WP-US-1101

STOCKHOLM ENVIRONMENT INSTITUTE

Casting DICE for 350 ppm

Ramón Bueno and Elizabeth A. Stanton

January 2011

Stockholm Environment Institute
Working Paper WP-US-1101

Abstract

The DICE model of climate economics, using its default assumptions and inputs, projects that the optimal climate policy is a gradual abatement of greenhouse gas emissions. In this paper we explore alternative assumptions and inputs under which DICE might recommend beginning abatement more rapidly, and stabilizing atmospheric concentrations near 350 ppm carbon dioxide (CO2). We start with several small technical adjustments to the DICE-2007 model, updating its population projections, and updating and partially endogenizing the effects of non-CO2 greenhouse gases, as well as lowering its discount rate to place greater emphasis on intergenerational equity. We then conduct sensitivity analyses varying the parameters for climate sensitivity, damage function exponent, and the cost of achieving 100-percent emissions abatement. We find that DICE's optimal policy recommendation changes markedly when inputs are varied within the range of likely values in the current literature. At the higher end of the current range of estimates for two key parameters, DICE calculates that human welfare is maximized by keeping peak temperature increases very low, and achieving a completely emission-free world economy within half a century.

For more information about this document,
contact Ramón Bueno at ramon.bueno@sei-us.org.

Stockholm Environment Institute - US
11 Curtis Avenue
Somerville, MA 02144-1224, USA
www.sei-us.org and www.sei-international.org

Introduction

The Dynamic Integrated model of Climate and the Economy (DICE) is one of the best-known models in the climate economics literature. According to its creator, William Nordhaus, DICE demonstrates that the optimal policy follows a “climate policy ramp” that begins with small, slow steps (Nordhaus 2008). In this paper we explore alternative assumptions and inputs under which DICE might recommend beginning abatement more rapidly, and stabilizing atmospheric concentrations near 350 ppm carbon dioxide (CO_2).

We explore three types of changes to the DICE model:

- We make a series of small adjustments to the DICE-2007 model, updating its population projections, and updating and partially endogenizing the effects of non-CO_2 greenhouse gases.
- We lower the model’s discount rate to match that used in the Stern Review. Results from this new “DICE-Adjusted” version of the model – with technical modifications and the Stern discount rate – are compared to original (unmodified) DICE results.
- We conduct additional sensitivity analyses, highlighting three other key policy-relevant parameters about which we are necessarily uncertain: climate sensitivity, climate damage function exponent, and greenhouse gas emissions abatement costs.

DICE determines an optimal scenario for achieving the greatest possible human welfare – defined as a function of per capita consumption. Our experiments show that if emissions have a big enough effect on temperatures (climate sensitivity), and if temperatures have a big enough effect on the economy (damage exponent), then human welfare in DICE is maximized by keeping temperature increases very low, and achieving a completely emission-free world economy within half a century. DICE model results are also very sensitive to changes in the cost of abatement: higher abatement costs delay the optimal pace of emission reductions.

The next section briefly describes the DICE model and some of its key parameter choices. One of these, climate sensitivity, and its crucial role in climate-economics models such as DICE is discussed in Section 3. Section 4 outlines the modifications that produce the DICE-Adjusted model used in our analysis. The results of exploring the model’s sensitivity to three key climate-related parameters are presented and discussed in Section 5. Section 6 offers conclusions and policy implications.

DICE-2007

The DICE-2007 model (Nordhaus 2008) is an “integrated assessment model” (IAM) of the costs and benefits of climate change.[1] DICE, like a number of other IAMs, is known for projecting that the optimal climate policy is one of very gradual greenhouse gas abatement (Nordhaus 2008).
DICE models both the climate system (emissions, concentrations, temperatures) and the economy (gross domestic product (GDP), per capita consumption, investment, climate damages and abatement costs) for the world as a whole without regional breakdown.

The climate sensitivity parameter plays a key role in DICE calculations, as it does in similar models. This parameter is defined as the global average annual temperature increase that will result from a

[1] For a review of the current climate economics modeling literature, see Stanton et al. (2009).

doubling of the atmospheric concentration of CO_2. A larger value for climate sensitivity means that the same amount of emissions give rise to a greater temperature increase. The DICE default value for climate sensitivity is 3°C. The current scientific assessment of this parameter value is discussed in Section 3 below.

There are two feedback mechanisms between DICE's climate and economics modules. First, a damage function takes the temperature as its input and gives economic damages as a share of GDP as its output. In DICE, economic damages are assumed to be proportional to the square of temperature increases above the 1900 level (Nordhaus 2008). In more general terms, damages could be viewed as proportional to the temperature increase raised to some power, where the exponent is a parameter chosen by the modeler; DICE's default damage exponent is 2. This exponent is a dominant factor in determining global damages from climate change. Our review of the literature has uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function – although the practice is common in IAMs.[2] Some recent research suggests that DICE underestimates the damages that result from particular temperature increases by a factor of two to four (Ackerman and Stanton 2008; Hanemann 2008; Ackerman et al. 2010).[3]

Second, an abatement function takes GDP (reduced by damages and abatement costs) as its input and gives the next period's greenhouse gas emissions as its output. The level of abatement, or "control rate," for each period is determined by an optimization algorithm that chooses the control rate and the level of economic investment, with a goal of maximizing discounted per capita consumption over the entire period covered by the model.

Climate Sensitivity

Climate sensitivity, the long-term temperature change that will result from a doubling of atmospheric CO_2 concentrations, is a common summary measure of the severity of the global warming threat. While it plays a central role in climate economic models as a driver of climate-related economic damages, the climate sensitivity values found in IAMs differ. No standard value exists in the literature and, indeed, the range of appropriate climate sensitivity values appears to be increasing with the introduction of new research.

The scientific literature as of 2006, as summarized in the Intergovernmental Panel on Climate Change's *Fourth Assessment Report* (*AR4)* (IPCC 2007a), suggested that the most likely estimate of climate sensitivity was 3°C. That is, every time atmospheric CO_2 doubles – from today's 385 ppm to 770 ppm CO_2, for example – the global average annual temperature would increase by 3°C.

Climate sensitivity is uncertain – perhaps inevitably so (Roe and Baker 2007). *AR4* viewed it as "likely" that the true value fell between 2.0°C and 4.5°C; in IPCC usage, this means the authors believed there is a one in six chance that climate sensitivity is actually above 4.5°C. As of 2009, the climate model that did best at simulating clouds (Clement et al. 2009, see also Kerr 2009) assumed a climate sensitivity of 4.4°C.

[2] Risbey et al. (1996) refer to this practice as the "wholesale uncritical adoption of archetypal models."
[3] See Stanton et al. (2009) for a discussion of damage exponents in the climate economics literature. See Ackerman et al. (2008) for an analysis of the likelihood of higher damage exponents.

Hansen et al. (2008) present significant evidence from the paleoclimatic record supporting a long-run climate sensitivity of 6°C.[4] That is, they argue that the global warming that will result from any given increase in atmospheric concentration of CO_2 is twice as great as *AR4*'s central projection. Hansen et al. report a 25 percent risk of serious harm with 300-500 ppm CO_2 and set a goal of getting concentrations below 350 ppm CO_2 by 2100. They conclude that the more widely discussed goal of 450 ppm CO_2 is roughly the threshold for transition to an ice-free world; loss of all the world's glaciers and ice sheets would entail catastrophic increases in sea levels and changes in water supplies.

Even at lower levels of climate sensitivity, the requirements for climate stabilization are demanding. In *AR4*, the IPCC (2007b) offers six categories of stabilization trajectories; these are the target atmospheric concentration levels for greenhouse gases, given either just for CO_2, or in terms of "CO_2-equivalents" (CO_2-e) to include the effects of non-CO_2 gases (see Table 1). According to these IPCC classifications, only categories I and II – with CO_2 concentrations in the range of 350 to 440 ppm – are likely to keep global temperature change below or near 2°C from 1990, even with a climate sensitivity of 3°C. Use of a higher range of climate sensitivities would call for lower CO_2-e concentrations to stay below the same temperature-increase ceilings.

Table 1: AR4 Classification of Stabilization Scenarios

AR4 Category	CO_2 concentration (ppm)	CO_2-equivalent concentration (ppm)	Global average annual temperature increase above 1990		SRES Scenarios
			°C	*°F*	
I	350-400	445-490	1.4 to 1.8	*2.5 to 3.2*	
II	400-440	490-535	1.8 to 2.2	*3.2 to 3.9*	
III	440-485	535-590	2.2 to 2.6	*3.9 to 4.6*	
IV	485-570	590-710	2.6 to 3.4	*4.6 to 6.1*	B1, A1T
V	570-660	710-855	3.4 to 4.3	*6.1 to 7.7*	B2
VI	660-790	855-1130	4.3 to 5.5	*7.7 to 9.8*	A1B, IS92a

Source:*AR4*, (IPCC 2007b: Working Group III, Technical Summary, Table TS.2); categorization of SRES scenario by *AR4* category was inferred by the authors from IPCC 2007 (Working Group I, Ch.10, Figure 10.24); SRES scenarios A2 and A1FI have stabilization trajectories higher than 790 ppm CO_2; temperature change converted from pre-industrial by subtracting 0.63°C, the pre-industrial to 1990 temperature increase.

The *Stern Review* (2006) presented the relationship between the atmospheric concentration of greenhouse gases and temperature change in terms of the likelihood of exceeding given temperature thresholds. An 82-percent chance of keeping global temperature change below 2.4°C from 1990 would require the CO_2 concentration to stabilize at 350 ppm; a 97 percent chance would require a 320 ppm CO_2 "stabilization trajectory" (or long-term concentration level). And like *AR4*, Stern's analysis assumed climate sensitivity levels below Hansen et al.'s: Stern's most likely value for climate

[4] Hansen et al. (2008, p.225): "Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity."

sensitivity was 3.0^{o}C, with the possibility that it might go as high as 4.5^{o}C; his high-sensitivity scenario assumed a most likely value of 3.9^{o}C, with the possibility of going as high as 5.4^{o}C.[5]

DICE-Adjusted

We experimented with a range of values for climate sensitivity, damage function exponent, and cost of achieving 100-percent abatement in DICE, exploring conditions under which the model recommends a quicker pace of abatement such that atmospheric CO_2 concentrations stabilize near 350 ppm.

In these sensitivity analyses we use a modified version of DICE in which we have:

- Updated the population projections to match the latest United Nations forecasts;
- Changed DICE's treatment of non-CO_2 greenhouse gases to be consistent with more detailed emissions modeling, and to allow abatement efforts to reduce future emissions of these gases; and
- Introduced the low discount rate used in the Stern Review, to place a greater value on future outcomes.

We refer to our version of DICE with these three modifications as "DICE-Adjusted," and to the model run without these modifications as "DICE-Original."

Technical modifications to DICE

DICE's exogenous population function was replaced by a time series that corresponds to the medium variant in UNDESA's most up-to-date population projections.[6] This change, made for sake of greater accuracy, increases population slightly in all periods.

Greenhouse gas emissions are often modeled in terms of their "radiative forcing," or the impact in W/m^2 of emissions on temperature change. DICE's exogenous non-CO_2 radiative forcings function was replaced by a time series that corresponds to a more standard set of non-CO_2 radiative forcings from MAGICC.[7] Among its suite of 49 pre-set scenarios, MAGICC includes the five well-known "WRE"[8] scenarios for CO_2 stabilization trajectories of 350, 450, 550, 650 and 750 ppm (Wigley et al. 1996). Specifically, we use the MAGICC WRE350 total non-CO_2 radiative forcings from 1765 with climate feedbacks turned off (to match the logic of the DICE climate module) at climate sensitivity 3°C. We kept non-CO_2 forcings for 3°C as a baseline in DICE-Adjusted when exploring different values of the climate sensitivity parameter in order to isolate the effects of those sensitivities (varying the non-CO_2 forcings would have only second-order effects).

---

[5] The "possibility of going as high as" refers to the upper end of the probability distribution for the Monte Carlo analysis employed in the Stern Review's modeling.

[6] Data for 2005 through 2050 taken from UNDESA (2008), *World Population Prospects: The 2008 Revision Population Database*, medium variant, http://esa.un.org/unpp/. Data for 2100 taken from UNDESA (2004), *World Population to 2300*, http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf. Population for 2055 to 2095 is a linear trend from cited data points. Population is assumed to be constant after 2100.

[7] The *Model for the Assessment of Greenhouse-Gas Induced Climate Change* (MAGICC 5.3) was developed at the U.S. National Center for Atmospheric Research (Wigley 2008) to model the technical relationships between emissions, atmospheric concentrations, and temperature levels.

[8] "WRE" refers to the last names of the research group that introduced these emissions profiles into the literature: Wigley, Richels and Edmonds (1996).

Together, all non-CO_2 gases including aerosols contribute radiative forcings close to zero in the current year.[9] This seems unlikely to continue, however, unless specific measures are taken to decrease the emission of non-CO_2 greenhouse gases such as methane, nitrous oxide, halocarbons, and ground-level ozone. In the absence of such measures, the impact of non-aerosol non-CO_2 greenhouse gases is likely to grow over time even as the countervailing effect of aerosols from fossil fuels shrinks; indeed, all of the IPCC's (2007b; 2001) SRES scenarios include the assumption of increasing non-CO_2 gases, at least in the short to medium term.[10]

MAGICC's representation of the WRE scenarios sets emissions such that atmospheric concentrations approach and stabilize at the given target level, assuming a climate sensitivity of 3°C. Because of climate feedbacks from temperature to atmospheric concentration, MAGICC's CO_2 concentration levels vary based on the assumed climate sensitivity. With a higher climate sensitivity, the same greenhouse gas emissions and concentrations translate into higher temperatures. These higher temperatures have a variety of positive feedback effects that increase concentrations in the next period (Wigley 2008).

In the absence of policy, DICE's non-CO_2 forcings rise linearly to 0.3 W/m2 by 2100 (and remain at this value thereafter) whereas MAGICC's WRE (and DICE-Adjusted) non-CO_2 forcings rise to 0.6 W/m2 in a similar time period (then gradually diminish over time to 0.3 by 2170 and less than 0.1 a century later). The MAGICC WRE assumptions are more consistent with no-policy, business-as-usual runs like IPCC's SRES A1 and A2.

In addition, we have modified the radiative forcing function in DICE-Adjusted such that non-CO_2 forcings are reduced by abatement policy in the same proportion as CO_2 emissions. For example, if 80 percent of CO_2 emissions are abated in a given period, then 80 percent of non-CO_2 emissions are also assumed to be abated. In the original DICE-2007 model, abatement affects only CO_2 emissions and never reduces other greenhouse gases.

Lowering the DICE discount rate

We make a final modification of DICE with the goal of placing a greater emphasis on intergenerational equity. A higher discount rate results in the treatment of future damage and abatement costs as less important to human welfare, relative to current costs; a lower discount rate increases the importance of future costs. We replaced the DICE rate of pure time preference, or utility discount rate, 1.5 percent, with the rate proposed in the *Stern Review (2006),* 0.1 percent. The Stern discount rate treats costs as

---

[9] Current emissions of non-CO_2 greenhouse gases (excluding aerosols) have been estimated to cause 1.15 W/m^2 in radiative forcing by Harvey (2007), and 1.21 W/m^2 in radiative forcing in MAGICC's WRE Scenarios (data for 2005 for methane, nitrous oxide, halocarbons, and tropospheric ozone only). Of the aerosols tracked by the IPCC (2007b), only black carbon from fossil fuels has positive radiative forcings (increasing temperature); most aerosols have a countervailing impact (negative radiative forcings that decrease temperature). Burning fossil fuels creates both large positive radiative forcings from CO_2 and smaller negative forcings from aerosols. The combined radiative forcings from aerosols is -1.18 W/m^2, and the current combined forcings from all non-CO_2 gases is, therefore, close to zero (IPCC 2007b: Working Group I, Technical Summary, p.29-30).

[10] For growth trends in non-CO_2 greenhouse gases in the SRES scenarios see the MAGICC 5.3 emissions profiles for these scenarios (Wigley 2008). For non-CO_2 emissions in the SRES A1FI scenario, see the IPCC's Data Distribution Centre database (2009), *DDC Home, Environmental Data, Atmospheric Data*, "The SRES A1FI Emissions Scenario," http://www.ipcc-data.org/sres/ddc_sres_emissions.html.

having almost the same impact on welfare regardless of the time period in which they occur.[11] This is not the only way to represent intergenerational equity; indeed, it could be argued that it is not the best way to do so (Howarth 1998). It is, however, the method that is most consistent with the structure of DICE.

DICE-Original versus DICE-Adjusted

The results for DICE-Original and DICE-Adjusted, using the DICE-2007 starting climate sensitivity of 3°C and damage exponent of 2, are marked in red in Tables 3 and 4, respectively. For these parameter values, DICE-Original reaches 100-percent emissions abatement in 2205, and hits a peak temperature increase of 2.8°C. DICE-Adjusted, in contrast, reaches 100-percent abatement 40 years earlier, and a peak temperature change of only 1.8°C. Atmospheric concentrations of CO_2 in 2105 are 598 ppm in DICE-Original, versus 542 ppm in DICE-Adjusted. The 350 ppm CO_2 level is centuries away in both models, reached in 2595 in DICE-Original versus 2535 in DICE-Adjusted.

DICE-Adjusted sets a higher priority on rapid abatement (by assuming a lower discount rate) and possesses more tools to keep temperatures in check (the option of abating non-CO_2 emissions). Slightly higher population trends in DICE-Adjusted also play a role: a larger population means a larger economy, generating more emissions and hence more risk of climate damages. Year 2105 damages are 2 percent of GDP in DICE-Original and 1.6 percent in the analogous run of DICE-Adjusted, again reflecting the latter version's greater urgency and greater ability to address climate change, and its stronger actions to keep temperatures and damages lower. For these same reasons, DICE-Adjusted spends more on abatement: 0.3 percent more of GDP in 2055 than DICE-Original (0.4 percent versus 0.1 percent).

Yet in the broader picture, both the original and adjusted versions of DICE-2007, run with climate sensitivity 3°C and damage exponent 2, agree that greenhouse gases can be abated slowly while maintaining high human welfare. The two models differ on whether to take 160 or 200 years to reach a carbon-free economy; they differ on which decade in the 26th century will see the atmospheric concentration of CO_2 dip below 350ppm for the first time.

Can DICE Stay Below 350ppm?

Welfare optimization models like DICE ask the question, what climate policy will result in the greatest human welfare? By running DICE-Adjusted for multiple climate sensitivity and damage exponent pairings, an additional question can be addressed: Under what circumstances would DICE recommend climate policy to achieve 350ppm CO_2 by 2100 as the policy leading to the greatest human welfare?

While DICE is normally run for a single set of "best guesses" at key parameters, it has also been modified to run in Monte Carlo mode to determine the effects on the model of uncertainty in key parameters. For an extensive Monte Carlo analysis of DICE, focusing on variation in climate sensitivity and the damage function exponent, see Ackerman et al. (2008). This research has shown that running DICE for a limited set of these parameters (the 32 possible combinations of climate sensitivity 3, 4, 5, 6, 7, 8, 9 and 10°C and damage exponents 2, 3, 4, and 5) is a near perfect substitute for running a computationally time-consuming Monte Carlo analysis. All of the results for climate sensitivity and

[11] See the Stern Review (2006), Ackerman et al. (2009), and Stanton et al. (2009).

damage exponent combinations that fall in between these integers follow a simple linear trend – there are no surprises or discontinuities.

We ran both the DICE-Original and DICE-Adjusted versions of the model for a limited subset of those parameter values – the four possible combinations of climate sensitivity 3 and 6°C, and damage exponents 2 and 3. Note that this set of values includes both of DICE-2007's assumed parameters – climate sensitivity 3°C and damage exponent 2. Again, a larger value for climate sensitivity means that the same amount of emissions give rise to a greater temperature increase. The larger the value of the damage function exponent, the more rapidly a given temperature increase causes significant economic harm.

The results for the four runs of the DICE-Original model are presented in

Table 2 and of the DICE-Adjusted model in

Table 3. We present the following six measures to represent the models' best efforts at successfully balancing economy growth and climate outcomes while limiting economic impacts:

- First year of 100 percent emissions control
- Peak temperature change in °C from 1990[12]
- Year 2105 CO_2 concentration (ppm)
- First year under 350 ppm CO_2 concentration
- Year 2105 damages as a share of GDP
- Year 2055 abatement costs as a share of GDP

[12] Temperature changes adjusted from the DICE output "change from 1900" to "change from 1990" by subtracting 0.6707°C (DICE's assumed temperature change from 1900 to 2000, 0.7307°C minus the historical climate change from 1990 to 2000). Historical data taken from World Resources Institute (2007) EarthTrends database, "Global Climate Trends 2005," http://earthtrends.wri.org/pdf_library/data_tables/cli5_2005.pdf.)

Table 2: DICE-Original Results

First Year of 100% Emissions Control

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**2205**	2135
	6	2155	2085

Peak Temperature Change in °C from 1990

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**2.8**	1.6
	6	3.6	1.9

Year 2105 CO_2 Concentration (ppm)

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**598**	504
	6	548	411

First Year Under 350ppm CO_2 Concentration

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**2595**	2435
	6	2545	2275

Year 2105 Damages as a Share of GDP

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**2.0%**	3.0%
	6	3.6%	4.6%

Year 2055 Abatement Costs as a Share of GDP

		Damage exponent	
		2	**3**
Climate sensitivity (°C)	**3**	**0.1%**	0.5%
	6	0.2%	1.5%

Notes: Results for DICE-2007 parameters – climate sensitivity 3°C and damage exponent 2 – are in red.
Source: Authors' calculation using a modified version of DICE-2007 (Nordhaus 2008).

Table 3: DICE-Adjusted Results

First Year of 100% Emissions Control

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	2165	2115
	6	2115	2065

Peak Temperature Change in °C from 1990

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	1.8	1.1
	6	2.2	1.3

Year 2105 CO_2 Concentration (ppm)

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	542	450
	6	455	377

First Year Under 350ppm CO_2 Concentration

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	2535	2345
	6	2345	2195

Year 2105 Damages as a Share of GDP

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	1.6%	1.6%
	6	2.2%	2.0%

Year 2055 Abatement Costs as a Share of GDP

		Damage exponent	
		2	3
Climate sensitivity (°C)	3	0.4%	1.1%
	6	1.0%	3.2%

Notes: Results for DICE-2007 parameters – climate sensitivity 3°C and damage exponent 2 – are in red.
Source: Authors' calculation using a modified version of DICE-2007 (Nordhaus 2008).

With a climate sensitivity of 3°C, a damage exponent of 2 results in DICE-Adjusted achieving 100-percent emissions abatement by 2165 (40 years before DICE-Original). With a climate sensitivity of 6°C, a damage exponents of 3 achieves this result by 2065; in this “worst case”, year 2055 abatement costs are 3.2 percent of GDP in DICE-Adjusted versus 1.5 percent in DICE-Original, while climate damages in 2105 are less than in DICE-Original by 2.6 percent of GDP (2.0 percent versus 4.6 percent); the DICE-Adjusted global mean per capita consumption is $13,000 by 2055. Note that with these "worst case" parameter values, both versions of the model achieve a CO_2 concentration if 350 ppm over three centuries earlier than with the default values in DICE (climate sensitivity of 3°C, a damage exponent of 2); DICE-Adjusted does so 80 years earlier than DICE-Original (2195 versus 2275).

In our “best case”, with climate sensitivity 3°C and a damage exponent of 2, year 2055 abatement costs are also higher with DICE-Adjusted (as discussed above), though an order of magnitude smaller than with a climate sensitivity of 6°C and a damage exponent of 3 in both versions of the model. In this “best case”, DICE-Adjusted climate damages in 2105 are less than in DICE-Original but by a much smaller percent of GDP than in the "worst case" combination of these parameters. As noted earlier in section 4, a CO_2 concentration if 350 ppm is only reached in the *26th* century with the "best case" values for climate sensitivity and damage exponent. The DICE-Adjusted global mean per capita consumption with the climate sensitivity of 3°C, a damage exponent of 2 is projected to be $13,600. In both cases, per capita consumption has grown sharply from its initial value of less than $7,000 in 2005.

Other combinations – climate sensitivity of 3°C with damage exponent of 3 or climate sensitivity of 6°C with damage exponent of 2 – generally produce results approximately in the middle of the range between the two extremes considered. Climate sensitivity of 3°C with damage exponent of 3, however, results in the lowest peak temperature increase of the four cases (1.1°C) and a climate damages share of GDP in 2105 that are as low (1.6 percent) as with the climate sensitivity of 3°C with damage exponent of 2.

These results demonstrate that with a new set of parameter values taken from the range found in the current literature, by 2105 DICE calls for a reduction of atmospheric concentrations of CO_2 to a level as low as 410 ppm using DICE-Original and 380 ppm using DICE-Adjusted.

Cost of abatement

Another key assumption driving these results is a parameter in DICE that sets the cost of 100-percent abatement in the first 10-year period at 5.6 percent of global output; abatement costs in future periods are a function of this initial value. Our sensitivity tests based on the DICE-Adjusted model show that this abatement parameter[13] strongly impacts the first year of 100-percent abatement, peak temperature change, time trend of CO_2 concentrations, and resulting damage and abatement costs.

Halving the cost of 100-percent abatement in the first period to 2.8 percent of global output speeds up emissions abatement: 100-percent emission control is reached 40 years sooner (in 2125 versus 2165 in DICE-Adjusted) at the default DICE climate sensitivity and damage exponent, and 20 years earlier at a climate sensitivity of 6°C and damage exponent of 3 (see

[13] Called "Pback" in DICE code.

Table 4). In contrast, doubling this cost parameter to 11.2 percent slows down full emissions control by 30 years with climate sensitivity of 6°C and damage exponent of 3. At the DICE default climate sensitivity and damage exponent, full abatement occurs 40 year later (in 2205 instead of 2165) (see Table 5).

Table 4: DICE-Adjusted with Abatement Costs Halved

First Year of 100% Emissions Control		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**2125**	2085
	6	2075	2045

Peak Temperature Change in °C from 1990		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**1.3**	0.8
	6	1.5	1.0

Year 2105 CO_2 Concentration (ppm)		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**471**	399
	6	391	360

First Year Under 350ppm CO_2 Concentration		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**2375**	2255
	6	2235	2145

Year 2105 Damages as a Share of GDP		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**1.0%**	0.7%
	6	1.3%	1.3%

Year 2055 Abatement Costs as a Share of GDP		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	**0.4%**	1.0%
	6	1.1%	1.8%

Notes: Results for DICE-2007 parameters – climate sensitivity 3°C and damage exponent 2 – are in red.
Source: Authors' calculation using a modified version of DICE-2007 (Nordhaus 2008).

Table 5: DICE-Adjusted with Abatement Costs Doubled

First Year of 100% Emissions Control		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	2205	2145
	6	2155	2095

Peak Temperature Change in °C from 1990		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	2.6	1.5
	6	3.2	1.7

Year 2105 CO_2 Concentration (ppm)		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	598	503
	6	529	406

First Year Under 350ppm CO_2 Concentration		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	2595	2455
	6	2495	2265

Year 2105 Damages as a Share of GDP		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	2.1%	2.7%
	6	3.4%	3.5%

Year 2055 Abatement Costs as a Share of GDP		Damage exponent 2	Damage exponent 3
Climate sensitivity (°C)	3	0.3%	1.2%
	6	0.8%	3.5%

Notes: Results for DICE-2007 parameters – climate sensitivity 3°C and damage exponent 2 – are in red.
Source: Authors' calculation using a modified version of DICE-2007 (Nordhaus 2008).

Conclusions and policy recommendations

DICE's optimal policy recommendation changes markedly with variation of the key inputs within the range of likely values in the current literature. With a climate sensitivity of 6°C and a damage exponent of 3, DICE-Adjusted recommends that:

- All carbon emissions be eliminated in less than 60 years;
- Peak temperature increases be limited to 1.3°C; and
- Atmospheric CO_2 concentrations be 380 ppm or less at the beginning of the next century (although more time is required for concentrations to sink back all the way to 350 ppm, since DICE does not include net negative emissions options).

Our analysis shows that at the higher end of the current range of estimates of two key parameters (climate sensitivity of 6°C or higher and damages at the third power of temperature), DICE calculates that its measure of human welfare is maximized by keeping peak temperature increases very low, and achieving a completely emission-free world economy in the next half century or so. We do not present our modified version of DICE as a perfect analysis of the economics of climate change, but rather as a demonstration that the cautious policy recommendations sometimes associated with IAMs such as

DICE result from their choice of input assumptions, and not from any theoretical or empirical insights about economics, climate, or their interactions.

In short, there are plausible combinations of values for key, uncertain parameters which would lead DICE to call for reaching 380 ppm CO_2 in about a century – down from 600 ppm in the unmodified DICE model – while still projecting rising incomes, with only slightly slower economic growth.

References

Ackerman, Frank and Elizabeth A. Stanton (2008). *Climate Change and the U.S. Economy: The Costs of Inaction.* Medford, MA. Tufts University Global Development and Environment Institute and Stockholm Environment Institute-US Center. Available online at http://www.sei-us.org/climate-and-energy/US_Costs_of_Inaction.doc.

Ackerman, Frank, Elizabeth A. Stanton and Ramón Bueno (2008). “Fat Tails, Exponents and Extreme Uncertainty: Simulating Catastrophe in DICE.” *SEI-US Working Papers*. Somerville, MA: Stockholm Environment Institute -- U.S. Center. Available online at http://www.sei-us.org/WorkingPapers/index.html.

Ackerman, Frank, Elizabeth A. Stanton and Ramón Bueno (2010). *CRED: A New Model of Climate and Development.* UN/DESA Working Paper No. 96. New York: United Nations Department of Economic and Social Affairs. Available online at http://www.un.org/esa/desa/papers/2010/wp96_2010.pdf.

Clement, Amy C., Robert Burgman and Joel R. Norris (2009). “Observational and Model Evidence for Positive Low-Level Cloud Feedback.” *Science* 235, 460-64.

Hanemann, W. Michael (2008). *What is the Economic Cost of Climate Change?* CUDARE Working Paper No. 1071. Berkeley, CA. University of California-Berkeley, Department of Agricultural and Resource Economics and Policy. Available online at http://repositories.cdlib.org/are_ucb/1071/.

Hansen, James, Makiko Sato, Pushker Kharecha, David Beerling, Robert Berner, Valerie Masson-Delmotte, Mark Pagani, Maureen Raymo, Dana L. Royer and James C. Zachos (2008). “Target Atmospheric CO2: Where Should Humanity Aim?” *The Open Atmospheric Science Journal* 2, 217-31.

Intergovernmental Panel on Climate Change (2001). *Third Assessment Report: Climate Change 2001 (TAR).* Geneva, Switzerland. IPCC.

Intergovernmental Panel on Climate Change (2007a). *Climate Change 2007 - IPCC Fourth Assessment Report*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (2007b). *Fourth Assessment Report: Climate Change 2007 (AR4).* Geneva, Switzerland. IPCC.

Nordhaus, William D. (2008). *A Question of Balance: Economic Modeling of Global Warming*. New Haven, CT: Yale University Press.

Risbey, James, Milind Kandlikar and Anand Patwardhan (1996). “Assessing integrated assessments.” *Climatic Change* 34:3, 369-95. Available online at http://dx.doi.org/10.1007/BF00139298

Roe, Gerard H. and Marcia B. Baker (2007). “Why is Climate Sensitivity So Unpredictable?” *Science* 318, 629-32.

Stanton, Elizabeth A., Frank Ackerman and Sivan Kartha (2009). “Inside the Integrated Assessment Models: Four Issues in Climate Economics.” *Climate and Development* 1:2, 166-84.

Stern, Nicholas (2006). *The Stern Review: The Economics of Climate Change.* London: HM Treasury. Available online at http://www.hm-treasury.gov.uk/stern_review_report.htm.

Wigley, T.M.L., R. Richels and J.A. Edmonds (1996). “Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations.” *Nature* 379:6562, 240-43. Available online at http://www.nature.com/nature/journal/v379/n6562/pdf/379240a0.pdf.

Wigley, Tom M.L. (2008). *MAGICC/SCENGEN 5.3: User Manual (Version 2).* Boulder, CO. National Center for Atmospheric Research. Available online at http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf.