The DICE model and its discontents

Emanuele Campiglio[1,2,3]

Climate macroeconomics & finance 2024/25 - Lecture 7

[1]University of Bologna - Department of Economics (DSE)
[2]RFF-CMCC European Institute on Economics and the Environment (EIEE)
[3]LSE Grantham Research Institute

Last lectures + Today

- Complex dynamic problem
  - How will we able to ensure a rapid and smooth low-carbon transition?
  - Multiple macro-financial implications/requirements
- We want to explore possible futures
  - $\rightarrow$ We need prospective models
  - Some key building blocks of climate-economy interactions
- Today: the DICE model
  - The ‘godfather’ of climate economic modelling
  - or.. ‘the model that everyone loves to hate’

The DICE model structure

The ‘dynamic integrated climate economy’ (DICE) model

- Start: 1992 paper on Science
- Latest version:
  - DICE2023 with Lint Barrage
  - See code available in both GAMS and Excel
  - Good reading: 2017 paper on PNAS
- 2018 Nobel Prize in Economics
  - “for integrating climate change into long-run macroeconomic analysis”
  - Nobel lecture (video) (AER article)

William Nordhaus (1941-)

Social welfare function

- Social welfare is the discounted sum of the future stream of population-weighted instantaneous utilities:

$$W = \sum_{t=1}^{T} \frac{U(c_t)L_t}{(1+\rho)^t}$$

- $U(c)$: utility as a function of per capita consumption
- L: population
- ρ: Pure rate of social time preference
    - Also called ‘rate of time impatience’ or ‘time discount rate’
    - Set to 2.2% in DICE; to 0.1% in the Stern Review
    - Choosing this value has ethical implications: how do we treat future generations compared to the present ones?

Utility function

- Isoelastic utility function

$$U(c_t) = \frac{c_t^{1-\varphi}}{1-\varphi}$$

- φ: Elasticity of marginal utility of consumption (set to 0.9)
  - It can be interpreted as a measure of relative intergenerational inequality aversion
  - The intertemporal elasticity of substitution is $\frac{1}{\varphi}$
  - Coincides with risk aversion here, but different concepts (see Epstein and Zin preferences)
- Remember Lecture 6: $SDR = \rho + \varphi g$
  - Given values for ρ and φ, discount rate in DICE roughly 4.6% in first period and declines to 3.4% in 2100

Production

- Cobb-Douglas production function

$$Y_t = A_t K_t^{\gamma} L_t^{1-\gamma}$$

- Y: Gross output (before damages and mitigation)
- A: TFP parameter
    - TFP increases exogenously at a declining growth rate
    - Hicks-neutral technological progress, i.e. $\frac{K}{L}$ is not affected
- K: Capital stock (endogenous)
- L: Population
    - L grows asymptotically to 10.8 billion
    - Population = labour
- γ: elasticity of output with respect to the capital (set to 0.3)

Emissions

- DICE2023 includes three types of emissions:
- CO2 industrial emissions (already present)
  - Function of production Y
  - σ: Carbon intensity, with $\sigma_{2015} \approx 0.29$
  - σ decreases exogenously, first rapidly (-1.5% per year) then more slowly (approaching -0.5%)
- Land use CO2 emissions (new)
  - Exogenous decline by 10% per time period
- non-CO2 GHG emissions (new)
  - Abateable fraction of non-CO2 emissions $\approx$ 12% of CO2 emissions

$$E_{base,t} = \sigma_t Y_t + E_{land,t} + E_{nonCO2,t}$$

Emission abatement

- Emissions can be abated
  - μ: Emission reduction rate (or 'control rate')
  - New in DICE2023: carbon price as additional control option
  - μ set to 0.05 in baseline scenario ($6/tCO2)

$$E_t = (1 - \mu_t) E_{base,t}$$

- Abating emissions is costly $\rightarrow$ Abatement cost function

$$\Lambda = \theta_{1,t} \mu_t^{\theta_2}$$

  - θ_1 is a function of the price of the backstop technology
  - $\theta_2 = 2.6$

Backstop technology

- Backstop technology concept
  - Set of technologies capable of replacing fossil fuels (renewables, CCS, CDR, nuclear fusion, etc.)
- Exogenous decrease in time

$$p_{b,t} = p_0(1 - g_b)^t$$

  - with $p_{b,2050} = 515\$/tCO2$ taken from larger IAMs (ENGAGE)
  - $g_b = 1\%$ in 2020-2050, $g_b = 0.1\%$ after 2050
- Calibrate $\theta_{1,t}$ so that MAC equals $p_{b,t}$ when $\mu = 1$
  - $\rightarrow \theta_{1,t} = \frac{p_{b,t}\sigma}{\theta_2}$
  - $\rightarrow$ Net-zero emissions in 2020 would cost ≈11% of output (2.7% in 2100)

Climate damages

- DICE2023 climate module is an adaption of the FAIR model. In a nutshell
  - Emissions affect GHG atmospheric concentration $\rightarrow$ Concentration affects radiative forcing $\rightarrow$ Radiative forcing causes increase in temperatures
- Finally, temperature creates damages

$$\Omega_t = \psi_1 T_{AT,t} + \psi_2 T_{AT,t}^2$$

  - where Ω is the damage ratio (damages/GDP)
  - with $\psi_1 = 0$ and $\psi_2 = 0.003467$
  - Based on recent estimates (see Piontek et al. (2021) from Lecture 2 + Estimates of tipping point damages (see Dietz et al. (2021) + adjustment for non-market damages
  - $\rightarrow$ 3.1% of GDP lost at 3°C; 7% at 4.5°C

Macro accounting variables

- Net output is equal to gross output less damages and abatement costs

$$Q_t = \frac{(1 - \Lambda_t) Y_t}{1 + \Omega_t}$$

- Net output is allocated between consumption and investments

$$Q_t = C_t + I_t$$

- Investments contribute to accumulating capital stock

$$K_{t+1} = (1 - \delta_K) K_t + I_t$$

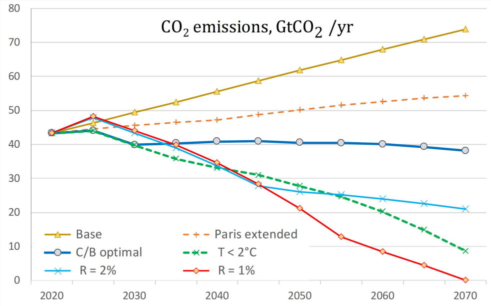
with depreciation rate $\delta = 10\%$

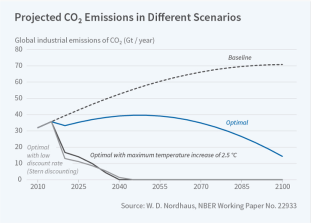
DICE numerical results

Scenarios

- No controls
  - μ set to zero for entire simulation
- Baseline (or 'BAU')
  - Extension of current policies
  - Carbon price=\$6/tCO2 in 2020, increasing 1% per year)
- Paris-extended
  - Updated NDCs to 2030 achieved
  - μ increases $\approx$0.5% per year after 2030
- Cost-benefit optimal
  - μ is a decision variable
  - Trade-off between abatement and damage costs
- Temperature-limited
  - Additional temperature constraint to CB run (e.g. 2°C)
- Change in parameters
  - Higher/lower discount rate
  - Higher/lower damage coefficient

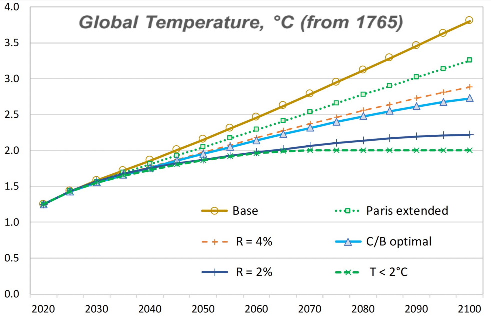
DICE results - Emission paths

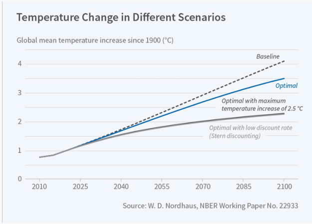




Source: Nordhaus and Barrage (2023) (left) Nordhaus (2017) (right)

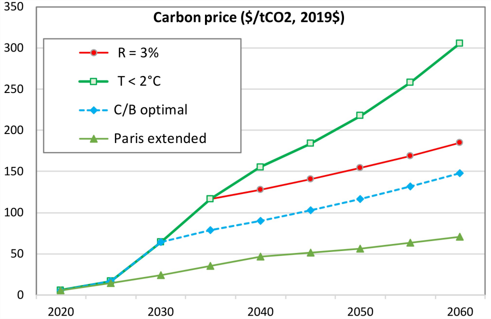
DICE results - Temperature paths

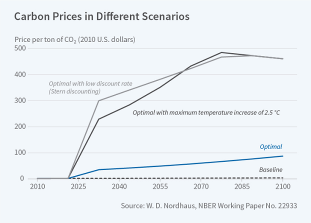




Source: Nordhaus and Barrage (2023) (left) Nordhaus (2017) (right)

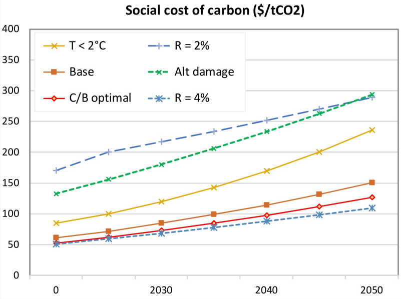
DICE results - Carbon price paths

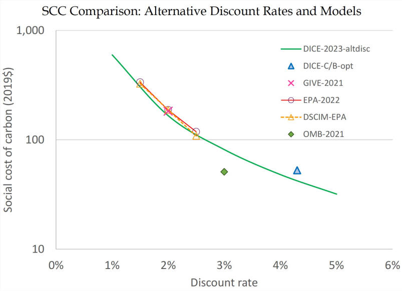




Source: Nordhaus and Barrage (2023) (left) Nordhaus (2017) (right)

DICE results - Social Cost of Carbon





DICE 2023-altdisc: alternative constant discount rates; DICE- C/B-opt: C/B optimal scenario with average 2020 – 2050 discount rate; GIVE-2021: estimate from GIVE model; EPA-2022: US Environmental Protection Agency; DSCIM-EPA estimates specific to damage module based on DSCIM framework; OMB-2021: US Office of Management and Budget. Source: Nordhaus and Barrage (2023)

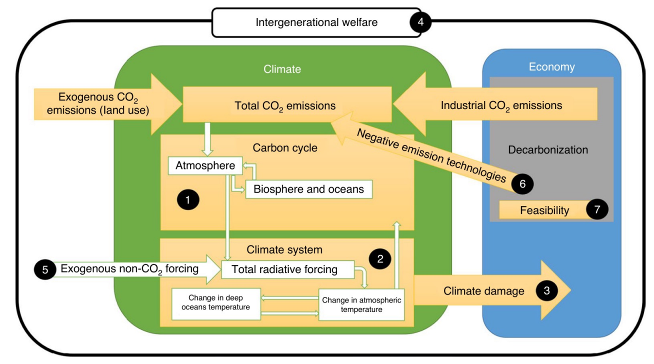
Moving beyond DICE

Strengths and limitations

- In climate econon, the DICE model is both the most followed..
    - The first to do it: benchmark for everyone else
    - Simple and following standard econ setting
    - Open-access: play for yourself
    - Most papers compare their results to DICE
- .. and the most criticised
    - Simplistic setting
    - No regional disaggregation (although RICE model)
    - Shaky empirical foundations (e.g. damage function)
    - No inertia: just turn up μ and get abatement; but really, painful structural change $K_d \to K_c$
    - Technological change is exogenous, no learning
    - Entirely deterministic: no uncertainty

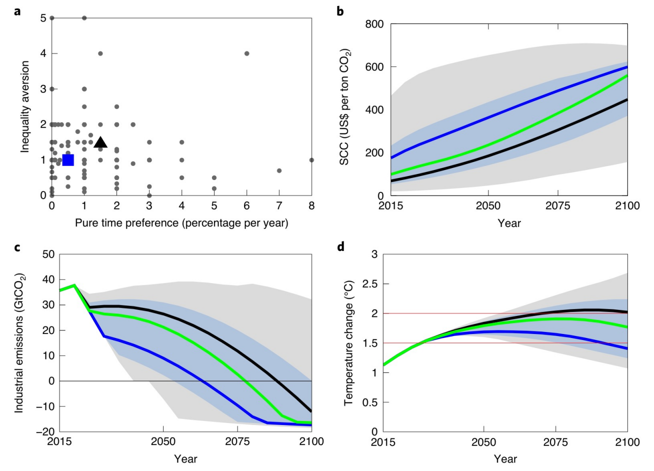
First strategy: Improve DICE

- See for instance Hansel et al. 2020
  - Note: some of these improvements were included in DICE2023



Updates to DICE2016: 1) carbon cycle based on FAIR model; 2) update of energy balance model; 3) damage estimate revised to Howard and Sterner (2017); 4) expert views on intergenerational welfare; 5) non-CO2 forcing; 6) earlier availability of NETs; 7) constraints on maximum rate of decarbonization. Source: Hansel et al. 2020

Hansel et al. 2020 results



a) Experts' judgements on discounting parameters (n = 173); Black triangle: DICE2016 values; Blue square: median expert view; b-d) climate policy pathways; black: updated DICE; blue: median expert view; green: median expert path. Source: Hansel et al. 2020

Second strategy: use something else

- Other pioneering medium-scale models
    - FUND model by Richard Tol and collaborators
    - PAGE model by Chris Hope and collaborators
    - DICE, FUND and PAGE are used to calculate SCC in US
- Two main evolutions from this first generation
    - Go big: large-scale numerical models with multiple regions and detailed representation of technologies
    - Go small: simplified models aimed at deriving analytical solutions

Addendum: An application to climate finance

- What would be the impact of climate change on asset values?
  - Value at Risk (VaR): potential portfolio loss over a given time horizon, at a given probability
- Starting point: DICE 2010
  - Modified climate damages: on both growth and capital stocks
- Some assumption
  - Asset values = NPV of discounted cash flows
  - Corporate earnings constant % of GDP $\rightarrow$ same growth rates
  - Debt and equity perfect substitutes

Table 1 | The present value at risk of global financial assets from climate change between 2015 and 2100—the climate VaR.

Emissions scenario	1st pctl.	5th	Mean	95th	99th
BAU (expected warming of 2.5 °C in 2100)	0.46%	0.54%	1.77%	4.76%	16.86%
Mitigation to limit warming to 2 °C with 2/3 probability	0.35%	0.41%	1.18%	2.92%	9.17%

Source: Dietz et al. (2016)