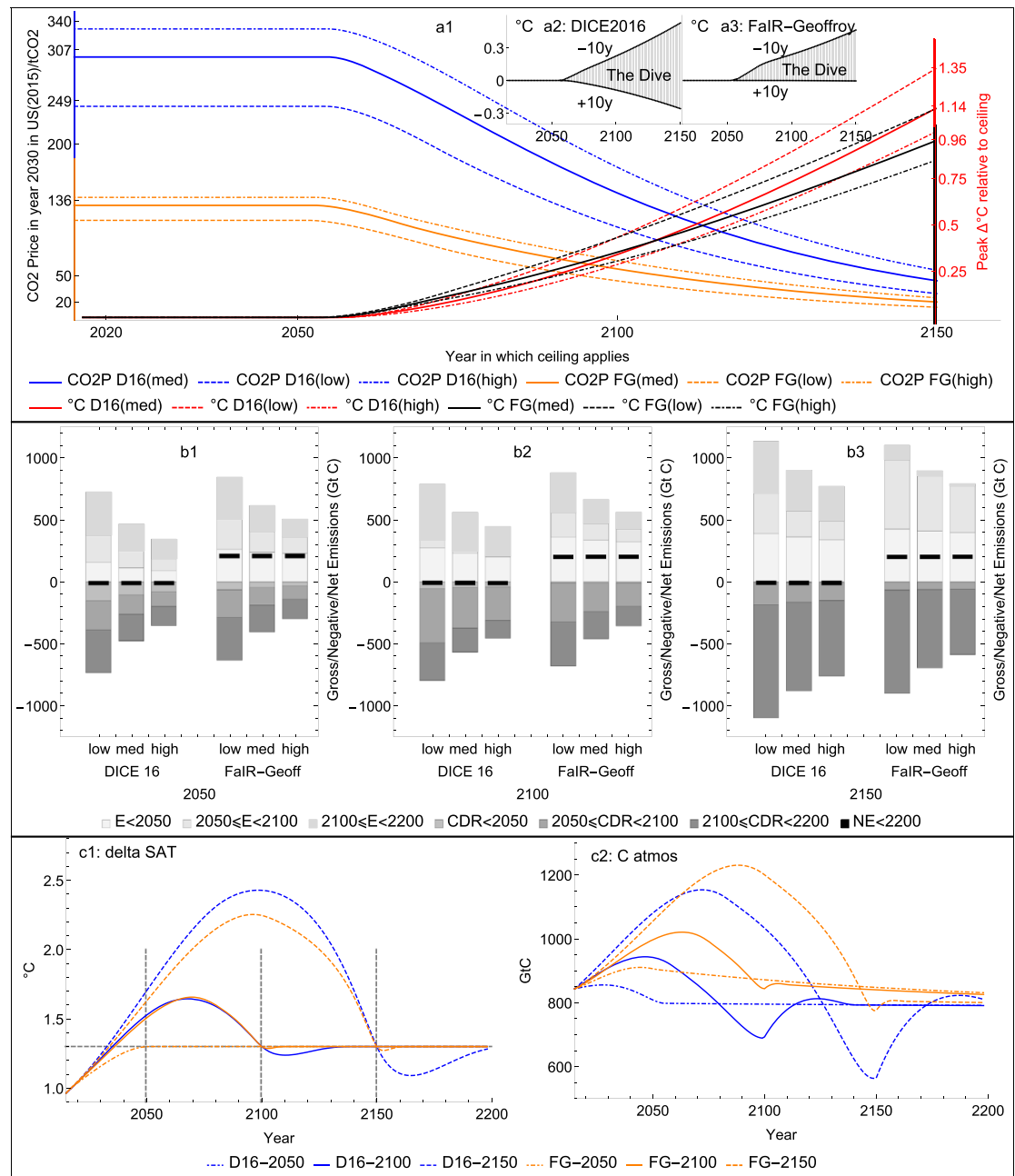
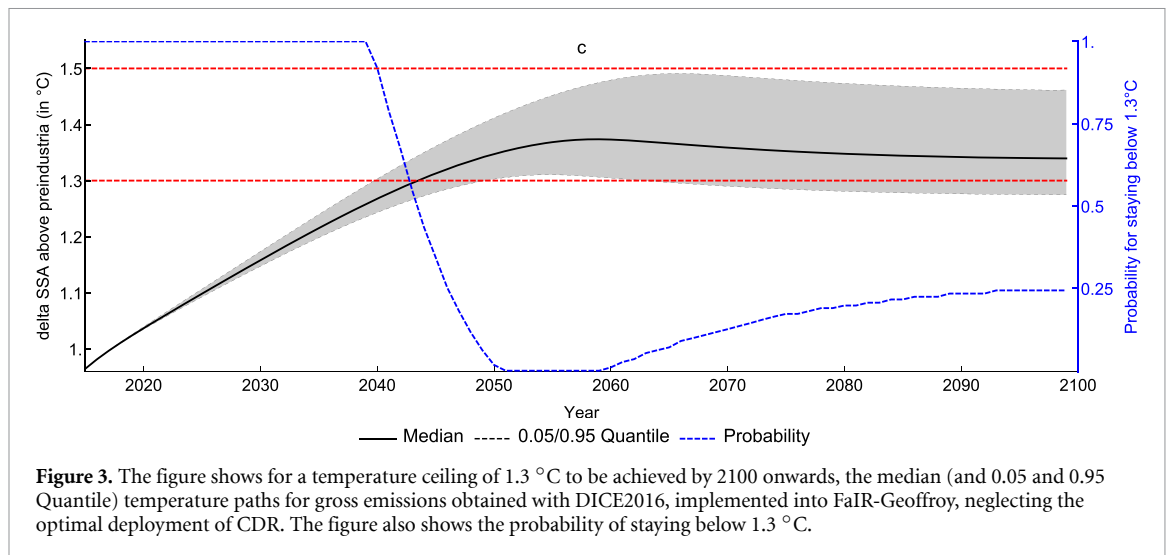


Figure 2. Implications of optimal overshoot climate policies. The upper panel shows the CO₂-price in the year 2030 and how much temperature increases above the temperature ceiling, both in dependence of the compliance date (a1); (a2) and (a3) show the 'Dive', i.e. the temperature difference to ceiling 10 years before and 10 years after the ceiling has become binding, again in dependence of compliance date, here for the low CDR cost scenario. The middle panel shows the distribution of gross emissions, CDR, and net emissions for three selected compliance dates, 2050 (b1), 2100 (b2), and 2150 (b3). The lower panel shows the profile of SAT temperature and atmospheric CO₂ for a ceiling of 1.3 °C with compliance in 2050, 2100, and 2150 for medium CDR costs. All information are provided for both specifications for the carbon cycle and climate dynamics, DICE2016 (D16) and FaIR-Geoffroy (FG).

physically requires CDR to achieve compliance while under FaIR-Geoffroy compliance without CDR would be feasible but not efficient. Without CDR the carbon price in the year 2030 is about 170 USD/tCO₂ (172 USD/tCO₂ for compliance by 2050 and 169 USD/tCO₂ for compliance by 2100) under FaIR-Geoffroy. This is considerably higher than the carbon prices with CDR which are even in the high

CDR cost scenario 139USD/tCO₂ and 67 USD/tCO₂ for compliance in 2050 and 2100, respectively. However, in climate policies without CDR compliance against the temperature ceiling is achieved basically without overshoot compared to climate policies with CDR.

The underestimation of the carbon sink capacity in DICE2016 also implies the optimal amount



of gross emissions is under- and the optimal amount of CDR is overestimated compared to FaIR-Geoffroy. This can be demonstrated as explained in the opening CBA illustrative example by implementing the optimal DICE2016 policies as emissions scenarios into FaIR-Geoffroy. Figure 3 shows the CO₂-only temperature pathway obtained from implementing the optimal gross CO₂ emissions obtained with DICE2016 into FaIR-Geoffroy. The emission pathways are derived under a climate policy with a temperature ceiling of 1.3 °C from 2100 onward with parameter uncertainty about the CDR costs (uniform distribution over the range from low to high CDR cost). However, we implement only the CO₂ emissions but no CDR. The scenario-based median temperature pathways have a maximum overshoot of 0.07 °C in 2060 (considering the time horizon until the year 2100) and there is almost 25% chance of staying below 1.3 °C by the end of the century (which is our proxy for the 1.5 °C target in the absence of non-CO₂ forcings). Accordingly, the inertia of the carbon cycle and climate dynamics in DICE2016 suggest optimal CO₂ prices which result in relatively precautionary overshoot climate policies (using instead DICE2013 or DICE2007, the ceiling of 1.3 °C is unambiguously exceeded, see SI7).

4. Discussion

In this study, we have neglected non-CO₂-forcings and consider CO₂-only temperature targets. Obviously, the development of warming non-CO₂-GHG and cooling aerosol emissions is crucial for the remaining emission budget and the possible temperature paths towards a temperature target (e.g. Kriegler *et al* 2018, Tanaka *et al* 2021). Here, we focus on CO₂-only temperature dynamics to show the difference in the balance between thermal inertia, carbon sinks and carbon removal between climate-carbon cycle models in DICE and FaIR-Geoffroy. Having non-zero

trajectories for non-CO₂-forcing would partly cover the CO₂-only temperature dynamics.

Furthermore, we have neglected any impacts (damages) from the level or the rate of temperature change and simply impose the temperature ceiling as pure constraint. Including such costs would reduce the level of the overshoot and the ‘dive’, i.e. implying a smoother approaching of the temperature ceiling. However, there is still considerable uncertainty about the monetary impacts of climate change (Tol 2018). Accordingly, a sophisticated treatment of the question in how far temperature overshoots would be limited by the associated impacts of the temperature increase in levels would have required to include a comprehensive set of impact functions. Using for example an economic impact function which accounts for impacts on economic growth (e.g. Moore and Diaz 2015) can be expected to result in smaller overshoots compared to using the original DICE impact specification. A few studies consider the impacts of rate of temperature change in integrated assessment models (see for a recent approach Michaelis and Wirths 2020), however, while already estimates on the impacts of temperature levels are poorly constraint, this is even worse for the impacts of the rate in temperature change. Accordingly, investigating the implications of the rate in temperature change requires a treatment on its own and inclusion of a somewhat arbitrary impact function would have blurred the limitations arising for overshoot scenarios from the carbon cycle and climate dynamics.

However, neglecting economic impacts of temperature (i.e. no damage function), the carbon prices reported in section 3 should not be confused with the social cost of carbon but measure the marginal abatement costs associated with the target under consideration. They could be interpreted as the required willingness to pay for imposing such a goal (Rogelj *et al* 2018). Accordingly, the absolute carbon price levels reported in section 3 are dependent from the

assumptions on exogenous technological progress with respect to carbon intensity and abatement technologies (backstop price) in the DICE model. However, as we use for all specifications of carbon cycle and climate dynamics the same economic module, the difference in carbon prices presented here can be interpreted. Furthermore, we have restricted CDR to methods with geological storage (in particular representing direct air capture with carbon storage, DACCS) while achieving ambitious temperature targets like the 1.5 °C goal is considered to require the full range of CDR methods (IPCC *et al* 2018, Rickels *et al* 2019), including also ecosystem-based methods like for example afforestation. Such methods which enhance the natural sinks are by themselves affected by temperature overshoots (Melnikova *et al* 2021) and in turn require a more detailed investigation for which our analysis provides important input.

5. Summary and conclusions

Compliance with the 1.5 °C target without temporary overshoot appears increasingly unlikely, implying that the temperature target is achieved from above, i.e. after a period of falling temperatures. We investigate climate policies with temperature overshoot in dependence of the compliance date. We focus in particular on implications of carbon cycle and climate dynamics and restrict our analysis to CO₂-only temperature increases by considering the non-CO₂ warming contribution to be exogenous. We analyze climate policies with respect to global emissions abatement and CDR deployment using the most recent DICE model and a version of DICE amended with the carbon cycle and climate dynamics represented by the FaIR-Geoffroy model. In both specifications, a compliance date around the middle of the century is equivalent to a permanent ceiling (i.e. it is not optimal to overshoot the temperature target). For compliance dates beyond 2050 (FaIR-Geoffroy) and 2054 (DICE2016) the peak temperature of the overshoot is increasing with the later compliance date. While the temperature overshoot dynamics look surprisingly similar on the first view, modelled temperature changes in DICE provide only a poor proxy for 'real' temperature changes and the underlying development of atmospheric carbon concentration. Hence, abatement and CDR policy differ considerable across the two model specifications. Optimal carbon prices are twice as high if the original DICE model is used compared to DICE/FaIR-Geoffroy. The inertia of the carbon cycle and climate dynamics in DICE2016 suggest optimal CO₂ prices which result in relatively strict climate policies for exogenous temperature targets. However, the dynamics towards the temperature ceiling with cooling following the overshoot, and undershoots of the temperature target clearly show that further research needs to improve our understanding of and accounting for

the (limited) reversibility of vulnerable Earth system components (permafrost, high latitude ecosystems, Greenland Ice Sheet, Atlantic Meridional Overturning Circulation, etc), and also the need to develop research on the impacts that the rate of climate change might exert, to derive meaningful overshoot climate policies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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