Lecture 1.b: Climate change in economic models

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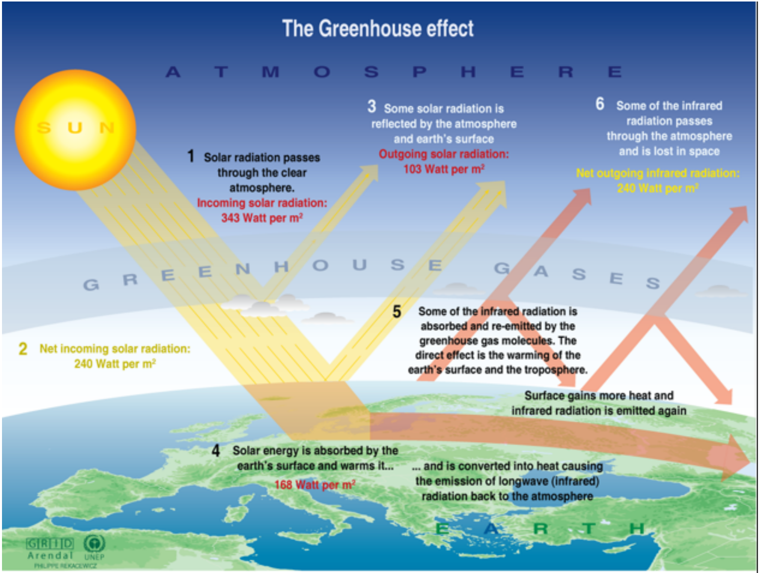
How are the climate and the economy linked?

Recall from previous lecture:

- economic growth relies on the use of growing quantities of energy;
- the energy we use mostly originates from fossil fuels;
- the combustion of fossil fuels generate greenhouse gas emissions;
- the accumulation of greenhouse gases in the atmosphere affects the climate through the quantity of solar radiation absorbed by the earth;
- the change in climate affects the economy through a wide set of damages.

Climate change: a reminder



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

The Kaya identity (1/2)

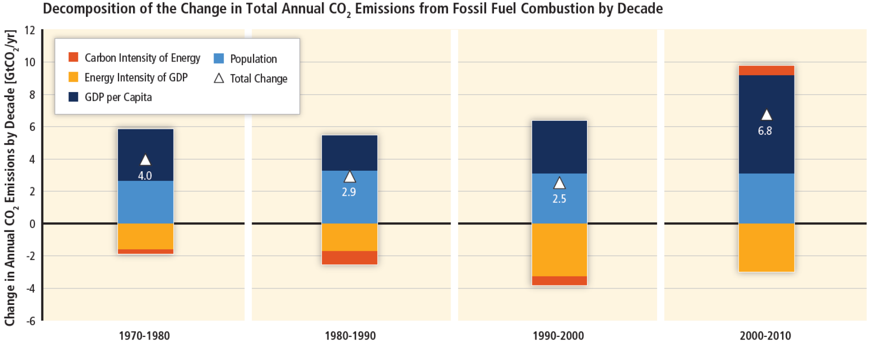
- Economic growth, energy use, and climate change are intertwined.
- To facilitate the understanding and decompose the drivers of climate change, one formula is sometimes used: the Kaya identity.
- If we denote F total anthropogenic GhG emissions, P the total population, G the global GDP, and E the global energy consumption, then one can decompose emissions as follows:

$$F \equiv P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \tag{1}$$

- Thus, the evolution of total anthropogenic GhG emissions results from the evolution of four disctinct factors:
  1. population (P);
  2. GDP per capita (G/P);
  3. the energy intensity of GDP (E/G);
  4. the GHG intensity of energy (F/E).

$\rightarrow$ Any increase (decrease) in one of these components leads, everything else equal, to an increase (decrease) in total GhG emissions.

The Kaya identity (2/2)



Source: IPCC 2014, summary for policy makers.

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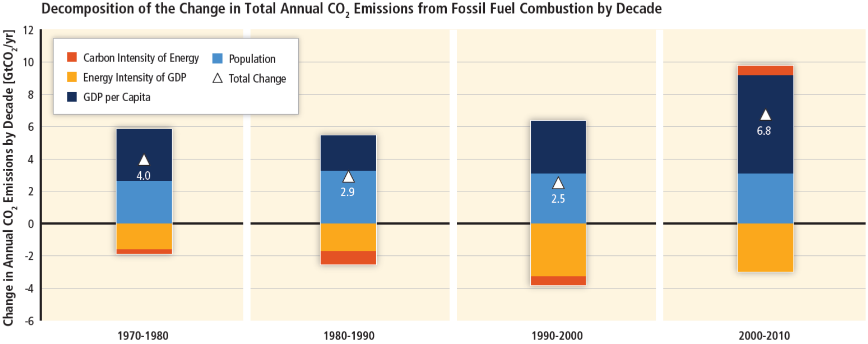

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→ Between 2000 and 2010, world's production has become more energy efficient, but this is more than compensated by higher population, higher GDP per capita, and higher carbon intensity of energy.

Modeling the climate-economy relationship

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  - does not allow to isolate the effect of policies;
  - not suited for prescriptive purposes.

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- Other example: how much should carbon cost to polluters to reduce their emissions so as not to exceed 2°C warming? $\rightarrow$ Not the appropriate tool.
- Other issue: economic growth affects the climate, but how does the climate affect economic activity?

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$\rightarrow$ To answer these questions, economists have developed a class of models, called Integrated Assessment Models (IAMs).

- The most well-known IAM is the DICE model, introduced by William Nordhaus (Economics Nobel Price 2018).

DICE: climate model

Objective: model climate change and how it interacts with the economy.

The DICE model contains the following elements:

1. households enjoy the consumption of a good;
2. the production of this good generates GhG emissions;
3. emissions accumulate into carbon stocks;
4. GhG atmospheric concentration warms the planet;
5. higher temperatures cause economic damages.

→ Trade-off: consuming more pollutes and leads to economic damages that reduce future consumption.

Consumption and production

- A population of L_t households enjoys the consumption c_t of a final good over T_{max} periods discounted at rate ρ. Objective of the planner:

$$\max_{c_t} \sum_{t=1}^{T_{max}} \frac{1}{1+\rho} L_t u(c_t)$$

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- Total consumption is $C_t = L_t c_t$, total capital is K_t, investment is I_t, and net output is Q_t, with:

$$Q_t = C_t + I_t$$
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- Net output Q_t depends on gross output Y_t, abatement costs Λ_t, and climate damages D_t. With A_t the technology, we have:

$$Y_t = A_t K_t^{\gamma} L_t^{1-\gamma}$$
$$Q_t = (1-\Lambda_t)(1-D_t)Y_t$$

$\rightarrow$ So far, very similar to a Solow model.

Emissions and abatement

- Production generates industrial emissions E_t^{Ind}.
- Firms can reduce these emissions through abatement activities. Cutting a share μ_t of emissions costs Λ_t, with:

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

- Emissions net of abatement are given by:

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- A_t, σ_t, $\theta_{1,t}$ are parameters that can change over time with technological progress. L_t changes with population growth. E_t^{Land} also changes exogenously.

Carbon stocks

- We model three distinct carbon reservoirs: S_t^{At}, S_t^{Up}, and S_t^{Lo} represent **carbon concentration** at time t in the atmosphere, upper oceans, and deep oceans. They evolve according to:

$$S_t^j = b_{j,0} E_t + \sum_{i=1}^{3} b_{i,j} S_{t-1}^i.$$

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- In each period t, a share $b_{i,j}$ of GhG from stock i move to stock $j \rightarrow$ Reservoirs communicate with each other.

Temperatures

- Atmospheric carbon concentration (S_t^{At}) increases "radiative forcing" (χ_t), *i.e.* the net radiation received by the earth:

$$\chi_t = \kappa\Big(\mathsf{ln}(S_t^{At}/S_{1750}^{AT})/\mathsf{ln}(2)\Big) + \chi_t^{\mathsf{ex}}.$$

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$$T_t^{At} = T_{t-1}^{At} + \zeta_1\Big(\chi_t - \zeta_2 T_{t-1}^{At} - \zeta_3(T_{t-1}^{At} - T_{t-1}^{Lo})\Big),$$

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- The more energy received by the earth (χ_t), the higher the atmospheric temperature T_t^{At}.
- A higher atmospheric temperature also warms the oceans, and vice versa.

Damages

- Atmospheric temperature T_t^{At} affects production through climate damages $D_t(T_t^{At})$, with:

$$D_t = a_1 T_t^{At} + a_2 (T_t^{At})^{a_3}$$

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- Key question: what are the right values for the parameters a_1, a_2, a_3?
  - Nordhaus takes $a_1 = 0$ and $a_3 = 2 \rightarrow$ Quadratic specification of climate.
  - Is that correct? Hard to say.

Solving the DICE model

- To solve the model, choose values for all parameters, and search for optimal path of consumption (c_t) and abatement activities (μ_t).
- Originally coded with GAMS, but versions for Python and R are available!
- Examples of variables computed:
  - Consumption
  - Abatement
  - CO_2 emissions
  - Radiative forcing
  - Temperature
- You can then play with the parameters and re-run the code.

N.B.: emissions, concentrations, or tax levels can be expressed in units of carbon dioxide (CO_2) or in units of carbon (C). Keep in mind: 1 ton of carbon equals 3.67 tons of carbon dioxide. Thus, a tax of \$100/tCO_2 is equivalent to a tax of \$367/tC.

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- This is the marginal social cost from emitting an additional unit of CO_2 (or other GhG expressed in CO_2-equivalent).
- Formally, can be expressed as:

$$\frac{\partial(\text{€ damages})}{\partial(\text{tons } CO_2 \text{ emissions})} \equiv \frac{\partial(\text{€ damages})}{\partial(°\text{C warming})} \times \frac{\partial(°\text{C warming})}{\partial(\text{tons } CO_2 \text{ emissions})} \quad (2)$$

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Most critical number in climate change economics, but no real consensus about its value. Different assumptions (over damages, technological progress, people's preferences, etc.) give different numbers.

The social cost of carbon: what is it used for?

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- Let's assume a person can choose to travel from Amsterdam to London by plane or by train.
- Doing so by plane saves her the equivalent (in money, time, etc.) of 100€, but emits an additional 1 ton of CO_2.
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- Should the person go by train or by plane?
- If the SCC is below 100€/tCO_2, then plane is preferable from the society's perspective. If it is above, then train is preferable.

→ If governments want to regulate emissions, critical for them to know how to assess their relative harm and compare it to other costs and benefits.

Critiques to DICE

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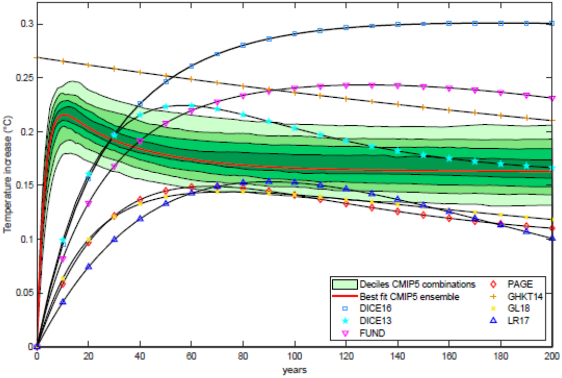
However, simplicity comes with some caveats. Among them:

- climate model not consistent with recent findings in climate science;
- actual damage function might not be quadratic;
- absence of risk;
- simplicity of the economy;
- choice of preference parameters (such as ρ, the pure rate of time preferences).

Other IAMs have been proposed (e.g. FUND, MERGE, PAGE, RICE, WITCH) with different climate dynamics, multiple economic sectors, multiple regions, heterogeneous households, etc.

Example: thermal inertia (from Dietz et al, 2021)

Figure 1: Dynamic temperature response of 256 climate science models (the CMIP5 ensemble) and seven IAMs to an instantaneous 100GtC emission impulse against a constant background atmospheric CO_2 concentration of 389ppm. The temperature response of the IAMs is much slower than the climate science models, except Golosov et al. (2014). After 200 years, the temperature response of the IAMs is often well outside the range of the climate science models. The CMIP5 model responses are emulated/fitted by combining the Joos et al. (2013) carbon cycle model and the Geoffroy et al. (2013) warming model.



Critiques to IAMs

Beyond these caveats, some deeper critiques about the use of IAMs:

- Deep uncertainty:
  - there is a lot we don't know about climate dynamics, economic prospects, and their interaction;
  - with some small probability, climate change will not be that bad; with some small probability, however, it will be cataclysmic;
  - climate change mitigation is not only about reducing smooth damages, it is about avoiding potential catastrophic events (see *e.g.* Weitzman, 2009; Pindyck, 2013).

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- Ethical parameters:
  - the optimal path of mitigation efforts depends on some preference parameters;
  - example: the discount rate, *i.e.* the weight given to the future relative to the present;
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Pyndick's 2013 article on IAMs is titled "Climate Change Policy: What Do the Models Tell Us?". → His short answer to that question: "Very little."

Example: discounting in theory

- Discounting is about weighting the future relative to the present.
- Discounting matters in all inter-temporal economic decisions.
- Ex: how much should I save now to consume later rather than today?
- Climate economics: how much efforts should present generations do to increase welfare of future generations?
- Standard Ramsey formula: trade-off between one unit of consumption today *vs.* in the future given by:

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$\rightarrow$ Future welfare discounted more to the extent that people have a higher preference for the present (higher ρ), future generations are richer (higher growth rate g_t), and people are averse to inter-temporal inequalities (higher η).

Example: discounting in practice

Table: Present value of 1,000,000€ damages in the future depending on when it occurs and the discount rate applied.

Discount rate	Occurs in 20 yrs.	Occurs in 100 yrs.	Occurs in 300 yrs.
1%	819,545€	369,711€	50,534€
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$\rightarrow$ For long-run issues, seemingly small differences in discounting can lead to strikingly different policy implications:

- Stern (2007) takes $\rho = 0.1\%$ based on ethical considerations, and assumes $\eta = 1.0$ and $g = 1.3\% \rightarrow r = 1.4\%$
- Nordhaus (2007) takes $\rho = 3.0\%$ based on observed market behaviors, and assumes $\eta = 1.0$ and $g = 1.3\% \rightarrow r = 4.3\%$.

$\rightarrow$ While the Stern Review recommends rapid and very ambitious action to combat climate change, Nordhaus reaches much less alarming conclusions.

Who is right?

The two approaches lead to conceptually different objects:

- Prescriptive approach: very appealing from a normative point of view.
- Descriptive approach: minimizes opportunity costs from social investments, pragmatic approach to policy.

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- Prescriptive approach: yes, since $(1.03)^{100} \simeq 19.2$, with a SDR below 3% the investment is worth it.
- Descriptive approach: if the market interest rate is higher (say 5-6%), then no, since $(1.05)^{100} \simeq 131.5$.
    - Society is better off investing in projects that pay the market interest rate and lead to higher future payoffs (with the possibility of using that money for an even more ambitious climate project).

Still, not always obvious which concept is the most relevant to use, hence heated debates.

Emissions Stern *vs.* Nordhaus discounting (Nordhaus, 2018)

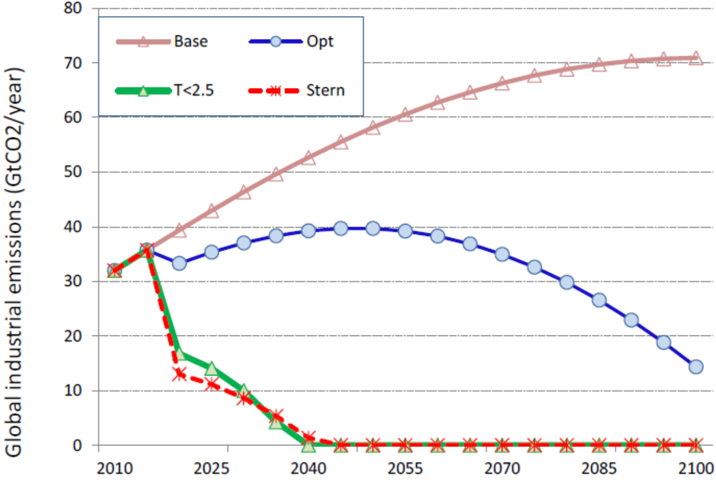

Figure 2. Actual and projected emissions of CO_2 in different scenarios

Temperatures Stern *vs.* Nordhaus discounting (Nordhaus, 2018)

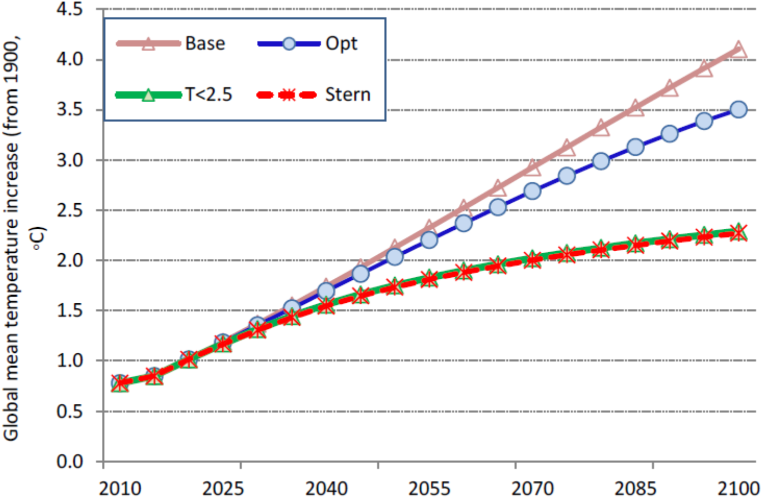

Figure 4. Temperature change in different scenarios

Answers of IAMs

Academics keep making efforts to answer these critiques:

- more and more models account for risk, including disasters, tipping points, or existential risk;
- more and more models account for individuals' sensitivity to these large risks;
- researchers try to better quantify potential damages, such as biodiversity losses;
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Are these efforts in vain? We will ever get an accurate model? $\rightarrow$ Probably not, but hopefully we can improve these tools to make them useful.

Alternative to IAMs: the carbon budget approach

Is there an alternative to IAMs for decision-making?

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Is there an alternative to IAMs for decision-making?

- In recent years, the "carbon budget" approach has gained grounds.
- Basic idea:
  - collectively determine a certain temperature target (*e.g.*, maximum +2°C warming);
  - determine the total carbon emissions that can be emitted without exceeding that target with too high probability;
  - look for the most efficient way (*i.e.* path of consumption and abatement) to attain it.
- Similar to a robust control approach: accept damages up to +2°C, but try to avoid as much as possible exceeding that target.
- Put differently: pass or fail approach to climate change mitigation. Acknowledge that we don't know how to evaluate what's best for society, simply use rule of thumb to stay of the "safe side".
- Caveats:
  - Back to the question: what's the right target? How to inform that decision?
  - What if we exceed the target? Damages from +2°C not the same as those from +4°C, climate impacts are not binary.

Where we stand

So far, we have:

- described climate change, how it works and what are some of its consequences;
- explained the link between the economy and the climate;
- defined the social cost of carbon (SCC), the concept used to assess the opportunity cost of GhG emissions.

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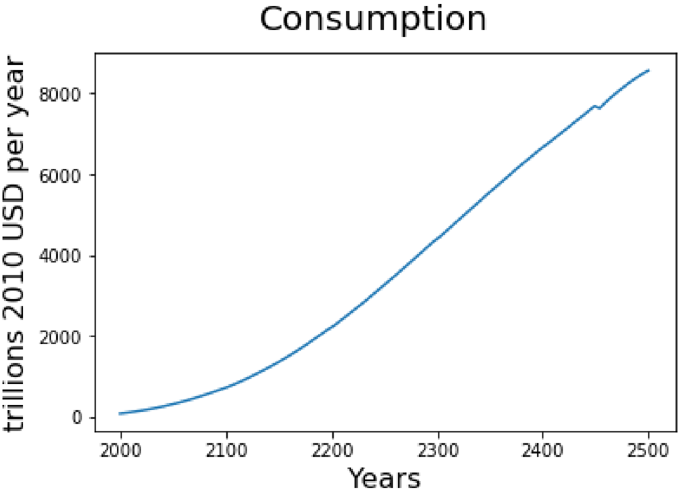
So far, we have:

- described climate change, how it works and what are some of its consequences;
- explained the link between the economy and the climate;
- defined the social cost of carbon (SCC), the concept used to assess the opportunity cost of GhG emissions.

Next week, we will:

- present the policies that can be used to deal with climate change;
- discuss how the SCC is used to determine optimal policies;
- compare policy options based on their cost-efficiency and distributional effects.

Consumption DICE



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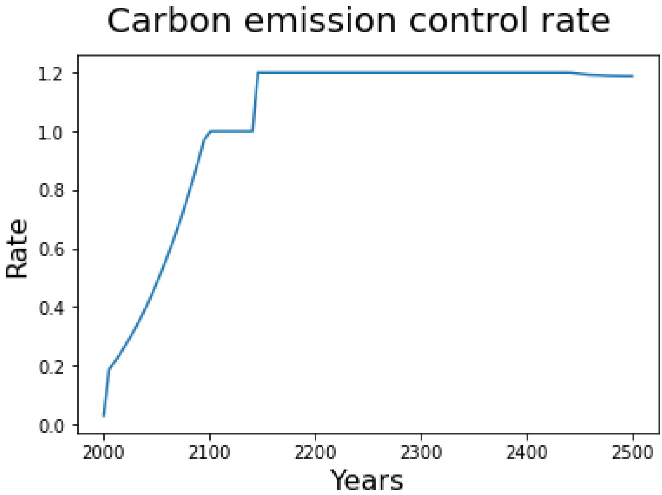
Abatement DICE



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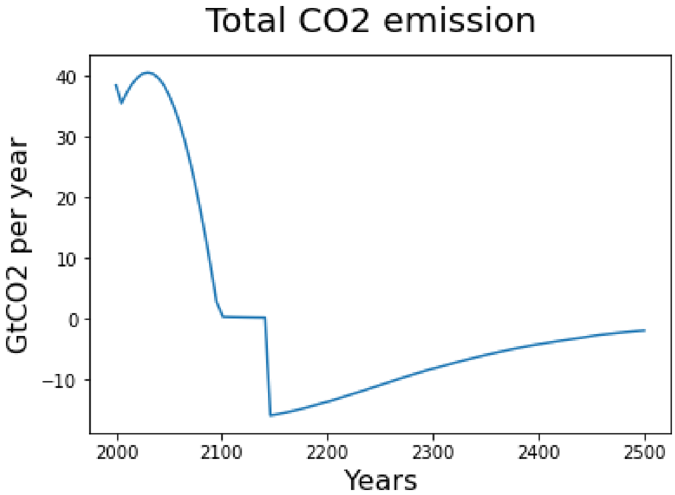
Emissions DICE



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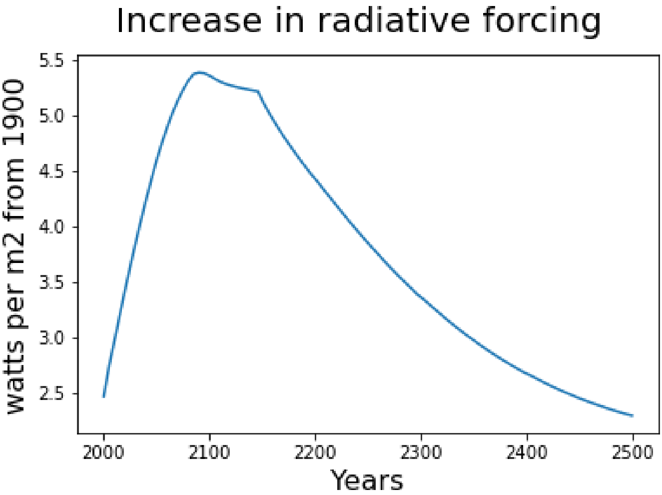
Radiative forcing DICE



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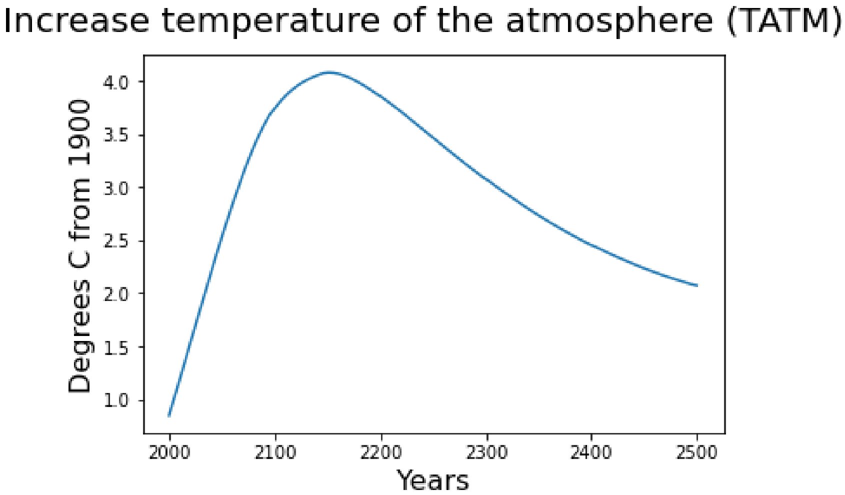
Temperature DICE



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