Summary of the DICE model

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This report gives a brief summary of the DICE (Dynamic Integrated Climate-Economy) model, developed by William Nordhaus, which "integrate[s] in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming" (Nordhaus and Boyer 2000 p 5). Section 1 of this report recounts the major milestones in the development of DICE and its regionally disaggregated companion model, RICE. This section also serves as a convenient reference for more detailed expositions of the model and applications in the primary literature. Section 2 describes the basic structure of the most recently published version of DICE, and Section 3 describes some key aspects of the model calibration. Section 4 gives additional details on the climate damage function in DICE, and Section 5 gives a brief description of the most recently published version of the RICE model.

1 Historical development

The DICE integrated assessment model has been developed in a series of reports, peer reviewed articles, and books by William Nordhaus and colleagues over the course of more than thirty years. The earliest precursor to DICE was a linear programming model of energy supply and demand with additional constraints imposed to represent limits on the peak concentration of carbon dioxide in the atmosphere (Nordhaus 1977a,b).[2] The model was dynamic, in that it represented the time paths of the supply of energy from various fuels and the demand for energy in different sectors of the economy and the associated emissions and atmospheric concentrations of carbon dioxide. However, it included no representation of the economic impacts or damages from temperature or other climate changes. Later, Nordhaus (1991) developed a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long term future climate impacts from climate change. This allowed for a balancing of the benefits and costs of carbon dioxide emissions to help determine the optimal level of near term controls. The analysis centered on

[2] While it has not been the focus of the DICE model, it should be emphasized that this type of cost-effectiveness framework is still useful. For example, if policy makers decide upon a 2 degree target, then the appropriate social cost of carbon to use is the shadow price associated with that path (Nordhaus, personal communication).

the global average surface temperature, which was "…chosen because it is a useful index (in the nature of a sufficient statistic) of climate change that tends to be associated with most other important changes rather than because it is the most important factor in determining impacts" (Nordhaus 1991 p 930). The categories of climate damages that were represented in the model were associated with market sectors that accounted for roughly 13% of GDP in the United States. [3]

The DICE model was first presented in its modern form by Nordhaus (1992a,b), who described the new, fully dynamic Ramsey-type optimal growth structure of the model and the optimal time path of emission reductions and associated carbon taxes that emerged from it. The full derivation and extended description of the DICE model and a wider range of applications were presented in a book by Nordhaus (1994a). The next major advance involved disaggregating the model into ten different groups of nations to produce the RICE (Regional DICE) model, which allowed the authors to examine national-level climate policies and different strategies for international cooperation (Nordhaus and Yang 1996). An update and extended description of both RICE (now with eight regions) and DICE appeared in the book by Nordhaus and Boyer (2000). The next major update of DICE, modified to include a backstop technology that can replace all fossil fuels and whose price was projected to decline slowly over time, appeared in another book by Nordhaus (2008). Finally, Nordhaus (2010) described the most recent version of the RICE model, which adds an explicit representation of damages due to sea level rise.

In addition to the studies by Nordhaus and colleagues mentioned above, DICE has been adapted by other researchers to examine a wide range of issues related to the economics of climate change. A comprehensive review is well beyond the scope of this summary, so only a few examples are mentioned here. Pizer (1999) used DICE to compare carbon tax and a cap-and-trade-style policies under uncertainty. Popp (2005) modified DICE to include endogenous technical change. Baker *et al.* (2006) used DICE to examine the effects of technology research and development on global abatement costs. Hoel and Sterner (2007) modified the utility function in DICE to include a form of non-market environmental consumption that is an imperfect substitute for market consumption, and Yang (2008) used RICE in a cooperative game theory framework to examine strategies for international negotiations of greenhouse gas mitigation policies and targets.

2 Basic model structure

DICE2007 is a modified Ramsey-style optimal economic growth model, where an additional form of "unnatural capital"—the atmospheric concentration of CO_2—has a negative

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[3] It should be emphasized that while this model and all subsequent versions of DICE necessarily make assumptions about climate and economic conditions in the far future, the important question is the extent to which current policies are robust to changes in assumptions about future variables (Nordhaus, personal communication).

effect on economic output through its influence on the global average surface temperature. Global economic output is represented by a Cobb-Douglas production function using physical capital and labor as inputs. Labor is assumed to be proportional to the total global population, which grows exogenously over time. Total factor productivity also increases exogenously over time. The carbon dioxide intensity of economic production and the cost of reducing carbon dioxide emissions decrease exogenously over time. In each period a fraction of output is lost according to a Hicks-neutral climate change damage function. The output in each period is then divided between consumption, investment in the physical capital stock (savings), and expenditures on emissions reductions (akin to investment in the natural capital stock). DICE solves for the optimal path of savings and emissions reductions over a multi-century planning horizon, where the objective to be maximized is the discounted sum of all future utilities from consumption. Total utility in each period is the product of the number of individuals alive and the utility of a representative individual with average income in that period. The period utility function is of the standard constant relative risk aversion (CRRA) form, and utilities in future periods are discounted at a fixed pure rate of time preference.

3 Calibration

The climate model in DICE2007 tracks the stocks and flows of carbon in three aggregate compartments of the earth system: the lower atmosphere, the shallow ocean, and the deep ocean. The transfer coefficients linking the flows among the compartments were "calibrated to fit the estimates from general circulation models and impulse-response experiments, particularly matching the forcing and temperature profiles in the MAGICC model" (Nordhaus 2008 p 54). The climate sensitivity parameter—the equilibrium change in global average surface temperature after a sustained doubling of atmospheric carbon dioxide concentration— was set to 3 degrees Celsius, which is near the middle of the range cited by the IPCC. The projected temperature change under the baseline scenario (with no climate controls for the first 250 years) is an increase in global average surface temperature of 3.2 degrees Celsius around year 2100 with a peak of around 6.5 degrees Celsius around year 2500.

The key economic growth and preference parameters of DICE2007 are calibrated as follows. The global population is projected to grow exogenously from around 6.5 billion in 2005 to 8.6 billion around 2200. Total factor productivity growth and the discount rate parameters were calibrated to match market returns in the early periods of the model: specifically, "We have chosen a time discount rate of 1½ percent per year along with a consumption elasticity of 2. With this pair of assumptions, the real return on capital averages around 5½ percent per year for the first half century of the projections, and this is our estimate of the rate of return on capital" (Nordhaus 2008 p 61).

The abatement cost function is specified such that the marginal abatement cost, measured as a fraction of output, increases roughly with the square of the fraction of emissions

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abated. The backstop price—the marginal cost of eliminating the last unit of emissions in each period—is $1,170 per metric ton of carbon in the first period and falls exponentially at a rate of 5% per decade to a long run value of $585 per metric ton of carbon.

The climate damage function is specified such that for small temperature changes the fraction of output lost in each period increases with the square of the increase in temperature above the preindustrial average temperature.[4] The coefficient of the damage function is calibrated so that roughly 1.7% of global economic output is lost when the average global surface temperature is elevated by 2.5 degrees Celsius above the preindustrial average.

4 Damages

The globally aggregated climate damage function in DICE has been calibrated to match the sum of climate damages in all regions represented in the RICE model. The potential damages from climate change are divided into seven categories: agriculture, sea level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes. A full recounting of the derivation of the damage functions in all categories is beyond the scope of this short summary, but to the give the reader a flavor for what is involved this section reviews three categories of damages: agriculture, heath, and catastrophes. This discussion draws heavily on Chapter 4 of Nordhaus and Boyer (2000), so the reader is referred there for more information.

Agriculture can serve as an illustrative example of some of the other categories not covered here. The basic strategy for calibrating the damage functions is to draw on estimates from previous studies of the potential economic losses in each category at a benchmark level of warming of 2.5 degrees Celsius, extrapolating across regions as necessary to cover data gaps in the literature. Some extrapolations were made using income elasticities for each impact category. As the authors explain, "United States agriculture can serve here as an example. Our estimate is that [the fraction of the value of agricultural output lost at 2.5 degrees Celsius] is 0.065 percent [based on Darwin *et al*. 1995]... The income elasticity of the impact index is estimated to be -0.1, based on the declining share of agriculture in output as per capita output rises" (Nordhaus and Boyer 2000 p 74-75).

The human health impacts of climate change were based on the effects of pollution and a broad group of climate-related tropical diseases including malaria and dengue fever. The increased mortality from warming in the summer and decreased mortality from warming in the winter were assumed to roughly offset and so were not included. The specification of the human health damage function involved "a regression of the logarithm of climate related [years

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[4] The DICE2007 damage function has an "S-shape," so for very large temperature changes the fraction of output lost increases with temperature at a decreasing rate and asymptotes to one. However, it should be emphasized that the damage function is calibrated to damages in the range of 2 to 4 degrees Celsius. The extent of non-linearity beyond this range is unknown, so extrapolations beyond this point should not be considered reliable (Nordhaus, personal communication).

of life lost] on mean regional temperature estimated form the data presented in Murray and Lopez [1996]" with judgmental adjustments "to approximate the difference among subregions that is climate related," and each year of life lost was valued at two years of per capita income (Nordhaus and Boyer 2000 p 80-82).

The damages from potential catastrophic impacts were estimated using results from a previous survey of climate experts by Nordhaus (1994b). The experts were asked for their best professional judgment of the likelihood of a catastrophe—specified as a 25 percent loss of global income indefinitely—if the global average surface temperature increased by 3 and by 6 degrees Celsius within 100 years. The averages of the survey responses were adjusted upward somewhat based on "[d]evelopments since the survey [that] have heightened concerns about the risks associated with major geophysical changes, particularly those associated with potential changes in thermohaline circulation" (Nordhaus and Boyer 2000 p 87). The probability of a 30 percent loss of global income indefinitely was assumed to be 1.2 and 6.8 percent with 2.5 and 6 degrees Celsius of warming, respectively. The percent of income lost was assumed to vary by region, and a coefficient of relative risk aversion equal to 4 was used to calculate the willingness to pay to avoid these risks in each region. The resulting "range of estimates of WTP lies between 0.45 and 1.9 percent of income for a 2.5^{o}C warming and between 2.5 and 10.8 percent of income for a 6°C warming. It is assumed that this WTP has an income elasticity of 0.1" (Nordhaus and Boyer 2000 p 89).

Damages in the remaining categories were estimated in a similar vein, using a combination of empirical estimates from previous climate impact studies and professional judgments when needed to close the sometimes wide gaps in the literature. The table below shows the resulting global estimates of damages in each category in the 1999 version of RICE.

Damages as a percent of global output at 2.5^{o}C of warming

	Output weighted	Population weighted
Agriculture	0.13	0.17
Sea level rise	0.32	0.12
Other market sectors	0.05	0.23
Health	0.10	0.56
Non-market amenities	-0.29	-0.03
Human settlements and ecosystems	0.17	0.10
Catastrophes	1.02	1.05
Total	1.50	1.88

(Nordhaus and Boyer 2000 p 91)

With damages in all categories estimated, the DICE damage function was then calibrated "so that the optimal carbon tax and emissions control rates in DICE-99 matched the projections of these variables in the optimal run of RICE-99" (Nordhaus and Boyer 2000 p 104).

5 Recent developments

Nordhaus (2010) presented results from an updated version of the RICE model. A major extension is a new sea level rise damage function, now explicitly modeled by region as a function of the global average sea level rise rather than rolled up in the aggregate damage function. "The RICE-2010 model provides a revised set of damage estimates based on a recent review of the literature [Toll 2009, IPCC 2007]. Damages are a function of temperature, SLR, and CO_2 concentrations and are region-specific. To give an idea of the estimated damages in the uncontrolled (baseline) case, those damages in 2095 are… 2.8% of global output, for a global temperature increase of 3.4^{o}C above 1900 levels" (Nordhaus 2010 p 3). Other parameter updates include climate sensitivity, now set to 3.2 degrees Celsius, the elasticity of the marginal utility of income, now set to -1.5, and parameters that control economic growth rates, which are re-calibrated such that world per capita consumption grows by an average rate of 2.2% per year for the first 50 years.

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