EVOLUTION OF MODELING OF THE ECONOMICS OF GLOBAL WARMING: CHANGES IN THE DICE MODEL, 1992-2017

By

William Nordhaus

March 2017

COWLES FOUNDATION DISCUSSION PAPER NO. 2084

COWLES FOUNDATION FOR RESEARCH IN ECONOMICS
YALE UNIVERSITY
Box 208281
New Haven, Connecticut 06520-8281

http://cowles.yale.edu/

Evolution of Modeling of the Economics of Global Warming: Changes in the DICE model, 1992 – 2017

William Nordhaus[1]

March 9, 2017

Abstract

Many areas of the natural and social sciences involve complex systems that link together multiple sectors. Integrated assessment models (IAMs) are approaches that integrate knowledge from two or more domains into a single framework, and these are particularly important for climate change. One of the earliest IAMs for climate change was the DICE/RICE family of models, first published in Nordhaus (1992), with the latest version in Nordhaus (2017, 2017a). A difficulty in assessing IAMs is the inability to use standard statistical tests because of the lack of a probabilistic structure. In the absence of statistical tests, the present study examines the extent of revisions of the DICE model over its quarter-century history. The study find that the major revisions have come primarily from the economic aspects of the model, whereas the environmental changes have been much smaller. Particularly sharp revisions have occurred for global output, damages, and the social cost of carbon. These results indicate that the economic projections are the least precise parts of IAMs and deserve much greater study than has been the case up to now, especially careful studies of long-run economic growth (to 2100 and beyond).

Keywords: Climate change, integrated assessment models, DICE model, revisions

JEL code: Q5, Q54, H4

---

[1] The author is Sterling Professor of Economics at Yale University. The research reported here was supported by the US National Science Foundation Award GEO-1240507 and the US Department of Energy Award DE-SC0005171-001. The author declares that he has no relevant and material financial conflicts with the research described in this paper. Author contact is William.nordhaus@yale.edu [File is DICE-evolution-030917.docx]

I. Introduction

Many areas of the natural and social sciences involve complex systems that link together multiple physical or economic sectors. This is particularly true for climate change, which has strong roots in the natural sciences and requires social and policy sciences to solve in an effective and efficient manner. As understanding progresses across the different fronts, it is increasingly necessary to link together the different areas to develop effective understanding and efficient policies. In this role, integrated assessment analysis and models play a key role. Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework. These are sometimes theoretical but are increasingly involve computerized dynamic models of varying levels of complexity.

One of the earliest IAMs for climate change was the DICE/RICE family of models, developed starting in 1989 and published in Nordhaus (1992, 1994). The DICE (Dynamic Integrated model of Climate and the Economy) and RICE (Regional Integrated model of Climate and the Economy) models have gone through several revisions since their first development. An intermediate version was Nordhaus (2008). The latest published version is DICE-2016R (Nordhaus 2017, 2017a), with a complete description of the penultimate model in Nordhaus and Sztorc (2013). Since the earliest versions, the DICE model has been through many iterations, incorporating more recent economic and scientific findings and updated economic and environmental data.

One of the major shortcomings of IAMs is that their structure makes it extremely difficult to use standard econometric techniques to assess their reliability – a feature that is shared with earth systems models and other large simulation models. In the absence of statistical tests, the present study examines the extent and area of revisions of the DICE model from its earliest publication in 1992 to its latest version published in 2017. This retrospective gives a flavor for changes in the underlying economic and earth sciences, data revisions, correction of mistakes, as well as the pure passage of time. In addition, for those estimates that have included estimated errors in past studies, it is possible to compare the actual revisions with the estimated errors.

Before presenting the details, I will highlight the results. The major revisions in the modeling have come from the economic sectors, whereas the environmental changes have been much smaller. In terms of elementary inputs, future global output was revised upwards massively over the years. Estimates of 2100 global output has been revised up by a factor of 3½ since the 1990 period. The second major revision has been in the damage function, which has been revised upwards by 60%. None of the other major input variables or functions have had anywhere near those levels of revisions. (The reasons for the revisions will be discussed below.)

In terms of major output variables, the major revision occurred for the estimate of the social cost of carbon (SCC). The estimate of the 2015 SCC increased from $5 to $31 per ton of CO_2. As we will see below, this was the results of compounded revisions in driving variables. Most of the environmental variables had relatively small revisions, and ones that were within the estimated error bounds. For example, 2100 temperature increase was originally 3.2 °C and was revised upwards to 4.3 °C in the latest version. Industrial emissions were revised downward slightly over the years.

II. Methods and Results

a. Methods

The approach to determining the impact of revisions was the following. I began with the 1992 GAMS version of the DICE model ("DICE.1.2.3").[2] Fortunately, the 1992 GAMS code was compatible with the 2017 software, so it could be run to duplicate the 1992 results. In the first estimates shown here, I will simply compare the estimates or projections in the two models. In the last section, I will show the sources of the changes.[3]

---

[2] The "1" indicates that it is a one-region model; the "2" that it is the second major version; and the "3" indicates that it uses the third-round estimate of the data. Documentation for this version is contained in Nordhaus (1992a).

[3] It will be instructive to indicate that the task of converting models is not always trivial. The earlier model was in 1989 US dollars at market exchange rates, while the latest model was in 2010 US international dollars. If we look at the US price index for GDP, the ratio of 2010 to 1989 prices is 1.57. However, this is not representative of the world because of the changing composition of output and growth rates of different countries. If we take the ratio of real to nominal GDP for the IMF data for market exchange rates, the ratio is 1.52 for 1985 (the last year with actual data for the 1992 model). The IMF's calculation of the global price level change from 1989 to 2010 is 2.02 for the PPP concept and 1.70 for the MER concept. We have taken a reflator of 2.0 to represent the PPP concept. This adjustment is only important for the first step in the process (v6). For the second step, which adjusts to 2015 levels of output, the reflator becomes irrelevant.

b. Results for 2015

It is useful to examine the results for 2015. These are historical data in the latest version (subject of course to revisions) but are projections in the earliest version. The 1992 version used data from the mid-1980, so the projections to 2015 can be seen as 30-year-ahead forecasts. Table 1 shows the projections and actual values for 2015. The errors were large in many areas. The first column shows the estimates for 2015 in the 1992 model, while the second column shows the estimate for 2015 from the 2017 model, which are actual data. The third numerical column shows the change from 1992 to 2017, which is the forecast error in the 1992 model.

Output and population were underestimated substantially. Emissions and other forcings were overestimated because the rate of decarbonization was underestimate. Concentrations were correctly projected, while temperature was overestimated (as with most earth system models). The largest error was the social cost of carbon (SCC), which was hugely underestimated because the different factors compounded. An interesting note is that the SCC was actually not calculated in the early version of the model and was first introduced in the 2008 version, so estimates of the SCC for early versions are retrospective estimates.

c. Projections for 2100[4]

Table 1 provides a guide to the errors that arise in IAMs like the DICE model, and it also shows how model histories can track errors when models have a sufficiently long history. Table 2 shows the estimated total revisions between 1992 and 2017 for major variables.

The first three columns are similar to those in Table 1. The last two columns show estimated uncertainties (measured as standard deviations) from two studies of uncertainty (Nordhaus 2008, 2017a). The first estimate used the 2008 DICE model and made estimates of uncertainty for several variables. These are shown in the uncertainty column labeled "2008." The second study calculated the standard deviation of the variables using the DICE-2016R model, and are shown as "2017."

The pattern of revisions for 2100 shown in Table 2 is similar to the pattern of errors in Table 1 for 2015. The most striking revision in the driving variables is a massive upward revision in world GDP. A major part of this revision is moving from market exchange rates (common until about 2000) to purchasing power parity exchange rates. A second change is the feature that early versions of the DICE model

[4] We have used the label "2100" in this study. Strictly speaking, the year was 2105 in the DICE model.

as well as other energy-economy models were based on estimates that had a strong stagnationist bias, with sharply falling productivity growth after 2025 (see Nordhaus and Yohe 1983, Table 2.7). Factors driving emissions and forcings, by contrast, were revised downward sharply.

If we look at the bottom group of variables in Table 2, we see an interesting pattern. Emissions, concentrations, and forcings were generally underestimated, but by a relatively small fraction. However, economic variables such as output, damages, and the SCC were massively underestimated. This finding, that the economic variables were the major sources of uncertainty, is one of the most striking results of the current retrospective.

As a final comparison, Table 3 shows the DICE 1992 and 2016R models and compares them with the IPCC reports of approximately the same dates (IPCC 1990, 2014). The first IPCC report had a "business as usual" scenario that is comparable to the DICE model baseline. The fifth report abandoned this approach and instead had representative concentrations pathways, for which the RCP 8.5 is the closest to a business as usual case. Note the upward revision in 2100 temperature in both IPCC and DICE model approaches.

d. Uncertainty estimates

Additionally, it is useful to determine whether estimates of the forecast errors were helpful in understanding the potential forecast errors. Systematic studies of forecast errors using Monte-Carlo-type techniques were undertaken for the 2008 model and the 2016R model. The latter set are more comprehensive but they have the drawback of being retrospective error estimates.

Table 4 shows the "error forecast ratio," which is the ratio of the change in forecasts between 1992 and 2017 relative to the estimated forecast uncertainty (measured as the standard deviation). Conceptually, these are similar to t-ratios although they do not have a formal probabilistic structure. Designate $x_i(m, n)$ as the observation or projection of variable x_i for a future period *m* when estimated at date *n*. Using this notation, the ultimate prediction error in 2100 relative to the 1992 model is $x_i(2100, 2100) - x_i(2100,1992)] = [x_i(2100, 2100)- x_i(2100, 2017)]+ [x_i(2100, 2017)- x_i(2100, 1992)]$. Table 4 shows the second of the two terms. Because this calculation omits the first term, this means that the ultimate error is very likely to be substantially larger than the second term, so the ratio shown in Table 4 is an underestimate of the ultimate error forecast ratio.

Notwithstanding this reservation, note that the largest error ratios are in the order of 1 and occur for temperature, per capita output, output, damages, and the

SCC. These estimates indicate that, while the projection errors to date and in some cases are very large (for example for the SCC), structural estimates of the underlying processes indicate that the uncertainties for variables like the SCC and output are intrinsically also extremely high. So we should not be surprised that output or SCC estimates have been substantially revised, or that there are more major revisions in sight.

III. Decomposition of the changes

A final question is the source of the changes for the projections of different variables with respect to revisions in the model structure and the economic and environmental data. The approach is straightforward in principle but complicated in practice. It involves starting with the earliest version of 1992 and then introducing model and data differences between 1992 and 2017 models one step at a time. We then evaluate the impact on different variables at each step. We can thereby determine how large are the revisions for the important variables, and the sources of the revisions. There is of course some ambiguity in this approach to the extent that there are interdependencies among revisions. However, most of the step-by-step changes come in a natural order, so the results are likely to be insensitive to ordering.

Table 5 shows the adjustments made step by step. We label the changes as being different "versions" marked by *vj*. Some of the steps or versions are trivial or make checks and will not be included in the discussion below. It is important to note that the sequence is a *logical* progression and not a *temporal* set of steps. Some of the earliest steps (such as the change to 2010$) came at the end, while there were several changes in the carbon cycle modeling in the intervening years.

It will be useful to show two important examples. Table 6 shows the decomposition for the social cost of carbon for 2015. This, it will be recalled, has the largest single revision. The change comes from multiple variables. The largest contributor is the revision in the treatment of the carbon cycle, while the others are primarily economic variables such as the damage function and the utility function.[5] With the exception of emissions intensity, all the revisions were upwards.

Table 7 shows a similar calculation for 2100 temperature increase. The total change here is much smaller, with the largest contributor being the carbon cycle. Most of the other changes were modest and were both positive and negative. (The

---

[5] The change in the utility function involved both a change in the rate of time preference and a change in the elasticity of the marginal utility of consumption. These affect the real return and the impact of changes in productivity growth on different variables.

line "DICE-2016R" refers to all other contributing factors that were not individually estimated.)

Tables 8 and 9 show the complete set of revision results for the years 2015 and 2100. The first column is the replication of the results for DICE-1992. The first column is useful for non-economic variables because it is in different prices. The second column (v6) updates the price level to that in the current study and is the version used for the endpoint comparisons in the prior sections.

The changes for selected variables are usefully displayed in Figures 1 and 2. Figure 1 shows the decomposition of the changes for variables in 2015, while Figure 2 shows for variables in 2100. The figures also show projections from the 1990 and 2014 IPCC reports as well as standard errors of the estimates where those are available.

A complete compilation is provided in Tables 8 and 9. The sources of the changes differ by variable. Here are some of the highlights. In this discussion, I will ignore the first line in the table, which is simple price-level change. In each of these decompositions, I examine what changes in model design or in data led to the major changes in the output variable from 1992 to 2017.

- If we look at the change in 2015 global output due to model changes, it is not surprising that most of the change came from the adjustment of the level of 2015 output. Other net changes for 2015 output were minor.
- The major environmental variables for 2100 were relatively stable. Emissions and concentrations wobbled around with revisions, but there were only minor net changes. These were stable in part because the mechanisms that drive these processes were relatively well understood in the 1990s and partially because there are no ambiguities in how to measure the variables.
- The huge increase in projected 2100 global output was partially because of the upward revision in the base 2015 output, but primarily because of a major change in projected productivity growth. For output, there are both measurement and process issues. It is clear that the mechanism underlying productivity growth is non-stationary, which makes forecasting extremely difficult.
- Most changes in economic variables are driven by upward revisions in the measures of output and in TFP (productivity) growth, as discussed above.

IV. Conclusions

This paper analyzes the changes in the DICE model analysis of the economics of climate change over the last quarter century. Over that period, the central analytical structure of the model has remained the same, while most of the components have been revised in small or large ways, and there have been major revisions and improvements in most of the underlying data.

The major message of the study is simple. The projections of most environmental variables (such as emissions, concentrations, and temperature change) have seen relatively small revisions (with the emphasis here on relatively). However, there have been massive changes in the projections of the economic variables, including those that were forecast in 1992 and have now been realized in 2017. The stability of the environmental variables largely reflects that these were relatively well-understood by the early 1990s, and therefore modeling of these components within IAMs could be based on a solid scientific foundation.

By contrast, the dominant underlying change in the results of this IAM has been in the economic sectors, particularly in the measurement or prospect of current and future global output per capita. A useful example is the revision in global output for 2015. The level of 2015 output (in 2010$) was revised upwards by 35% over the period. Most of this was conceptual, involving the change from market exchange rates to purchasing power parity. The major revision in the 2100 outlook for output was a change from the stagnationist view of global growth in the 1980s and 1990s to a view of continued rapid growth today. This change can be seen by comparing the survey in Nordhaus and Yohe (1983) with that of Christensen et al (2017). As a result of these two changes, projected 2100 output per capita was revised upward by a factor of 3½ over the period. This major upward revision drove all economic variables, including damages and the social cost of capital.

A further major revision has been in the damage function. There was essentially no established aggregate damage function in the early 1990s, and this module of the DICE model was put together based on very rudimentary primary information.

Another large change has been in the rate of decarbonization, where the revisions have been to lower emissions per unit output over the period. This was largely due to the upward revision in output (which was not well measured) compared to a stable estimate of emissions (which was relatively well measured).

Perhaps the most dramatic revision has been the social cost of carbon (SCC). The SCC for 2015 has been revised upwards from $5 to $31 per ton of CO_2 over the last quarter-century. This is the result of several different model changes as shown in Table 6. While this large a change is unsettling, it must be recognized that there is a large estimated error in the SCC. The estimated (5%, 95%) uncertainty band for the SCC in the 2016R model is ($6, $93) per ton of CO_2. This wide band reflects the compounding uncertainties of the temperature sensitivity, output growth, damage function, and other factors. Moreover, it must be recognized that analyses of the social cost of carbon were not widespread until after 2000. Finally, estimates of the SCC are both highly variable across model and specification and have increased substantially over the last quarter-century. If we take early estimates of the SCC from two other well-known models (PAGE and FUND), these were close to estimates in the DICE1992 model.

A final result concerns the estimated uncertainty of the estimates. Because of their non-statistical structure, it is difficult to estimate the uncertainties associated with future forecasts of IAMs. Two sets of formal estimates of uncertainty for the model (in 2008 and 2017) were examined and compared with actual errors. While a complete comparison is not available, the actual errors to date (measured as forecast revisions) are reasonably within the error bands. This suggests that studies of the uncertainties of IAM projections are an important companion to standard projections as a way of signaling the reliability of different projections (a recent multi-model study of uncertainty is in Gillingham et al. 2015).

Both earlier studies and the results of this retrospective indicate that the economic components and projections are the least precise and the most deserving of future study. This applies especially to studies of long-run economic growth (to 2100 and beyond). Aside from climate-change policies, uncertainties and revisions about economic growth are likely to be the major factors behind changing prospects for climate change in the years to come.

References

Christensen, Peter, Kenneth Gillingham, and William Nordhaus. 2017. “Uncertainty in forecasts of long-run productivity growth,” manuscript in preparation.

Gillingham, Kenneth, William D. Nordhaus, David Anthoff, Geoffrey Blanford, Valentina Bosetti, Peter Christensen, Haewon McJeon, John Reilly, and Paul Sztorc. 2015. “Modeling uncertainty in climate change: a multi-model comparison.” No. w21637. National Bureau of Economic Research.

IPCC. 1990. J. T. Houghton, G. J. Jenkins and J. J. Ephraums, eds., *Climate Change: The IPCC Scientific Assessment,* Cambridge, UK, Cambridge University Press.

IPCC. 2014. Thomas Stocker, ed., *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

Nordhaus, William D. 1992. “An optimal transition path for controlling greenhouse gases,” *Science,* 258, November 20: 1315-1319.

Nordhaus, William D. 1992a. “The DICE model: Background and Structure,” Cowles Foundation Discussion Paper 1009, February, available at http://cowles.yale.edu/publications/cfdp.

Nordhaus, William D. 1994. *Managing the Global Commons: The Economics of Climate Change*, Cambridge, MA, MIT Press, USA.

Nordhaus, W. 2008. *A Question of Balance: Weighing the Options on Global Warming Policies*. New Haven, CT: Yale University Press.

Nordhaus, William. 2014. "Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches." *Journal of the Association of Environmental and Resource Economists,* 1, no. 1/2: 273-312.

Nordhaus, William. 2017. “The social cost of carbon: Updated estimates.” *Proceedings of the U. S. National Academy of Sciences*, January 31.

Nordhaus, William. 2017a. “Projections and uncertainties about climate change in an era of minimal climate policies,” No. w21637. National Bureau of Economic Research.

Nordhaus, William and Paul Sztorc. 2013. *DICE 2013R: Introduction and User’s Manual,* October 2013, available at http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_100413r1.pdf.

Nordhaus, William and Gary Yohe. 1983, “Future Carbon Dioxide Emissions from Fossil Fuels,” in National Research Council-National Academy of Sciences, *Changing Climate*, Washington, D.C., National Academy Press, 1983.

	DICE 1992	DICE-2016R	Change 1992 to 2016
	2015	2015	[%]
Major driving variables			
Economic			
Population (billions)	6,868	7,403	8%
Per capita GDP (2010$)	11,293	14,183	26%
Consumption per capita (2020$)	9,195	10,501	14%
Geophysical			
Other Forcings (W/m2)	0.89	0.50	-44%
CO2/output ratio (tCO2/000 2010$)	0.607	0.350	-42%
Outcome variables			
Industrial Emissions (GTCO2 per year)	42.3	35.7	-15%
Output (trillions 2010$)	77.6	105.0	35%
Atmospheric concentration C (ppm)	399	400	0%
Atmospheric concentrations (GtC)	849	851	0%
Atmospheric Temperature (°C)	1.16	0.85	-27%
Total forcings (W/m2)	3.04	2.46	-19%
Social cost of carbon ($/tCO2 2010$)	4.54	30.98	582%

Table 1. Major variables estimated for 2015 [i]

	DICE 1992	DICE-2016R	Change 1992 to 2016	Estimated error	
	2100	2100	[%]	2007	2016
Major driving variables					
Economic					
Interest Rate (% per year)	3.4%	3.5%	2.8%	na	0.9%
Population (billions)	9,812	11,126	13%	na	2,421
Savings rate	0.17	0.24	43%	na	na
Per capita GDP (2010$)	22,272	73,367	229%	na	49,165
Damage parameter (% at 3 °C)	1.3%	2.1%	62%	na	1.1%
Consumption per capita (2020$)	18,536	55,825	201%	na	na
Geophysical					
Other Forcings (W/m2)	1.42	1.00	-30%	na	na
CO2/output ratio (tCO2/000 2010$)	0.113	0.094	-16%	na	0.03
Outcome variables					
Industrial Emissions (GTCO2 per year)	78.7	70.8	-10%	50.40	52.60
Output (trillions 2010$)	218.5	816.3	274%	206.0	581.0
Atmospheric concentration C (ppm)	670	854	27%	162	234
Atmospheric concentrations (GtC)	1,428	1,820	27%	334	498
Atmospheric Temperature (°C)	3.20	4.29	34%	1.00	0.89
Climate Damages (% output)	1.5%	4.3%	191%	na	0.028
Total forcings (W/m2)	6.65	7.00	5%	na	na
Social cost of carbon ($/tCO2 2010$)	11.79	265.73	2154%	na	na

Table 2. Major variables estimated for 2100 [ii]

	1980	2000	2015	2050	2100
CO2 emissions (GtCO2)					
IPCC 1990	22.0	26.0	36.7	55.0	89.8
DICE1992	24.6	36.9	46.7	67.6	89.1
DICE2016			35.8	58.2	70.9
IPCC 8.5				64.2	95.3
CO2 Concentrations (ppm)					
IPCC 1990	340	375	412	535	825
DICE1992	334	368	404	513	700
DICE2016			399	552	826
IPCC 8.5			400	530	940
Total radiative forcing (W/m2) (a)					
IPCC 1990	2.00	3.10	4.20	6.60	9.90
DICE1992	1.66	2.49	3.12	4.78	6.86
DICE2016			2.46	4.39	6.82
IPCC 8.5 (d)	1.50	1.30	2.50	4.80	8.00
Global temperature (°C)					
IPCC 1990(b)	0.20	0.40	0.80	1.90	3.45
DICE1992 (c)	0.19	0.56	0.87	1.72	2.77
DICE2016	0.21	0.38	0.85	2.13	4.10
IPCC 8.5 (e)			0.85	2.05	4.55

(a) Radiative forcing in principle since 1750 or 1850 but unclear for different sources
(b) Subtracts 0.3 °C to correct for initial condition of 1965 = 0.2 °C.
(c) Adds 0.2 °C to correct for initial conditions of 0 °C at 1990.
(d) Adds 0.5 to normalize.
(e) Adds 0.35 to make comparable to other estimates.

Table 3. Comparison DICE and IPCC projections, early 1990s and mid-2010s

Variables	Ratio: (difference 2016-1992)/ estimated error
Major driving variables	
Economic	
Interest Rate (% per year)	0.11
Population (billions)	0.54
Savings rate	
Per capita GDP (2010$)	1.04
Damage parameter (% at 3 °C)	0.77
Consumption per capita (2020$)	
Geophysical	
Other Forcings (W/m2)	
CO2/output ratio (tCO2/000 2010$)	-0.70
Outcome variables	
2100	
Industrial Emissions (GTCO2 per year)	-0.15
Output (trillions 2010$)	1.03
Atmospheric concentration C (ppm)	0.79
Atmospheric concentrations (GtC)	0.79
Atmospheric Temperature (°C)	1.22
Climate Damages (% output)	1.02
Total forcings (W/m2)	
2015	
Social cost of carbon, 2015 ($/tCO2 2010$)	0.93

Table 4. Forecast error ratios for different projections[iii]

The forecast error ratio is the ratio of the forecast error to the estimated standard deviation of the variable. See text for a discussion.

v1: Takes the 1992 version to recreate the 1992 results (1989 $).
v5: Adjusts for inflation with price increase of factor of 2 for all economic variables (1989$ to 2010$).
v6: Adds the calculation of the real interest rate from 2016R calculation.
v7: Updates GDP and capital to match 2015 levels.
v9: Adjusts emissions and concentrations to match 2015 levels and match through 2100.
v10: Updates damage function parameter to 2016R model.
v11: Increases TFP growth to 2016R model.
v12: Adjusts sigma growth and other TFP parameters to 2016R model.
v13: Adjusts utility function.
v14: Adjusts climate model to 2016R model.
v18: Final adjustment of carbon cycle to match 2016R.
V20: Final adjust of climate model and other forcings; match equilibrium and transient temperature sensitivity from 2016R model.
v21: Adjusts for abatement in 2016R model.
v22: Is the current model (DICE-2016R).

Table 5. Major steps to move from 1992 to 2017 DICE model to test for impact of revisions [iv]

This list shows the “versions” of the model used to move from DICE 1992 to DICE-2016R. It omits versions that were trivial or to check adjustments for accuracy.

Change in social cost of carbon, 2015			
From	***To***	***Changed variable***	***Change due to this variables***
v14	v18	Carbon cycle	66%
v9	v10	Damage function	59%
v12	v13	Utility function	47%
v6	v7	Initial output	36%
v10	v11	Productivity growth	15%
v21	v22	DICE-2016R	13%
v13	v14	Climate model	8%
v18	v20	Climate parameters	2%
v20	v21	Abatement function	0%
v7	v9	Initial Emissions and Concentrations	-1%
v11	v12	CO2 /GDP ratio and trend	-9%

Table 6. Decomposition of changes in social cost of carbon, 2015[v]

The list shows the major sources of the revision of estimates of the social cost of carbon from 192 to 2017 in order.

Change in global temperature, 2100			
From	***To***	***Changed variable***	***Change due to this variables***
v14	v18	Carbon cycle	22%
v21	v22	DICE-2016R	11%
v10	v11	Productivity growth	8%
v13	v14	Climate model	4%
v6	v7	Initial output	4%
v12	v13	Utility function	1%
v20	v21	Abatement function	0%
v9	v10	Damage function	0%
v18	v20	Climate parameters	-3%
v11	v12	CO2 /GDP ratio and trend	-4%
v7	v9	Initial Emissions and Concentrations	-10%

Table 7. Decomposition of changes in global temperature 2100[vi]

The list shows the major sources of the revision of projections of global temperature from 1992 to 2017 in order.

For year 2100											
From	To	Changed variable	Industrial Emissions (GTCO2 per year)	Atmospheric concentration C (ppm)	Atmospheric Temperature (°C)	Output (trillions 2010$)	Climate Damages (% output)	Consumption per capita (2020$)	Carbon Price (per t CO2)	Emissions Control Rate (%)	Social cost of carbon ($/tCO2 2010$)
v4*	v6	Price level	0%	0%	0%	100%	0%	100%	100%	0%	100%
v6	v7	Initial output	7%	4%	4%	35%	7%	25%	34%	3%	34%
v7	v9	Initial Emiss and Conc	-20%	-12%	-10%	0%	-19%	0%	-93%	-80%	4%
v9	v10	Damage function	0%	0%	0%	-1%	58%	-1%	0%	0%	56%
v10	v11	TFP	51%	13%	8%	217%	17%	216%	7952%	682%	252%
v11	v12	CO2 /GDP	-28%	-8%	-4%	-15%	-8%	-15%	-61%	-48%	-19%
v12	v13	Utility function	3%	1%	1%	3%	2%	1%	0%	0%	48%
v13	v14	Climate model	0%	0%	4%	0%	9%	0%	0%	0%	8%
v14	v18	Carbon cycle	0%	34%	22%	-2%	48%	-1%	0%	0%	43%
v18	v20	Climate params	0%	2%	-3%	0%	-6%	0%	0%	0%	6%
v20	v21	Abatement function	0%	0%	0%	0%	0%	0%	0%	0%	-1%
v21	v22	All others	-5%	-3%	11%	2%	28%	-9%	-67%	0%	52%

For year 2100											
From	To	Changed variable	Interest Rate (% per year)	Population (billions)	Per capita GDP growth, difference (% per year)	Capital stock (trillions, 2010$)	Savings rate (%)	Investment (trillions, 2010$)	CO2/output ratio (tCO2/000 2010$)	Total forcings (W/m2)	Other Forcings (W/m2)
v4*	v6	Price level	0%	0%	0%	100%	0%	100%	-50%	0%	0%
v6	v7	Initial output	0%	8%	0%	35%	0%	35%	-21%	4%	0%
v7	v9	Initial Emiss and Conc	0%	0%	1%	0%	0%	1%	-21%	-11%	0%
v9	v10	Damage function	0%	0%	-1%	-1%	0%	-1%	1%	0%	0%
v10	v11	TFP	41%	0%	154%	166%	1%	220%	-52%	12%	0%
v11	v12	CO2 /GDP	-3%	0%	-4%	-14%	0%	-15%	-15%	-7%	0%
v12	v13	Utility function	-16%	0%	1%	13%	10%	13%	0%	1%	0%
v13	v14	Climate model	0%	0%	0%	0%	0%	0%	0%	0%	0%
v14	v18	Carbon cycle	-1%	0%	-1%	-1%	0%	-2%	1%	27%	0%
v18	v20	Climate params	0%	0%	0%	0%	0%	0%	0%	-4%	-30%
v20	v21	Abatement function	0%	0%	0%	0%	0%	0%	0%	0%	0%
v21	v22	All others	-9%	5%	1%	13%	29%	31%	-7%	-11%	0%

Table 8. Decomposition of the changes in important variables, 2100[vii]

The table shows the impact of different revisions on each variable for the 2100 projected level. For example, the top left column labelled "Industrial emissions" shows the impact of the change in the variable labeled "Changed variable." That is, moving from v6 to v7 made a correction for initial (2015) output. This increased projected 2100 emissions by 7 percent.

For year 2015											
From	To	Changed variable	Industrial Emissions (GTCO2 per year)	Atmospheric concentration C (ppm)	Atmospheric Temperature (°C)	Output (trillions 2010$)	Climate Damages (% output)	Consumption per capita (2020$)	Carbon Price (per t CO2)	Emissions Control Rate (%)	Social cost of carbon ($/tCO2 2010$)
v4*	v6	Price level	0%	0%	0%	100%	0%	100%	100%	0%	100%
v6	v7	Initial output	7%	2%	2%	35%	5%	26%	36%	4%	36%
v7	v9	Initial Emiss and Conc	-23%	-2%	4%	0%	7%	0%	-94%	-82%	-1%
v9	v10	Damage function	0%	0%	0%	0%	59%	0%	0%	0%	59%
v10	v11	TFP	15%	1%	1%	13%	1%	13%	-2%	0%	15%
v11	v12	CO2 /GDP	-7%	1%	3%	-9%	5%	-9%	107%	49%	-9%
v12	v13	Utility function	2%	0%	0%	2%	1%	0%	0%	0%	47%
v13	v14	Climate model	0%	0%	3%	0%	7%	0%	0%	0%	8%
v14	v18	Carbon cycle	0%	-2%	-24%	0%	-42%	0%	0%	0%	66%
v18	v20	Climate params	0%	2%	11%	0%	22%	0%	0%	0%	2%
v20	v21	Abatement function	0%	0%	0%	0%	0%	0%	0%	0%	0%
v21	v22	All others	-6%	-2%	-24%	-5%	-42%	-100%	171%	0%	13%

For year 2015											
From	To	Changed variable	Interest Rate (% per year)	Population (billions)	Capital stock (trillions, 2010$)	Savings rate (%)	Investment (trillions, 2010$)	CO2/output ratio (tCO2/000 2010$)	Total forcings (W/m2)	Other Forcings (W/m2)	
v4*	v6	Price level	0%	0%	100%	0%	100%	-50%	0%	0%	
v6	v7	Initial output	0%	8%	35%	0%	35%	-21%	3%	0%	
v7	v9	Initial Emiss and Conc	0%	0%	0%	0%	0%	-23%	-5%	0%	
v9	v10	Damage function	0%	0%	0%	0%	0%	0%	0%	0%	
v10	v11	TFP	22%	0%	2%	0%	14%	2%	2%	0%	
v11	v12	CO2 /GDP	-1%	0%	-9%	0%	-9%	2%	2%	0%	
v12	v13	Utility function	-11%	0%	9%	7%	10%	0%	1%	0%	
v13	v14	Climate model	0%	0%	0%	0%	0%	0%	0%	0%	
v14	v18	Carbon cycle	0%	0%	0%	0%	0%	0%	-3%	0%	
v18	v20	Climate params	0%	0%	0%	0%	0%	0%	-7%	-44%	
v20	v21	Abatement function	0%	0%	0%	0%	0%	0%	0%	0%	
v21	v22	All others	12%	0%	0%	31%	24%	-2%	-12%	0%	

Table 9. Decomposition of the changes in important variables, 2015[viii]

The table shows the impact of different revisions on each variable for the 2015 projected level. For example, the top left column labelled "Industrial emissions" shows the impact of the change in the variable labeled "Changed variable." That is, moving from v6 to v7 made a correction for initial (2015) output. This increased projected 2015 emissions by 7 percent.

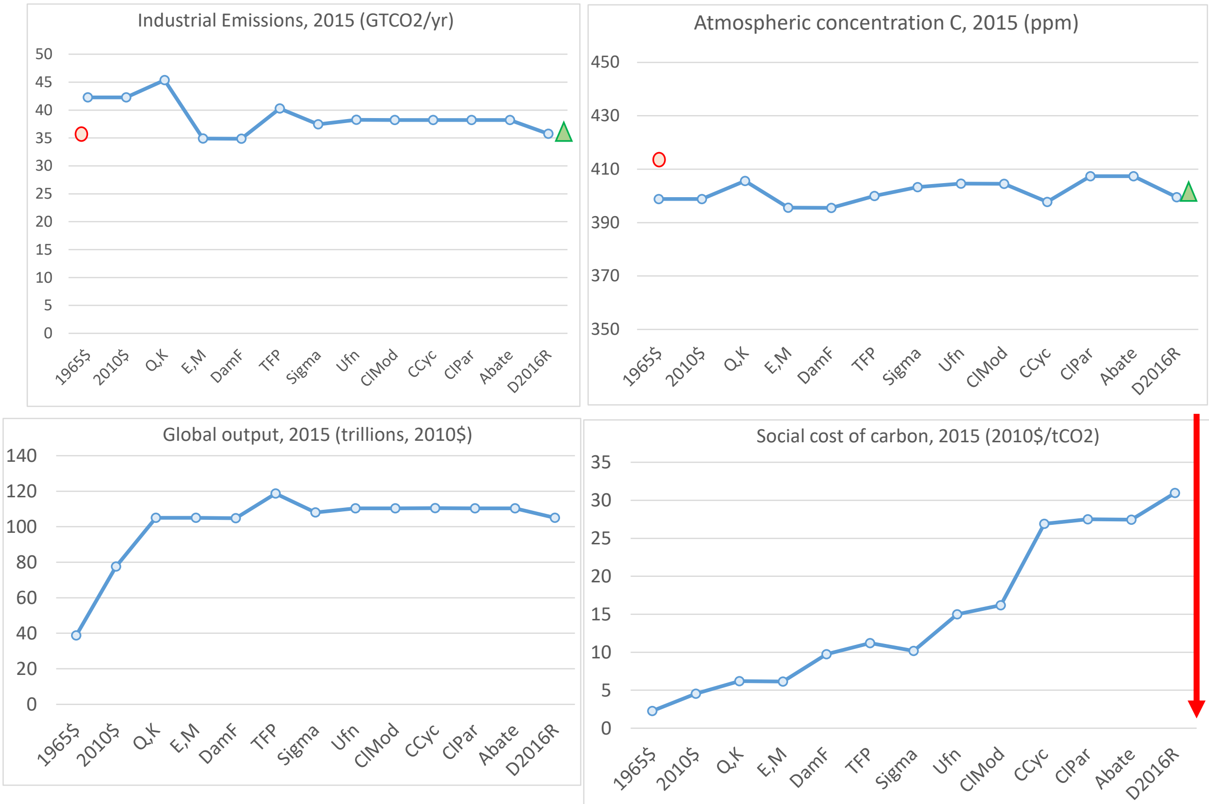

Figure 1. Changes in estimates for variables in 2015 [ix]

The figure shows the level of the variable for each version. For example, moving from 1989 $ to 2010 $ had no effect on emissions but doubled output. The red circles at the left are estimates from IPCC (1990), the green triangles at the right are estimates from IPCC (2014). The arrows are 2016 estimates plus or minus one standard deviation from Nordhaus (2017a). Where the line ends without an arrow, the figure is off the chart.

Interpretation of legend on horizontal axis:

1965$: DICE-1992 model (in 1989 $)
2010$: DICE-1992 model (reflated to 2010$)
Q, K: Adjustment for estimated output, capital in 2015
E, M: Adjustment for estimated emissions and concentrations in 2015
DamF: Change to 2017 damage function
TFP: Change to level and growth of TFP (productivity) in 2017 model
Sigma: Change to level and growth of global CO_2/output ratio in 2017 model
Ufn: Change to 2017 utility function
ClMod: Change to 2017 climate model
CCyc: Change to 2017 carbon cycle and parameters
ClPar: Change to 2017 climate sensitivities
Abate: Change to 2017 abatement function
D2016R: Rest of changes to full DICE-2016R model

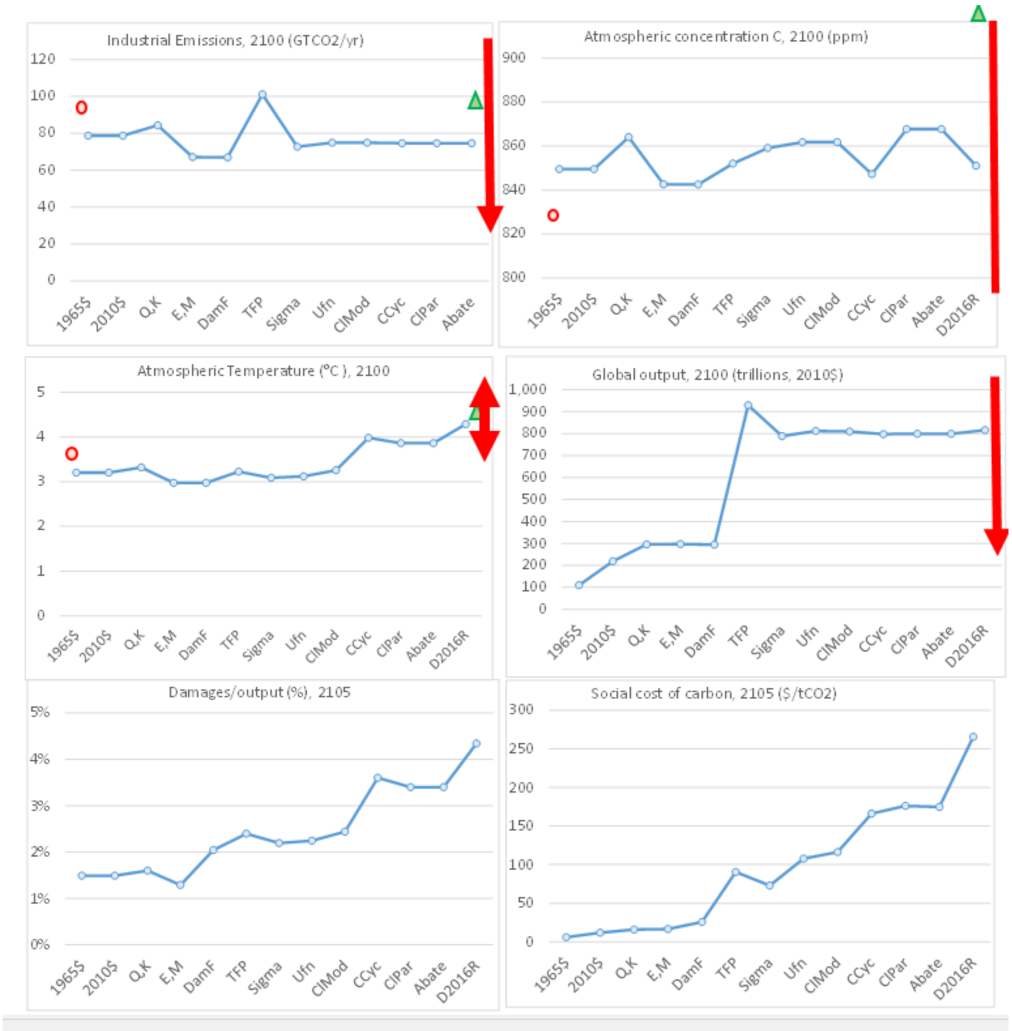

Figure 2. Changes in estimates for variables in 2100 [x]

The figure shows the level of the variable for each version. For example, moving from 1989 $ to 2010 $ had no effect on emissions but doubled output.

For meaning of legend on horizontal axis, see Figure 1.