DICE and the carbon budget for ambitious climate targets

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Abstract

The DICE model is one of the most influential Integrated Assessment Models available. Its founder Professor William Nordhaus was recently awarded Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel due to his pioneering work on the economics of climate change. In a recent paper in *American Economic Journal: Economic Policy* Nordhaus uses the model to conclude that a 2.5°C target is almost out of reach. In this paper we update DICE 2016 R2 with state-of-the art models of the carbon cycle, heat uptake into the oceans and the role of non-CO_2 forcers. We find that the allowable remaining carbon budget (over the period 2015-2100) to meet a 2.5°C target to be 2360 $GtCO_2$ whereas the estimate obtained using DICE 2016 R2 is about 460 $GtCO_2$. Nordhaus's estimate of the remaining carbon budget for this target is hence five times lower than estimates made by our recalibrated version of DICE. We also compare our results with estimates by the Intergovernmental Panel on Climate Change (IPCC) and find our results to be in line with the carbon budgets presented in IPCC SR 1.5. We explain the reasons behind the difference between our result and that of Nordhaus and propose that an updated climate module in DICE is warranted.

Supplementary Information: DICE and the carbon budget for ambitious climate targets

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Supplementary information

Here we describe the changes we made to the carbon cycle, the energy balance model and the radiative forcing scenario from non-CO_2 forcers in DICE 2016R2. For all model runs the DICE 2016R2 model implemented in GAMS dated August 2017 was used (file name DICE-2016R2-083017.gms downloaded at https://sites.google.com/site/williamdnordhaus/dice-rice 2019-02-07).

SI 1. Impulse response of the carbon cycle

In figure SI 1 we compare the impulse response to a pulse emissions of CO2 in DICE 2016 2R to the pulse response used for calcluating Global Warming Potentials (GWP) in IPCC AR5 (Myhre et al, 2013). The Impule response used in IPCC AR5 chacterizes the impulse response close to present days concentrations and is the basis for the carbon cycle in the FAIR model. As can be seen in the figure, a substantially larger fraction of a CO_2 pulse emission stays in the atmosphere for the carbon cycle in DICE 2016 R2 than in the carbon cycle in IPCC AR5. However, it must be kept in mind that the carbon cycle is non-linear and the removal rate decreases with increasing atmospheric concentrations (which is considered in the revised carbon cycle, but not in DICE-2016R2). The impulse response in DICE-2016R2 is likely to be representable for far higher concentration than those compatible with keeping the global mean surface temperature at or below 2.5 °C above the pre-industrial level.

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Figure SI 1. Impulse response to CO_2 emissions obtained from the carbon cycle used in DICE compared to the one used in IPCC AR5 for metric calculations.

SI 2. The energy balance model in DICE

In figure SI 2 we compare the Energy Balance Model (EBM) in DICE 2016 2R with the response in state of the art climate system models (based on Geoffroy et (2013) and it is this EBM that we have used when we recalibrated the DICE model). The forcing step is 1 W/m^2 in both models. For both versions of the EBM we assume that the climate sensitivity is equal to 3.1 °C for a CO_2 doubling. As is seen in the figure, the temperature response in DICE 2016 R2 to a forcing step is slower in the short term, but relatively faster in the long term (after 50 years and onwards) and approaches the equilibrium level faster than the EBM calibrated to CMIP5 climate system models. This has, as was shown in main text, large implications for the the emissions space of CO_2compatible with 2 & 2.5°C warming targets.

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Figure SI 2. Temperature response for a 1 W/m2 forcing step using the energy balance model in DICE as well an energy balance model calibrated to emulate global climate system models (average of CMIP 5).

SI 3. Non-CO_2 forcing

The non-CO_2 forcing assumption in DICE is substantially higher than in other scenarios that analyse CO_2 (or greenhouse gas) emission pathways consistent with 2°C or 2.5°C warming. In figure SI 3 we show the non-CO_2 forcing assumption in DICE 2016 R2 as well as our recalibrated version of DICE compared to the non-CO_2 forcing in RCP 2.6 and 4.5 as presented in Meinshausen et al (2011).

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Figure SI 3. Non-CO_2 forcing in RCP 2.6 (blue dashed line) and RCP 4.5 (grey dashed line) and the non-CO_2 forcing in the original DICE version (black line) and the recalibrated version (red line).

SI4. Additional updates to DICE

In addition to the changes described above we made some additional minor changes. 1) We excluded the possibility to have negative CO_2 emissions in both DICE 2016R2 and in our recalibrated version (in DICE 2016R2 negative CO_2emissions are allowed beyond 2160). This was made in order to avoid that larger emissions during the 21st century can be compensated by negative emissions at later years in the model. This only has a minor impact on the results. 2) We also set damage estimates to zero in both DICE 29016R2 and our modified version since we are in this paper only interested in pathways for different stabilization targets and not in the damage estimates. This change has only a minor impact on CO_2 emissions pathway towards stabilization at 2.5°C or less.

SI5. Additional results

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Figure SI 4. Cumulative CO_2 emissions over the period 2015-2100 in DICE-2016 R2, the recalibrated version for different stabilization targets compared to estimated cumulative emissions for different stabilization levels and probabilities as presented in IPCC SR 1.5.

In figure SI4 we present the cumulative emission budgets using DICE 2016 R2 for the 2.5°C target and compare that with the cumulative emission budget for the same temperature target using the recalibrated DICE model. We also use the recalibrated DICE model to estimate the carbon budget for the 2°C target and compare that with the IPCC SR 1.5 estimate (assuming a 50% probability of meeting the target). It shows that our recalibrated DICE model gives results that are in line with the IPCC estimate. In the same figure we also show the carbon budget from IPCC SR 1.5 for the 2°C target assuming a 67% probability of meeting the target and the 1.5°C (assuming a 50% probability of meeting the target). It may be noted that the DICE 2016 R2 carbon budget for meeting the 2.5°C is lower than the IPCC SR 1.5 estimate for the carbon budget for the 1.5°C target.

The CO_2 emission budgets presented in figure SI4 for the IPCC cases are from table 2.2 in IPCC SR1.5 (Rogelj et al, 2018). These budgets refer to the period 2018 and onwards, while we present budgets for the period 2015-2100. Thus, we have added an estimated 120 $GtCO_2$ to the IPCC budget in order to include the emissions that took place over the period 2015-2017.

Finally, we compare our estimated temperature to the average temperature during the period 1850-1900 when assessing the temperature stabilization targets. This is done in order to ensure comparability with the approach taken in DICE 2016 R2 where the surface temperature level is given in relation to the level in the year 1900. Further, the estimates of cumulative CO_2 emissions compatible with different stabilization levels presented in IPCC SR 1.5 are based on temperature anomalies relative to the estimated global annual average surface temperature over the period 1850-1900 (Rogelj et al, 2018).

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Three key points of research:

- We use the DICE model, one of the most commonly used Integrated Assessment Models, to estimate the available carbon budget for meeting Paris styled temperature targets.
- We find that the available carbon budget is a factor of five lower than IPCC's estimates for the same temperature target.
- We then update DICE using state-of-the art models of the carbon cycle and the heat uptake in the oceans. This recalibration of DICE is used to explain why DICE estimates are off by a factor of five for ambitious climate targets, and we recommend that the next version of DICE is updated reflecting these features.

Abstract:

The DICE model is one of the most influential Integrated Assessment Models available. Its founder Professor William Nordhaus was recently awarded Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel due to his pioneering work on the economics of climate change. In a recent paper in *American Economic Journal: Economic Policy* Nordhaus uses the model to conclude that a 2.5°C target is almost out of reach. In this paper we update DICE 2016 R2 with state-of-the art models of the carbon cycle, heat uptake into the oceans and the role of non-CO_2 forcers. We find that the allowable remaining carbon budget (over the period 2015-2100) to meet a 2.5°C target to be 2360 $GtCO_2$ whereas the estimate obtained using DICE 2016 R2 is about 460 $GtCO_2$. Nordhaus's estimate of the remaining carbon budget for this target is hence five times lower than estimates made by our recalibrated version of DICE. We also compare our results with estimates by the Intergovernmental Panel on Climate Change (IPCC) and find our results to be in line with the carbon budgets presented in IPCC SR 1.5. We explain the reasons behind the difference between our result and that of Nordhaus and propose that an updated climate module in DICE is warranted.

Keywords: Climate stabilization, integrated assessment models, emission pathways, DICE.

1. Introduction

Professor William Nordhaus was in December 2018 awarded the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel due to his pioneering work on the economics of climate change. A substantial part of Professor Nordhaus's research in this field has been to develop and continuously improve the Dynamic Integrated Climate-Economy (DICE) model. The DICE model pioneered the field when it was first presented in early 1990s (Nordhaus, 1992, 1994), and it is still highly influential within the field of the economics of climate change.

In a recent paper in *American Economic Journal: Economic Policy* Nordhaus presents results from the most recent update of DICE, version 2016R2 (Nordhaus, 2018a). Among a range of results presented in the paper, he finds that "the international target for climate change with a limit of 2°C appears to be infeasible with reasonably accessible technologies even with very ambitious abatement strategies. This is so because of the inertia of the climate system, of rapid projected economic growth in the near term, and of revisions in several elements of the model. A target of 2.5°C is technically feasible but would require extreme and virtually universal global policy measures in the near future."

Reaching ambitious temperature requires strong and internationally coordinated climate policies. However, in this paper we find that reaching such climate targets is likely much easier than what Nordhaus concludes from running DICE. The reason for this is that DICE 2016 R2, his most recent version of the DICE model, significantly underestimates the allowable emission space for carbon dioxide emissions when it comes to reaching temperature targets in the range 1.5-2.5°C.

The recent special report "Global Warming of 1.5 °C" by the Intergovernmental Panel on Climate Change (Rogelj et al 2018), finds significantly higher carbon emission trajectories towards these low temperature targets, and even concludes that “limit global warming to 1.5°C with no or limited overshoot “ is not necessarily out of reach. They also provide emissions, energy and land use scenarios generated by Integrated Assessment Models that reach a stabilization at around 1.5°C above the pre-industrial level.

The aim of this this short note is to (i) to recalibrate and update some key features of the physical aspects of the DICE and (ii) use this updated version of DICE to generate estimates of the allowable carbon budget to meet Paris styled temperature targets, and (iii) explain why the most recent version of the DICE model (version 2016R2) generates so low estimates of the allowable carbon budgets for ambitious climate targets compared to the IPCC SR 1.5 report.

In short, we have identified three reasons explaining why DICE generates this low carbon budget for stringent climate targets. The first is related to the carbon cycle, the second to the inertia of the climate system (basically the heat uptake by the oceans) and, the third to the assumed exogenous trajectory for the radiating forcing from non-CO_2 climate forcers.

In several earlier studies the geophysical module in DICE has been analysed or modified, see for example Azar & Sterner (1996), Joos et al, (1999), van Vuuren et al (2011), Glotter et al (2014), Su et al (2017), Faulwasser et al (2018), Rickels et al (2018), Dietz et al (2020), Hänsel et al (2020) and Johansson et al (2020), but none has explicitly analyzed what it means for the remaining cumulative carbon emission budget for a given stabilization target, and none has compared the implications for the most recent version of DICE.

Furthermore, when analyzing which changes in DICE from its 1992 version to its most recent version that had the largest impact on the social cost of carbon and the temperature in the year 2100 in the business as usual scenario, Nordhaus identified changes in the way he represents the carbon cycle as the most important modification (Nordhaus, 2018b). This suggests that further analysis of the way the carbon cycle is modeled is of interest.

2. Methodology

In this note we solely focus on how the geophysical module of DICE matters for emission pathways and cumulative emissions budgets compatible with stabilization targets and leave economic issues, such as finding the optimal climate target, the cost of stabilization and social cost of carbon aside.

The following changes to the DICE model were introduced (see SI for more details):

1. The linearized carbon cycle representation in DICE is changed to the carbon cycle representation in the simple climate model FAIR (Millar, 2017; Smith et al, 2018). The FAIR model was used to assess the climate impact of various emissions pathways in IPCC SPR 1.5 (Rogelj et al, 2018) and it takes into account non-linarites in the carbon cycle as well as climate carbon cycle feedbacks.

   In his article in American Economic Journal, Nordhaus (2018) writes that the 2016 version of DICE "incorporates new research on the carbon cycle. Earlier versions of the DICE model were calibrated to fit the short-run carbon cycle (primarily the first 100 years). Because the new model is in part designed to calculate long-run trends, such as the impacts on the melting of large ice sheets, it was decided to change the calibration to fit the atmospheric retention of CO_2 for periods up to 4,000 years. Based on studies of Archer et al. (2009), the 2016 version of the three-box model does a much better job of simulating the long-run behavior of larger models with full ocean chemistry. This change has a major impact on the long-run carbon concentrations."

Clearly, this improvement over previous versions is worth acknowledging. However, his approach still does not take into account non-linearities in the carbon cycle. This is important since larger fractions of a CO_2 emissions pulse stays in the atmosphere the higher the CO_2 concentration is (Archer, 2009, Caldeira &Kasting, 1993; Maier Reimer & Hasselmann, 1993). In DICE 2016R2 the carbon cycle appears to have been linearized around a relatively high concentration of CO_2. This implies that more carbon stays in the atmosphere (in DICE) for each pulse emissions of CO_2 than in more advanced representations that take this non-linearity into account (for atmospheric CO_2 concentrations compatible with Paris styled temperature targets). As a consequence, the temperature effect of each ton of CO_2 emitted is likely to be too high in DICE2016R2 for concentration levels compatible with a stabilization of global mean surface temperature around 2°C (see SI for more information).

2. The temperature response to changes in radiative forcing in DICE is somewhat at odds with the response in state-of-the art climate system models (see SI for more information). We have thus recalibrated the Energy Balance Model (EBM) so that its parameterization represents the average characteristics of climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Geoffroy et al, 2013). The equilibrium response, i.e. the climate sensitivity, is fine in DICE (being 3.1°C for a doubling of the CO_2 concentration), and it is hence left unchanged.
3. The scenario assumption for the radiative forcing from non-CO_2 climate forcers in DICE is substantially higher than what is estimated in other climate scenario work, e.g., Representative Concentration Pathways (RCP) 2.6 and 4.5 (W/m^2), when analyzing pathways compatible with stabilization of global mean surface temperature around 2-3°C above the pre-industrial level (see SI for more information). The IPCC SR 1.5 states

that "non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions". Hence, abatement of non-CO_2 emissions is critical and economically justified when aiming for stringent climate stabilization levels but in Nordhaus's DICE model they are exogenously given at a somewhat high level. In this modification of the model, we have changed the radiative forcing scenario from non-CO_2 forcers so that it matches an intermediate value of the forcing in the RCPs 2.6 and 4.5 (Meinshausen et al, 2011).

3. Results

In figure 1 we report our main result. We find that the changes described above lead to a substantial increase the CO_2 emissions space for a stabilization of the global mean surface temperature at 2.5°C above the pre-industrial level compared to Nordhaus's finding (2.5°C is basically the lowest stabilization target that can be met in DICE 2016 R2). The cumulative carbon budget between 2015 and 2100 for a 2.5°C stabilization target in DICE 2016 R2 is about 460 $GtCO_2$, while in the recalibrated version it is 2360 $GtCO_2$, i.e., an increase by a roughly a factor of five.

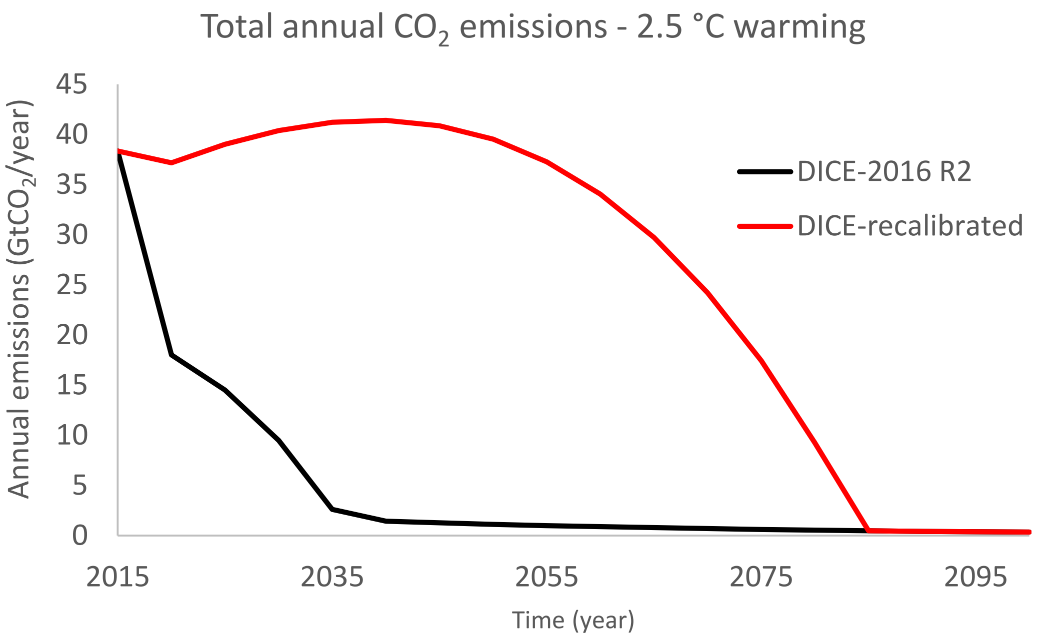

Figure 1. CO_2 emission pathways in DICE for 2016 R2 version as well as for the recalibrated version presented in this paper.

All three changes described above contribute to increase the CO_2 budget for a 2.5°C target. The impact of each change on the emission budget depends on the order with which the changes are implemented in the model due interdependencies between the changes. Changing the carbon cycle increases the CO_2 budget with about 400 to 800 $GtCO_2$, the budget impact of changing the EBM is largely similar to that of the carbon cycle, while changing the non-CO_2 pathway has a slightly larger impact on the cumulative budget.

Furthermore, we estimate the carbon budget for the 2°C target (see figure SI 4). In DICE 2016 R2, this target cannot be met, so no budget is available. In the recalibrated version the cumulative emissions are about 1400 $GtCO_2$ for the period 2015-2100. This is in line with the remaining estimated cumulative CO_2 emissions budget for the 2°C target taken from IPCC SR1.5 where it is 1620 $GtCO_2$ if the target should be met with a 50% chance and 1290 $GtCO_2$ if the target should be met with a 67% chance (Rogelj et al, 2018). Hence, our recalibrated version of DICE gives results in line with IPCC SR1.5 (see SI for further details).

It can be noted that the estimated carbon budget for the 1.5°C target as given in IPCC is higher than the emission budget for the 2.5°C target in DICE 2016 R2. This means that Nordhaus's policy conclusion that pertains to the 2.5°C target is more relevant for the 1.5°C target.

For the 2°C target the estimated budget after 2015 in the recalibrated version of DICE is about three times as large as the budget for a 2.5°C target estimated using DICE 2016 R2.

Finally, we also want to point out that for large cumulative CO_2 emissions, in the order 10 000 $GtCO_2$, the current version of the DICE model gives roughly correct results for the relationship between cumulative emissions and long-run CO_2 concentration. Hence, in a scenario with large cumulative CO_2 emissions the carbon cycle in DICE 2016R2 work well to estimate long-run concentration levels.

4. Conclusion

The DICE model is perhaps the most influential IAM. In this paper we have analysed the geophysical module of the DICE 2016R2 model (Nordhaus 2018). We did that by modifying the carbon cycle, the energy balance model and the assumed radiative forcing from non-CO_2 greenhouse gases and aerosols. We then used this modified DICE model to estimate the carbon budget available to meet the 1.5°C, 2°C and 2.5°C targets (see figure SI

4). Our estimates are compatible with the estimates made by state-of-the art integrated assessment models as reported by the IPCC (Rogelj et al, 2018).

We then compared Nordhaus version (DICE 2016 R2) with our results and found that the estimated carbon budget for a 2.5°C target is five times higher than in DICE. More specifically, in DICE 2016 R2, the carbon emissions associated with the 2.5°C target drops to roughly zero by the year 2040. However, with the modification implemented to the DICE model in this paper, emissions can remain roughly constant to the year 2050 and then fall to around zero by 2085 (see figure 1).

Clearly, this conspicuous difference in carbon emission trajectories has a major impact on the political, economic and technical effort required to meet ambitious temperature targets. For that reason, we believe that caution is required when using DICE 2016 R2 to draw firm conclusions about the feasibility to meet stringent temperature targets. Although meeting the 2°C or 2.5°C targets still require a huge political and technological effort, it is significantly less than what is suggested by the DICE 2016 R2 model.

One reason for the difference in results has to do with how Nordhaus has implemented the carbon cycle in his model. His approach gives a too large atmospheric concentration response for each pulse emission (given CO_2 concentrations compatible with the Paris agreement targets). However, his approach works fine for much higher atmospheric concentrations. For cumulative carbon budgets reaching approximately 10 000 $GtCO_2$, his carbon cycle is better in line with state-of-the art assessments.

Our results suggests that the earth system component of DICE may need to be updated and that such an updated version should be used when assessing the costs and emission trajectories of meeting in particular ambitious climate targets as well as the social cost of carbon. Hänsel et al, 2020, for instance, carry out a number of updates to DICE 2016R2 including those related to the carbon cycle and the energy balance model as well as new assessments of the economic damage related to climate change in an effort to find the economically optimal response to the climate problem.

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