Empirical and Methodological Flaws in Applications of the DICE Model

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1 Introduction

Simple climate-economy models are still being used for climate policy analysis, despite the limitations associated with their lack of regional and process detail. The main argument brought forward in favor of these models is their relative transparency, which should enable researchers to easily interpret the simulation results and adapt the model design to their specific research interests. I investigate to which degree this claim is supported in the case of the DICE (Dynamic Integrated model of Climate and the Economy) model, arguably one of the simplest and most widely used global climate-economy models ever developed.

2 The DICE Model

DICE denotes a family of optimizing global integrated assessment models of climate change. DICE links an optimal economic growth model to a description of anthropogenic climate change with the implied economic impacts. Economic output is described by a constant-returns-to-scale Cobb-Douglas production function with labor and capital as input factors. DICE maximizes a global welfare function (discounted logarithmic utility from consumption) by determining the optimal division of economic output over time into consumption, investment, and emissions abatement (Figure 1). DICE has been revised and extended both by the original model developers and by other scholars. The analysis here focuses on the original DICE-99 model as described by Nordhaus and Boyer (2000) and on the modified version applied by Yohe et al. (2004).

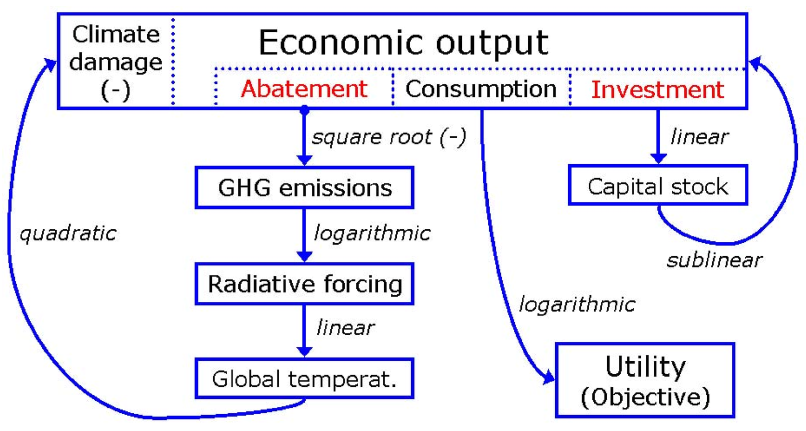

Figure 1: Simplified relationship between key variables in the DICE model (dynamics not considered).

3 Evolution of abatement costs

DICE identifies the 'optimal' climate policy subject to pre-defined constraints by solving an intertemporal optimization problem. One of the key factors affecting the results is the development of emission reductions costs over time. The costs of emissions abatement, expressed as the deviation of actual emissions from an unabated reference emissions scenario, are determined in DICE-99 as

$$\mathrm{Cost}(t) = \mathrm{b}_1(t) \cdot \mu(t)^{2.15} \cdot \mathrm{Y}^*(t)$$

whereby t is the year, $\mathrm{b}_1(t) \in [0,1]$ is a time-dependent abatement cost factor, $\mu(t) \in [0,1]$ is the emission control rate, and $\mathrm{Y}^*(t)$ is the global GDP in the reference scenario.

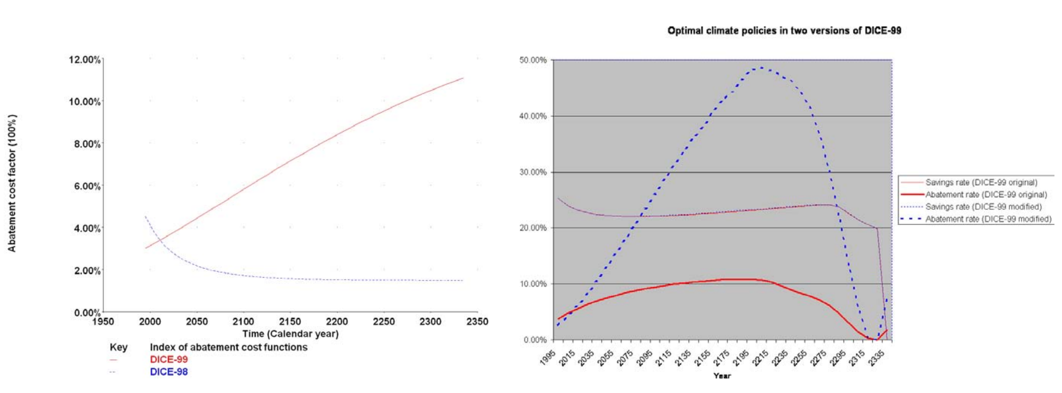

Figure 2: Different abatement cost functions in DICE-98 and DICE-99. *Left:* Evolution of the abatement cost factor, $b_1(t)$, in DICE-98 and DICE-99. *Right:* Optimal climate policies determined by the original DICE-99 model and by a modified version that applies the abatement cost function of DICE-98.

Two versions of DICE-99 are available for download from the main developer's homepage. The Excel implementation of DICE-99 assumes a significant *increase* in the abatement cost factor over time, whereas the GAMS implementation assumes abatement costs to *decrease* (Figure 2, left panel). The GAMS implementation seems to represent an undocumented earlier model version, denoted as DICE-98 here. (DICE-99 and DICE-98 are distinguished not only by their different abatement cost functions.)

The 'optimal' policies determined by the two model versions in a cost-benefit analysis are radically different (Figure 2, right panel). The original DICE-99 model assuming increasing abatement costs calculates much lower emissions abatement rates (thick red curve) than the version applying the decreasing abatement cost function of DICE-98 (thick blue curve). Even stronger differences between the two models are found for the lower discount rates applied in some studies (*e.g.*, Yohe et al., 2004). Since most researchers are not aware of the large differences between the two model implementations, they may unknowingly arrive at very different 'optimal' climate policies depending on whether they use the Excel or GAMS implementation of the model(s) denoted as DICE-99.

4 Different welfare metrics

The ultimate goal of economic analysis of climate policy within the optimal-growth framework is to assess alternative climate policies according to the implicit or explicit preference structure of current decision-makers. This preference structure is represented in the analysis by a scalar welfare function, which is maximized in order to determine the 'optimal' policy strategy. The main welfare metrics that have been used for comparing alternative climate policies are discounted utility of consumption (DU), present value of consumption (PVC), and present value of economic output (PVO), each of which may be calculated based on different time discounting schemes. Analysts often assume that the different welfare metrics are consistent with each other but this is not necessarily the case. The inappropriate use of different welfare metrics may lead to policy conclusions that are not supported by the actual simulation results.

Inconsistent rankings across welfare metrics

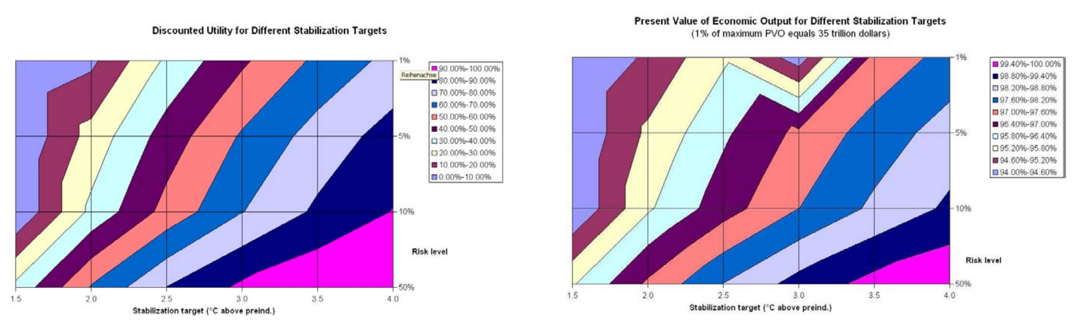

Figure 3: Two different welfare metrics for utility-maximizing policy strategies across different probabilistic climate constraints. *Left:* Discounted utility of consumption (DU). *Right:* Present value of economic output (PVO).

Different welfare metrics may rank alternative policy strategies differently (Figure 3). In one case depicted in Figure 3, the utility-maximizing decision strategy determined for a less stringent climate constraint (3.0 °C, 1% risk) is associated with higher DU (and PVC) but with lower PVO than that for a more stringent constraint (2.5 °C, 1% risk). Analysts may thus overestimate the 'real' costs of meeting a constraint if they calculate these costs as the difference in PVO between the utility-maximizing strategies with and without that constraint (*e.g.*, Yohe et al., 2004). (The direct optimization of PVO in DICE results in an unrealistic 'optimal' policy that is characterized by a savings rate of 100% over the full time horizon, thus having zero consumption and a discounted utility of minus infinity.)

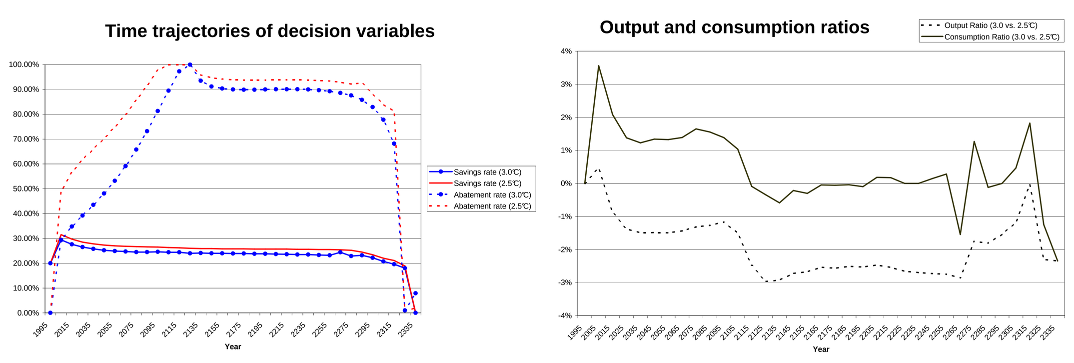

Figure 4: Presumably optimal decision strategies determined by DICE-99 for two probabilistic climate constraints over time. *Left:* Time trajectories of the two decision variables. *Right:* Ratios of economic output and consumption.

Figure 4 shows why DU and PVO rank the (presumably) utility-maximizing strategies for the 3.0 °C and the 2.5 °C constraints differently. The strategy for the 3.0 °C constraint involves lower abatement rates (*i. e.*, higher emissions) and lower savings rates than the strategy for the 2.5 °C constraint (left panel), which leads to generally higher consumption but lower output levels (right panel).

Inappropriate implementation of growth discounting

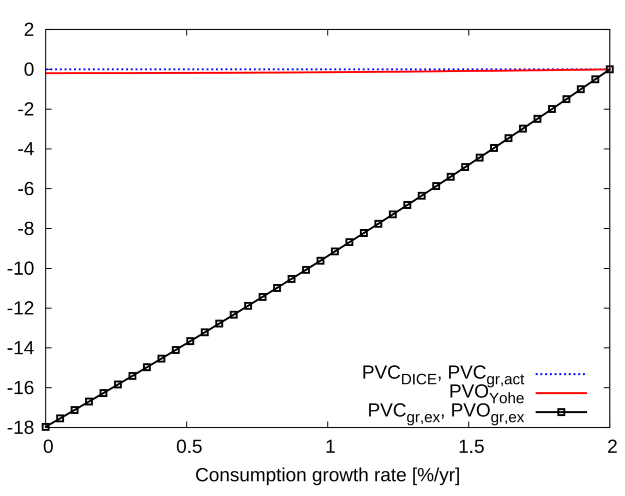

Figure 5: Relative loss of present value 10 years from now for consumption streams growing at 0 to 2%/yr compared to a stream growing at 2%/yr for various discounting schemes applied in monetized welfare functions (see text).

According to the Ramsey growth discounting rule, the discount rate applied to future consumption should equal the sum of the per-capita consumption growth rate and a time preference factor. Monetized welfare metrics applied in connection with DICE-99 have implemented this rule in (at least) three different ways, with large implications for the sensitivity of PVC (or PVO) to differences in future welfare (Figure 5). The large difference in future consumption between alternative policies is adequately reflected only in $\mathrm{PVC}_{\mathrm{gr,ex}}$ (the black curve), which applies the same discounting factors across all alternative policies. The monetary welfare differences are severely underestimated by $\mathrm{PVC}_{\mathrm{DICE}}$ (the blue curve) and $\mathrm{PVO}_{\mathrm{Yohe}}$ (the red curve), which apply different discount factors to different policy alternatives.

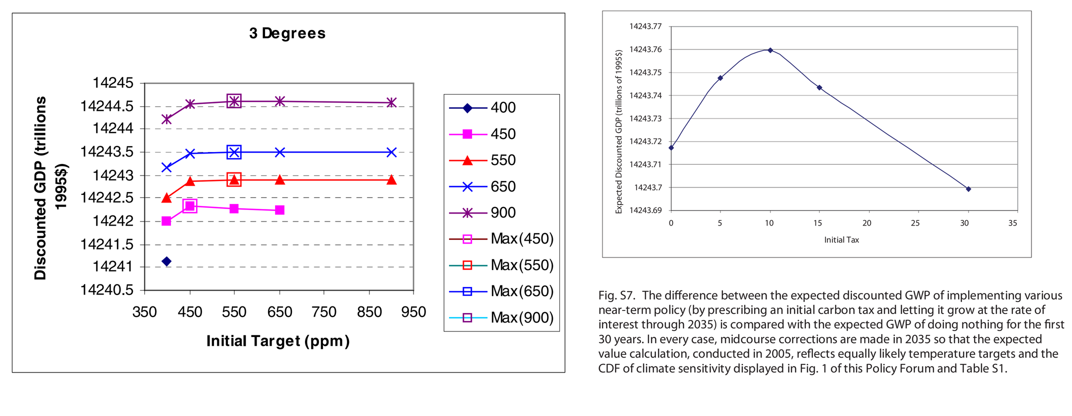

Figure 6: Key results from Yohe et al., 2004. *Left:* Discounted gross world product (GWP), determined according to $\mathrm{PVO}_{\mathrm{Yohe}}$, for a range of greenhouse gas stabilization targets. *Right:* Expected value of discounted GWP for a range of initial carbon tax levels.

Application of $\mathrm{PVO}_{\mathrm{Yohe}}$ in DICE-99 results in cost estimates for greenhouse gas reduction targets that are at least two orders of magnitude smaller than those determined by other modeling studies (Figure 6; by Yohe et al., 2004). The PVO difference between a 450 ppm CO_2 concentration target and a 900 ppm target are only 0.015% (left panel), and the PVO difference between the best and worst inital policy to achieve a specific policy target are a mere 0.0004% (right panel).

5 Calibration of uncertain climate parameters

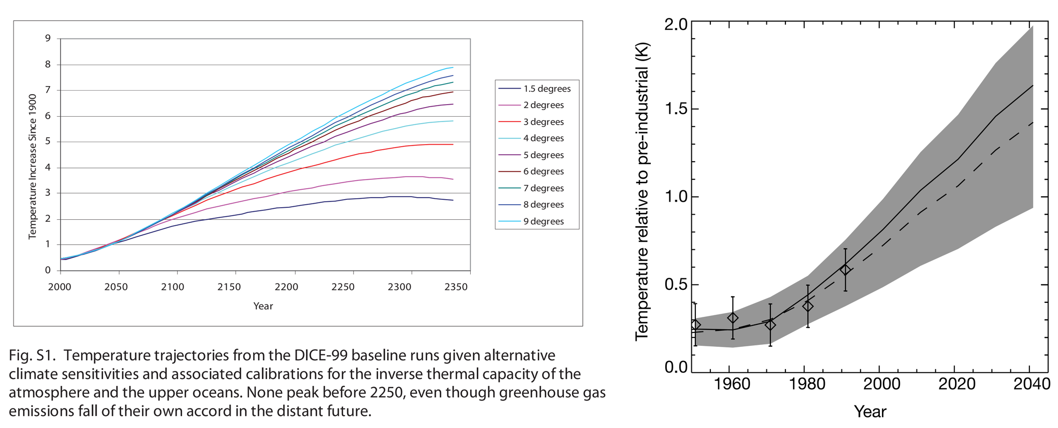

Figure 7: Uncertainty ranges for global mean temperature projections. *Left:* Temperature trajectories until 2335 for the DICE-99 baseline emissions scenario determined for climate sensitivities from 1.5 to 9 °C (Yohe et al., 2004). *Right:* Uncertainty range (5–95% confidence interval) of temperature trajectories until 2040 for the IPCC IS92a emissions scenario based on a comprehensive probabilistic analysis (Allen et al., 2000).

Consideration of the uncertainty about future climate change requires a probabilistic approach. The dominant uncertain parameter determining long-term global mean temperature change is the climate sensitivity (α_2), and the key determinant for transient temperature change in DICE is the inverse thermal capacity of the atmosphere and the upper oceans (α_1). Yohe et al. (2004) assume a deterministic relationship between α_1 and α_2, in which α_2 is "calibrated" within a range of factor 8. This range includes values for the thermal capacity of the atmosphere and the upper oceans that are far outside the physically plausible range. As a result, the true uncertainty about the transient climate response is significantly underestimated (Figure 7). This misrepresentation can significantly affect the policy recommendations in some types of policy analysis.

6 Conclusion

The continued use of simple climate-economy models is often justified by the relative transparency of these models. A reanalysis of various studies with the DICE-99 model has revealed several flaws that clearly question this optimistic assumption.

- Parameterizations of key aspects of the real world, such as the evolution of carbon abatement costs over time, are based on completely different assumptions in two undocumented variants of the (supposedly) same model.
- Social welfare functions have sometimes been specified incorrectly, and different welfare metrics have been combined uncritically in a single analysis. These inconsistencies have lead to wrong estimates of the costs associated with different climate constraints, and to suboptimal policies falsely declared as optimal.
- The inadequate linking of two key uncertain parameters in a probabilistic analysis falsely suggests that uncertainties about future climate change and its impacts will not become relevant before late in the 21^{st} century.

The above flaws in applications of DICE-99 are not only of theoretical interest, they have also strongly affected the policy recommendations drawn from the simulation results. The existence of these flaws is particularly disturbing given that the DICE model has been publicly available for many years, and that it has been used and adapted by many scholars.

Increased efforts of original model developers, other scientists applying and adopting an existing model, and peer reviewers are required to ensure that applications of simple climate-economy models are scientifically sound, and that the policy conclusions drawn from a particular model experiment are actually supported by the simulation results.