Climate economic modelling

Climate macro and finance course 2021 - Lecture 4

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Introduction

A recap: What are the societal objectives?

- 1. A rapid low-carbon transition
  - Anthropogenic GHG emissions contribute to climate change
  - Policy objective: keep temperatures below 1.5-2°C
  - Decarbonisation of productive systems needed (+ wider sustainability)
  - This requires reallocation of physical/financial investments
- 2. A smooth low-carbon transition
  - Almost all productive activities require fossil fuels as direct/indirect input
  - An abrupt transition could lead to macro-financial instability?

What do we need to understand?

	Rapid transition	Smooth transition
Obstacles	Obstacles to physical/financial low-carbon investments?	Drivers and transmission channels of transition-related disruptions?
Solutions	How to accelerate physical/financial low-carbon investments?	How to mitigate climate-related risks?

Four main broad research questions

1. Obstacles to low-carbon investment

- Underlying question:
  - How do individuals take investment decisions?
- Relative returns/productivity of technologies
  - Low-carbon options still often less competitive
  - Some of the returns are system-dependent (network effects)
- Uncertainty
  - Policy implementation, technical progress, climate impacts, changes in preferences, etc..
  - Hedging and diversification strategies
- Inertia and lock-ins
  - Past investments still needing to provide returns
- Cognitive elements
  - Emotions, sentiments, biases, habits, routines, imitation

2. Policies for low-carbon investments

- Policy options to orient investments
  - Carbon pricing, public investment/lending, monetary policies, 'prudential' policies
- Understand what happens if implemented
  - Effectiveness, their implications for other macro variables, their synergies/clashes
- Can they be implemented?
  - Institutional feasibility, political acceptability, law

3. Sources of transition risks

- Drivers
  - Where in the system could a disruption originate?
  - Role of expectations alignment
- Transmission channels
  - Through which mechanisms would disruptions propagate?
  - Analysis of production/financial networks
- Impacts
  - How could socio-economic and financial systems be affected?
  - Impact on transition dynamics?

4. Policies to mitigate climate-related risks

- Methods to assess exposure to physical/transition risks
  - Companies, financial institutions, financial system
  - Stress-testing vs long-run models
- Calibrate financial policies to incorporate risks?
  - Institutional feasibility
  - What happens if implemented?
- Impacts on monetary policy
  - Inflation and interest rate setting

Ideal methodological dimensions (I)

- Representation of multiple technologies
  - At least green vs dirty dichotomy
- Representation of physical assets
  - Including capacity utilisation rates (physical stranding)
  - Vintages of stocks; technological development; inertia
- Representation of financial markets
  - Assets: credit, bonds, equities
  - Institutions: firms, banks, asset managers, central banks
  - Realistic representation of credit creation and allocation
- Representation of climate damages
  - Disaster impact; temperature change; tipping points
- Representation of networks of exchanges and assets
  - Production and financial networks

Ideal methodological dimensions (II)

- Representation of investment behaviour
  - Realistic representation of expectations (planning horizons)
  - Representation of ‘sentiments’ (realisation, reversal, herding)
  - Role of uncertainty
- Representation of structural change
  - Shifts in technological paradigms
  - Sunrise and sunset industries
- Representation of policies
  - Social/fiscal/monetary/financial/
  - Synergies and clashes among them
- Representation of institutions
  - Especially central banks and governments
  - Including their balance sheets

Possible research strategies

- No single methodology includes (or will ever include) all dimensions
  - Pluralistic methodological approaches needed
- Several research strategies:
  - Conceptual frameworks (e.g. Semieniuk et al. 2021)
  - Empirical analysis (e.g. financial asset pricing; but: backward-looking)
  - Dynamic macroeconomic modelling (multiple methods)
  - Network analysis (e.g. Cahen-Fourot et al. 2021)
  - Political economy of transitions (e.g. Baer et al. 2021)

Outline

- Today: Overview of dynamic modelling methodologies
- Start from climate economics
  - The DICE model
  - Integrated Assessment Models (IAMs)
  - Computable General Equilibrium (CGE) models
- Next lecture: Overview of alternative approaches
  - Dynamic Stochastic General Equilibrium (DSGE) models
  - Capital Asset Pricing Models (CAPM)
  - Stock-Flow Consistent (SFC) models
  - Agent-Based Models (ABMs)

Two main methodological avenues

	Equilibrium	Non equilibrium
Behaviour drivers	Intertemporal optimisation of a welfare function	Macro-econometric relations
Determination of output	Supply-driven: output (production) is allocated between different uses (consumption and investment) Y=AKL	Demand-driven: output (income) is determined by the expenditure desires (consumption and investment) Y=C+I+G
Expectations	Forward-looking expectations by rational agents	Adaptive expectations by agents in a context of deep uncertainty
Decisions	Rational	Routines in a context of deep uncertainty
Equilibrium	The system moves to an equilibrium state (balanced growth path)	There is not necessarily an equilibrium (cycles, emergent behaviours)
Money	Money as a 'veil' (banks as intermediaries)	Endogenous money (credit creation by commercial banks)
Modelling approaches	IAM, CGE, DSGE, CAPM	SD, SFC, ABM
Communities	Economics, Finance, Environmental/Energy Economics	Social sciences, Ecological/Evolutionary Economics

Let’s start with integrated assessment

- Aim: assess in an integrated manner the interactions between
  - Human activities
  - Natural environment
- Usually applied to climate change issue
  - Human activities (esp. energy) create emissions..
  - ..emissions affect climate dynamics..
  - ..climate damages human activities
- Two main uses
  - Cost-benefit analysis (optimal path)
  - Cost effectiveness (reach exogenous constraint)

The DICE model

The ‘dynamic integrated climate economy’ (DICE) model

- Start: 1992 paper on Science
- Latest version:
  - DICE2016 (see code)
  - Available in GAMS and Excel
  - 2017 paper on PNAS
- 2018 Nobel Prize in Economics
  - “for integrating climate change into long-run macroeconomic analysis”
  - Nobel lecture on AER

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 1.5% in DICE; to 0.1% in the Stern Review
    - Choosing this value is an ethical question: how do we treat future generations compared to the present ones?
    - $SDR = \rho + \alpha g$

Utility function

- Isoelastic (or 'power', or 'CRRA') utility function
$$U(c_t) = \frac{c_t^{1-\alpha}}{1-\alpha}$$
- α: Elasticity of marginal utility of consumption (set to 1.45)
  - It can be interpreted as a measure of relative intergenerational inequality aversion
  - The intertemporal elasticity of substitution is $\frac{1}{\alpha}$
  - Coincides with risk aversion here, but different concepts (see Epstein and Zin preferences)

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 logistically in time (exogenous)
  - Hicks-neutral technological progress, i.e. $\frac{K}{L}$ is not affected
- K: Capital stock (endogenous)
- L: Population
  - L grows asymptotically to 11.5 billion
  - Population = labour
- γ: elasticity of output with respect to the capital (set to 0.3)

Emissions

- Emissions result from production

$$E_t = \sigma_t(1 - \mu_t)Y_t$$

- σ: Carbon intensity
  - $\sigma_{2015} \approx 0.35$
  - σ decreases exponentially, first rapidly (-1.5% per year) then more slowly (exogenous)
- μ: Emissions reduction rate (endogenous)
- Abating emissions is costly

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

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

Backstop technology

- Backstop technology concept
  - A technology capable of satisfying demand with a virtually infinite resource base
  - Fossil emissions: renewables, CCS, CDR, nuclear fusion, etc.
- Exogenous decrease in time

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

  - with $p_{b,2015} = 550\$$ per tCO2 and $g_b = 2.5\%$
- Calibrate $\theta_{1,t}$ so that marginal abatement cost when $\mu = 1$ equals $p_{b,t}$
  - Marginal abatement cost

$$\frac{\partial Q_t}{\partial E_t} = -\frac{\theta_{1,t}\theta_2}{\sigma_t}\mu^{\theta_2 - 1}$$

  - So we set

$$\theta_{1,t} = \frac{p_{b,t}\sigma}{\theta_2}$$

Climate damages

- Emissions enter the carbon cycle, made of three interacting reservoirs
  - Carbon in the atmosphere (M_{AT})
  - Carbon in the upper oceans and the biosphere (M_{UP})
  - Carbon in the deep oceans (M_{LO})
- M_{AT} affects radiative forcing F
  - F is a measure of the difference between incoming and outgoing solar radiation, relative to 1750 ($F_{1750} = 0$)
- Higher F warms the atmospheric layer (T_{AT})
- 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 $\psi_2 = 0.00236$
  - $\rightarrow$ 2.1% of GDP lost at 3°C; 8.5% at 6°C

Macro 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

$$Q_t = C_t + I_t$$

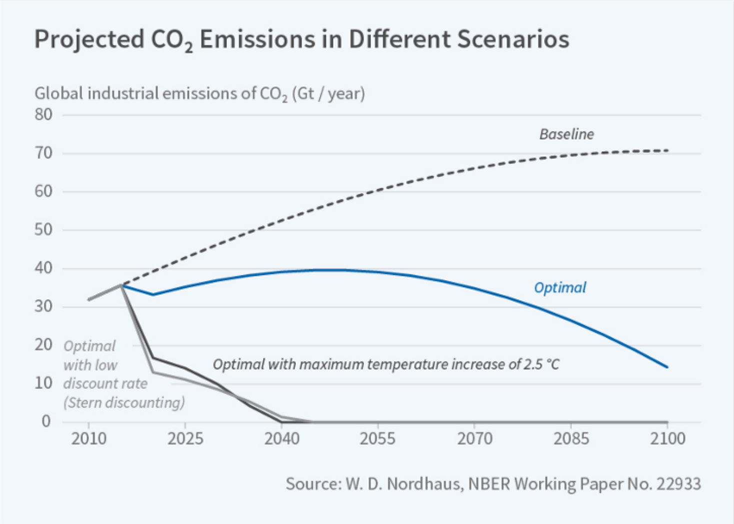
- Investments contribute to accumulating capital stock

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

Scenarios

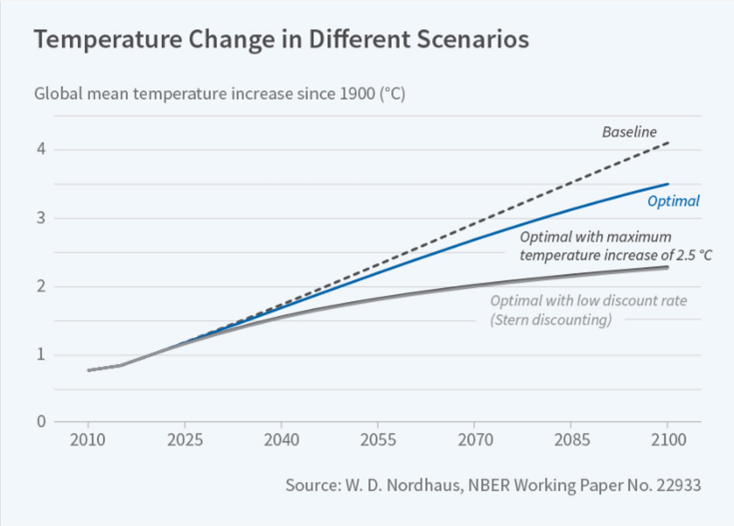
- Baseline (or ‘BAU’)
  - μ set to zero for entire simulations
- Optimal run
  - μ is a decision variable
  - It can be used to derive the social cost of carbon
- Temperature constraints
  - Set peak or average temperature to respect a threshold (e.g. 2°C)
- Change in parameters
  - E.g. Higher/lower discount rate

DICE results - Emission paths



Source: Nordhaus (2017)

DICE results - Temperature paths



Source: Nordhaus (2017)

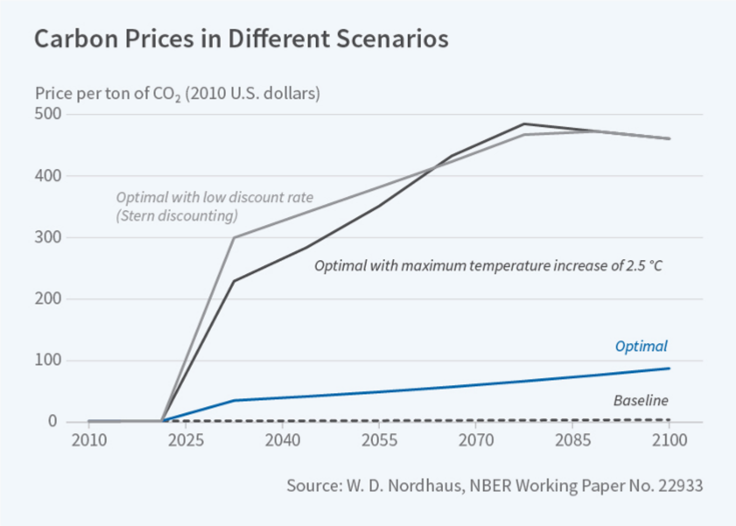
The social cost of carbon (SCC)

- The SCC computes the monetary present value of all costs and benefits deriving from emitting an additional tonne of CO_2.
- Nordhaus calculates it as

$$SCC_t \equiv \frac{\partial W}{\partial E_t} \Big/ \frac{\partial W}{\partial C} \equiv \frac{\partial C_t}{\partial E_t}$$

  - It's a shadow price, the cost of emitting an additional unit of CO_2 in terms of consumption
- This has come to signify the optimal carbon price to apply

DICE results - Carbon price paths



Source: Nordhaus (2017)

Other IAMs

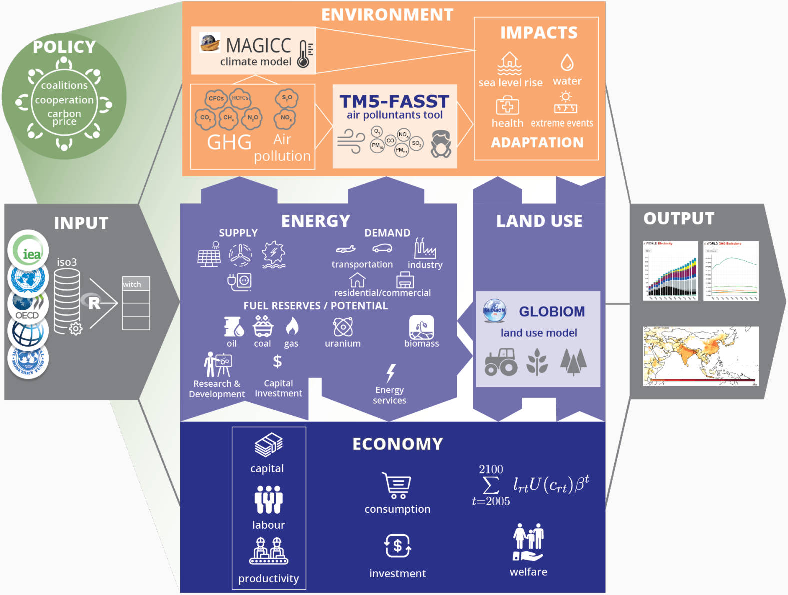
- Other well-known medium-scale models
  - FUND model by Richard Tol and collaborators
  - PAGE model by Chris Hope and collaborators
  - DICE, FUND and PAGE are used to calculate SCC in US
- Two main evolutions from this first generation
  - Go big: large-scale numerical models with multiple regions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

Large-scale numerical IAMs

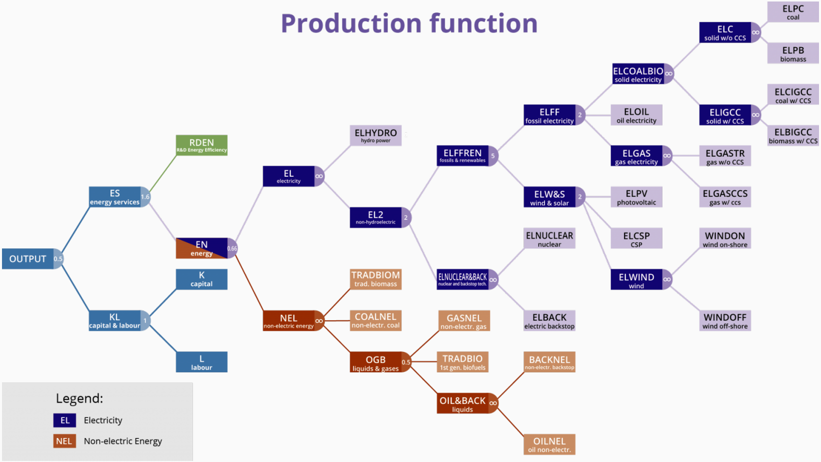
Large-scale numerical IAMs

- Common features across models
  - Multiple regions
    - Cooperative/non-cooperative behaviour; coalitions
    - Equity issues (burden-sharing, transfers)
  - Detailed energy sources/technologies and pollutants
  - Small climate modules (or links to larger climate models)
  - Economic modules also tend to be simple (or absent)
    - Exception: CGE models (are they IAMs?)
- But large variability across models
  - Partial vs general equilibrium
  - Simulation vs optimization
  - Recursive dynamic (myopic) vs intertemporal optimization (foresight)
  - Different representation of climate impacts, non-energy sectors, land use, regions..

An example: The WITCH model



The WITCH production function



Source: WITCH website

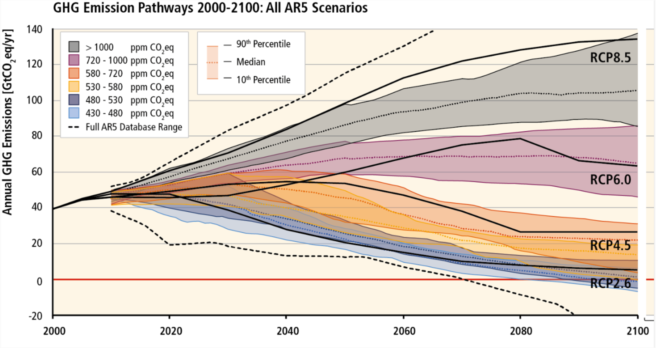
- More details in the WITCH documentation

Many other large IAMs exist

- Other notable models:
    - MESSAGE model (IIASA, Austria)
    - GCAM model (JGCRI, United States)
    - IMAGE (PBL, Netherlands)
    - REMIND model (PIK, Germany) IMACLIM (CIRED, France)
    - E3ME (Cambridge Econometrics, United Kingdom)
- An overview:
    - See the IAM Consortium Wiki paper

Common scenarios: RCPs

- IPCC AR5: Representative Concentration Pathways (RCPs)
  - Based on radiative forcing in 2100; expressed in W/m2
  - RCP2.6 (stringent mitigation); RCP4.5; RCP6.0; RCP8.5 (high emissions)



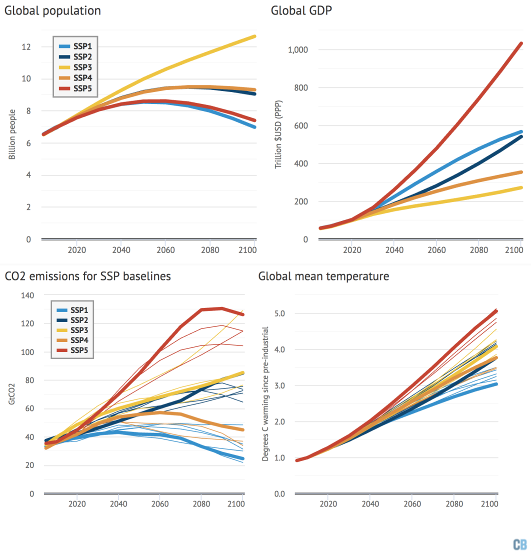
Source: IPCC (2014)

Common scenarios: SSPs

- IPCC AR6: Shared Socioeconomic Pathways (SSPs)
  - Based on socio-economic narratives (irrespective of climate policy)
  - Population, urbanization, GDP, technology..

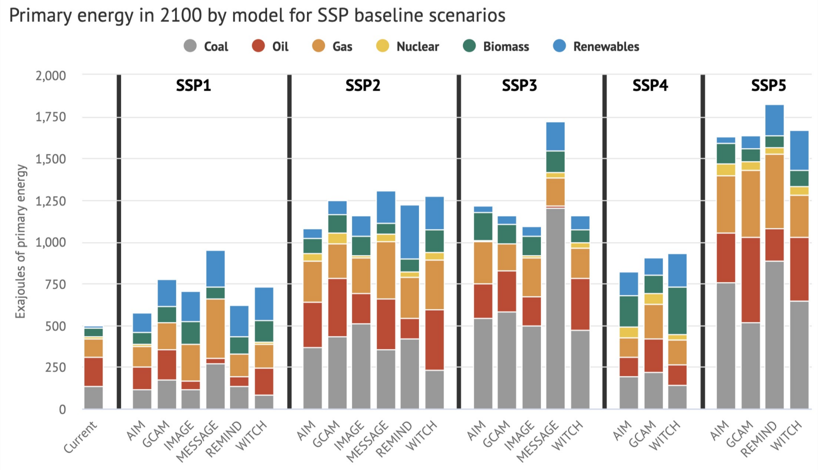
Source: O'Neill et al. (2017) and Rihai et al. (2017)

SSP scenarios



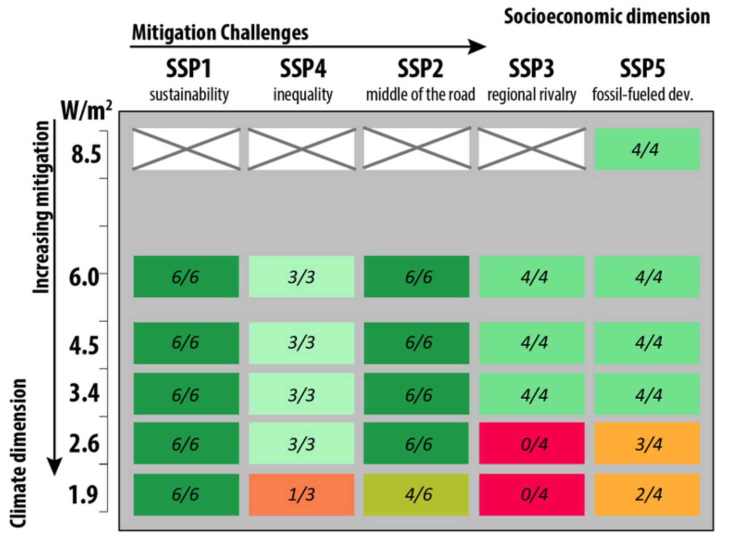
Source: Carbon Brief (2018)

SSP energy implications



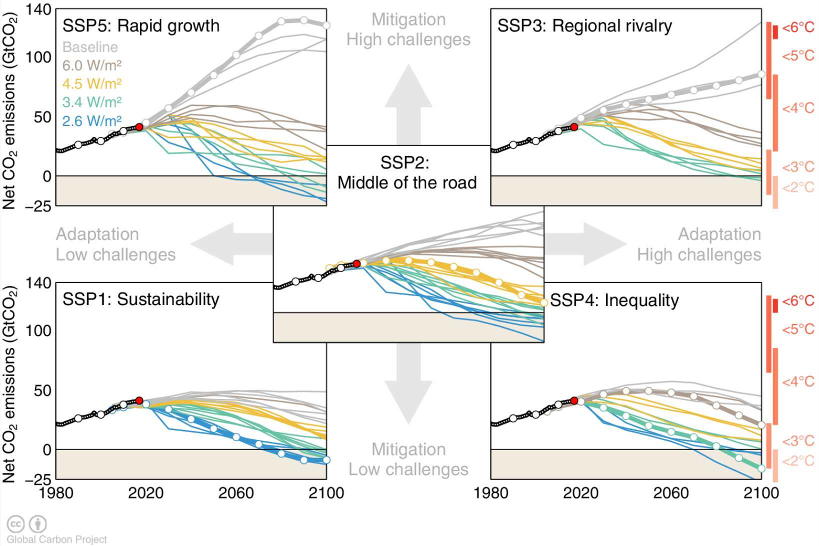
Source: Carbon Brief (2018)

Combining RCPs with SSPs



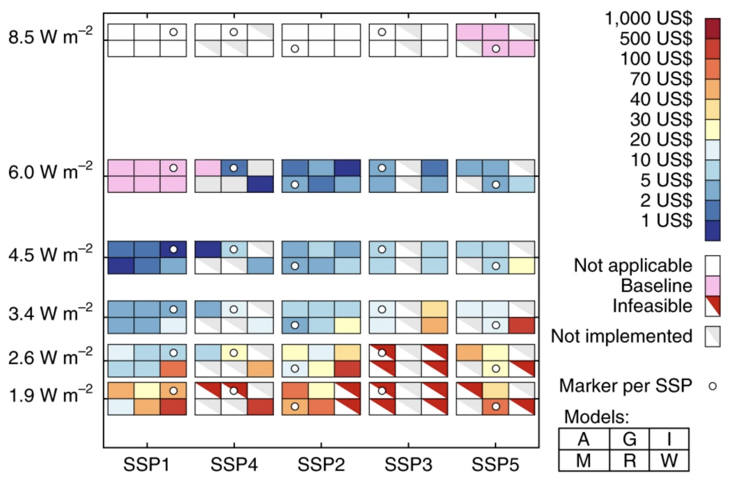
In cells: numbers of models with feasible scenarios. Source: Rogelj et al. (2018)

Combining RCPs with SSPs



Source: Peters (2017)

Combining RCPs with SSPs



Average global average carbon prices over the 20202100 period discounted to 2010 with a 5% discount rate. Source: Rogelj et al. (2018)

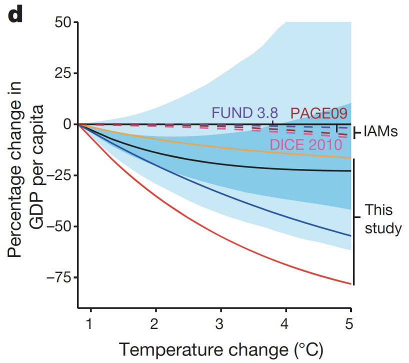
Analytical IAMs

Analytical IAMs

- Small-scale IAMs with simplified relations
- Usually aimed at deriving analytical rules for the SCC (i.e. optimal carbon price)..
    - Golosov et al. (2014) on Econometrica
    - Rezai and Van der Ploeg on JAERE
    - Gerlagh and Liski (2018) on EJ
    - Cai and Lontzek (2018) on JPE
    - van den Bijgaart et al (2016) on JEEM
- .. or cost-efficient paths to a temperature target / carbon budget
    - Lemoine and Rudik (2017) on AER
    - Rozenberg et al. (2020) on JEEM
- Let's look at an example from van der Ploeg (2020)

Damages from temperature

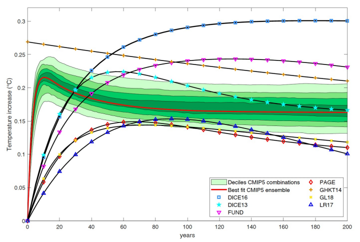
- Assumption:
  - Damages proportional to GDP
- Assumption:
  - Damage/GDP ratio linear function of temperature
  - Justification: Burke et al. (2015) on Nature
- Constant Marginal effect of temperature on damage ratios (MDR): $\dfrac{\partial\Omega}{\partial T}$

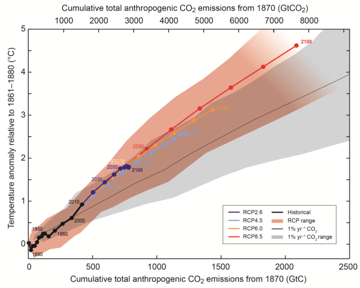


Source: Burke et al. (2015)

Effect of emissions on temperature

- We assume T to be a linear function of cumulative emissions (S)
- That is, $\frac{\partial T}{\partial S}$, the Transient Climate Response to Cumulative Emissions (TCRE), is independent of time and concentration M
- Assume TCRE≈1.8°C per tn tons of carbon (Matthews et al. 2018 give a 0.8-2.4°C range)





Source: Dietz et al. (2021) and IPCC (2013)

A simple formula for the SCC

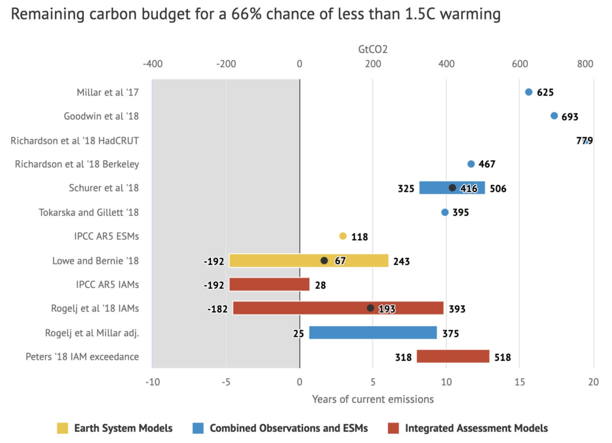
- Further assuming:
  - Exponential discounting with RTI: rate of time impatience (ρ in DICE); and IIA: relative intergenerational inequality aversion (α in DICE)
  - Constant trend growth rate g
- We can write the optimal carbon price as

$$P_t = \frac{MDRTCRE}{RTI + (IIA - 1)g} Y_t$$

- Depending on assumptions on damages, discount rate, IIA, etc. we can obtain a large range of optimal prices..
- P increases at rate g (adjusted for inflation)

Alternative approach: put a cap on temperature

- Remember: T linear function of S
  - Temperature cap → Carbon budget



Source: Carbon Brief (2018)

Objective: find efficient path to get there

- Hotelling structure applicable
  - Remember Hotelling rule: optimal net price ('Hotelling rent') of an exhaustible resources grows at the rate of interest
  - Remaining allowable CO_2 emissions are like an exhaustible resource
- Optimal carbon price is a function of interest rate (or SDR) $P_t = e^{rt} P_0$
- Risk-adjusted interest rate is what we're interested in
  - Gollier et al. (2020): 3.75%
  - If it's too high, it means that, for a specific carbon budget, price today is too low
  - More on uncertainty later on

Conclusions

Conclusions

- We have multiple dimensions to explore to understand how to achieve a smooth and rapid low-carbon transition
- Traditional climate economics (IAM/CGE) offers multiple insights..
    - Carbon prices, energy composition, energy investments, etc.
- .. but lacks several important dimensions
    - Namely, financial dynamics and related institutions/policies
- So, let's look at macroeconomics and finance literature
    - Dichotomy between neoclassical methods (DSGE, CAPM, IAM+)..
    - .. and complexity-driven approaches (SFC, ABM)
- They are all being used to study macro-financial implications of climate/transition
    - Student presentations in coming weeks