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**What Social Cost of
Carbon? A Mapping of the
Climate Debate**

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Keywords: Optimal control, Mitigation, Social Cost of Carbon, Uncertainty

JEL Classification: Q54, Q21, 041, D81

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What Social Cost of Carbon? A mapping of the climate debate

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Abstract

Given disparate beliefs about economic growth, technical change and damage caused by climate change, this paper starts with the seeming impossibility of determining a unique time profile of the social costs of carbon as a benchmark for climate negotiations and for infrastructure decisions that need to be made now in the absence of an inclusive international accord on climate policies. The paper demonstrates that determining a workable range of the social costs of carbon is however possible in a sequential decision-making framework that permits revising initial decisions in the light of new information. To do so, the paper exploits the results of a stochastic optimal control model run for more than 2000 scenarios that represent the set of beliefs presented about key uncertain parameters in the literature. The paper provides a heuristic mapping of the climate debate in the form of six "clubs of opinions" and shows the possibility of determining a range of social costs of carbon that might permit a compromise between the maximum range of "clubs" and those most likely to emerge in the future.

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1 Introduction

Even though some of the results of the two last United Nations Climate Change Conference in Copenhagen (2009) and in Cancun (2010) can be ascribed to the vagaries of the diplomatic process and the divergences in views about how to untie the climate and development Gordian Knot (Hourcade et al, 2009b), it revealed large differences in the willingness to pay to tackle climate change.

The persistence of such differences, nearly 20 years after the adoption of the United Nations Framework Convention on Climate Change (in Rio de Janeiro in 1992) casts doubts on the relevance of the main advice stemming from well-established public economic principles. This advice is first, to set a trajectory of world carbon prices that would reveal the “social costs of carbon” (SCC) equating the discounted sum of the marginal cost of abatement with the discounted sum of the marginal cost of remaining damage, and second to arrange for financial compensations (by means of direct transfers or generous emissions quotas) to take into account the variations in social welfare among countries¹.

These principles seem hard to enforce in a context where, at first glance, the published literature provides little credible guidance. The most recent Intergovernmental Panel on Climate Change report gives an SCC range of US\$3 to US\$95 per ton of CO₂ (IPCC, 2007); R.S.J.Tol (Tol, 2005) gathers 103 estimates and finds out that the median estimate is US\$4 per tCO₂, the mean US\$26 per tCO₂ and the 95 percentile US\$97 per tCO₂. The UK’s Department for Environment, Food and Rural Affairs recommends using an SCC value of US\$29 per tCO₂ for public decisions (a range of US\$14 to US\$58 per tCO₂) (Watkiss, 2005) and a committee of French experts recommended a SCC value of US\$60/tCO₂ in 2010 rising to US\$135 per tCO₂ in 2030 (Quinet, 2008). The US government selected four SCC estimates for use in regulatory analyses based on three leading integrated assessment models (DICE, PAGE, FUND) ranging from US\$5 to US\$65 per tCO₂ in 2010 and rising to [US\$16, US\$136 per tCO₂] in 2050 contingent on different assumptions about the discount rate (US Regulatory Impact Analysis, 2010).

Such a large range of estimates might suggest that a compromise between such opposing beliefs is simply unattainable². But time is running out and decisive scientific information may not be available in time to end controversies about the ultimate consequences of climate change damage and the costs of greenhouse gas (GHG) abatement. Furthermore, given current levels of infrastructure investment in developing countries, the windows of opportunity for preventing temperature increases from overshooting not only the commonly accepted 2°kelvin (K) target but even a 3°K target will quickly close (ref récente IPCC?).

¹This comes back to the Bowen-Lindahl-Samuelson theorem. Obviously, the idea that mitigating climate change constitutes a net social cost is questionable; not only because doing so should provide a net intertemporal social benefit by reducing total mitigation costs and damage (Shalizi and Lecocq, 2009; Stern, 2006) but also because mitigation could be financed by redirecting investments instead of limiting consumption (Foley, 2009), thereby avoiding a net burden for early generations. However, the mainstream view that mitigation constitutes a net social cost at first period holds for tight climate targets and once potentials from Pareto-improving policies are exhausted.

²The virulent reactions (Dasgupta, 2007; Maddison, 2007; Nordhaus, 2007; Weitzman, 2007; Tol and Yohe, 2007; Yohe, 2006) to the Stern Review (Stern, 2006) reinforce this pessimistic diagnosis.

This paper suggests the possibility of making better use of current (weak) information on stakeholders' beliefs about future growth, abatement costs, technical progress, discounting, climate outcomes to frame deliberations about climate policies as soon as this information is employed within a transparent integrated assessment model (IAM) framework. The paper, by means of hopefully a transparent enough modelling approach, allows us to disclose the main drivers of the climate controversy. It makes it possible to reveal a structure of "clubs of opinion" behind the apparent ocean of uncertainty (Lave, 1991), either exposing the underlying worldviews of a position in the climate debate (in terms of level of abatement or SCC) or computing the position consistent with a given set of beliefs. Thereby it offers a consistent frame of analysis to clear up the climate debate and makes the search for a compromise a less risky venture.

We eventually present a method to delineate different sensible spaces of negotiation within which an international agreement about the SCC may occur.

2 RESPONSE: a Model of Optimization under Uncertainty

2.1 Storyline of the model

RESPONSE is designed as an IAM that couples a macroeconomic optimal growth model³ with a simple climatic model, following the tradition launched by Nordhaus (1994) seminal DICE model by Nordhaus.

The program maximizes under uncertainty an intertemporal social welfare function composed of the consumption of a composite good. GHG emissions that are considered as a fatal product of the production, are responsible for temperature increase and thus for climate damage. As climate damage negates part of the production, the optimization process consists in allocating the optimal share of the output among consumption, abatement and investment. Rather than traditional power functions, we use a sigmoid function (Ambrosi et al, 2003) to represent nonlinearity effects in damage (see next section for a mathematical formulation of the function). Uncertainty holds on both climate sensitivity (and on atmospheric temperature increase $\theta_{A,t}^\omega$) and climate damage denoted by D^ω .

To encompass the entire range of beliefs about climate damage, the model considers different states of nature for climate sensitivity (θ_{2x}^ω) and for the form of damage consistent with existing literature. As climate change is basically a nonreproducible event, a subjective distribution of probabilities is given to each state of the world considering that climate sensitivity and damages are independant as presented in table 2. These probabilities can be interpreted as the level of confidence a stakeholder attaches to each existing climate scenario and to each assessment of climate change impacts.

These uncertainties are resolved at a point in time denoted t_i . Some may argue that the two most recent Intergovernmental Panel on Climate Change reports, the Stern Review, and the series of climate catastrophes over the past decade have already provided the "climate proof", but all kinds of controversies

³much like Ramsey-Cass-Koopmans' models (Ramsey, 1928; Koopmans, 1965; Cass, 1966).

⁴We assume that both uncertainties are independant

are far from resolved. What we mean here by resolution of uncertainty is the emergence of a consensus on the validity of information that is broad enough to trigger ambitious collective action.

In the forthcoming simulations, the date t_i is set at 2050. At the end of the learning and self-convincing process (after t_i), people adapt their behavior to new information. They accelerate abatement in the case of “bad news” and relax their efforts in the case of “good news”. The question each stakeholder must consider then becomes what is the good trade-off between the economic risks of rapid abatement now (that premature capital stock retirement would later be proved unnecessary) against the corresponding risks of delay (that more rapid reduction would then be required, necessitating premature retirement of future capital stock)?

2.2 The program of optimization

Consistently with a sequential decision-making framework, a two-step analysis is conducted that mainly consists in solving the program recursively. The intertemporal optimization program is divided between two subprograms, after and before the information arrival date t_i respectively.

- After uncertainty is resolved

We consider first the optimization program starting at time t_i when the true state of nature of the climate sensitivity and the threshold damage is revealed. Then $\omega = \omega^*$. The intertemporal maximization program between t_i and T (with $T = 2200$) simply writes:

$$V(\omega^*) = \underset{a_t, C_t}{Max} \sum_{t=t_i+1}^{t=T} N_t \frac{1}{(1+\rho)^t} u(C_t^{\omega^*}),$$

where $u(\cdot)$ is the standard logarithmic utility function ($u(C) = \ln(C)$), N_t is the population at t , which is assumed to grow at an exogenous rate; and C_t^ω is the consumption of a composite good at t in the states of the world ω , and ρ being the pure time preference.

- Before uncertainty is resolved

Before information on the true states of the climate sensitivity and the threshold parameter is revealed at time t_i , the objective function of the economy to maximize (under the two control variables a_t and C_t) writes, depending on the possible states of nature ω :

$$W = \mathbf{E}[U]$$

with \mathbf{E} standing for the expectation operator according $\mathbf{E}[f] = \sum_{\omega} p(\omega) f(\omega)$, and

$$U(\omega) = \sum_{t=0}^{t=t_i} \frac{1}{(1+\rho)^t} u(C_t^\omega) + V(\omega).$$

This program is solved under the three following constraints $\forall \omega$:

- Capital Dynamics:

$$K_{t+1}^\omega = (1 - \delta)K_t^\omega + (Y(K_t^\omega, L_t) - C_t^\omega - C_a(a_t^\omega, a_{t-1}^\omega, K_t^\omega) - D^j(\theta_{t,at}^\omega, K_t^\omega)),$$

where K_t^ω is the capital at t , which is set at the level \bar{K}_t whatever the states of the world are, when $t \leq t_i$; δ is the parameter of capital depreciation; and L_t is an exogenous factor of labor that enters $Y(\cdot)$, the traditional Cobb-Douglas function of production. As technical inertia is a key determinant of the problem, we follow the route initiated by (Ha-Duong et al, 1997) and consider the following abatement cost function:

$$C_a(a_t^\omega, a_{t-1}^\omega, K_t^\omega) = PT_t \left(a_t^\omega \zeta + (BK - \zeta) \frac{(a_t^\omega)^\nu}{\nu} + \frac{Y_0}{E_0} \xi^2 (a_t^\omega - a_{t-1}^\omega)^2 \right) E_t^\omega$$

where a_t^ω is the fraction of emissions cut⁵. a_t^ω is set at the level \bar{a}_t whatever the states of the world are, when $t \leq t_i$. As the capital is also set before t_i , this means that only the consumption C_t^ω may vary depending on and climate damage. The cost function has two main components: the absolute level of abatement $\frac{(a_t^\omega)^\nu}{\nu}$, with ν being a power coefficient, and a path-dependent function that penalizes the speed of decarbonization $(a_t^\omega - a_{t-1}^\omega)$ so that the costs of totally decarbonizing the economy in 50 years is 1% of annual GDP, whereas the cost is 25 percent of annual gross domestic product (GDP) if total abatement is achieved within 10 years. PT_t is a parameter of exogenous technical progress, BK stands for the current price of backstop technology, ζ and ξ are fixed parameters, and E_t^ω represents the level of emissions. Emissions are considered here as a fatal product and can be written as:

$$E_t^\omega = \sigma_t(1 - a_t^\omega)Y(K_t^\omega, L_t),$$

where σ_t is the carbon intensity of production which declines progressively thanks to technical progress ($\sigma_0 = E_0/Y_0$).

Finally $D^\omega(\theta_{t,at}^\omega, K_t^\omega)$ denotes damage induced by $\theta_{t,at}^\omega$, the temperature increase due to GHG emissions from the pre-industrial period to the date t . Rather than traditional power functions, we use sigmoid functions (Ambrosi et al, 2003) to represent nonlinearity effects in damage (see the appendix for a mathematical formulation of the function). Within capital dynamics, damage negates part of the production, which has to be shared among consumption, abatement and investment.

- Abatement constraint:

$$0 \leq a_t^\omega \leq 1 \tag{2.1}$$

- Temperature and Carbon Dynamics:

⁵If $a_t^\omega = 1$, then emissions become null. By contrast, if $a_t^\omega = 0$, then no attempts at abatement have been made.

The following equation links temperature increase at time t to past carbon emissions flows E_t, E_{t-1} up to \bar{E}_0 ⁶.

$$\theta_{t,at}^\omega = F(E_T^\omega, E_{T-1}^\omega, \dots, E_{t_{info}+1}^\omega, \bar{E}_{t_{info}}, \dots, \bar{E}_0).$$

This function incorporates the linear three-reservoir model of carbon cycle by Nordhaus (Nordhaus and Boyer, 1999) and a temperature model resembling Schneider and Thompson’s two-box model (Schneider and Thompson, 1981) (see appendix for a detailed presentation of carbon and temperature dynamics).

2.3 The Social Cost of Carbon

The SCC accounts for the monetized value of the climate externality or society’s willingness to pay to tackle climate change. Along an optimal path of CO₂ emissions, the SCC is the value equating at each date the discounted sum of the marginal cost of abatement with the discounted sum of the marginal cost of remaining damage (Nordhaus, 2008; Pearce, 2003; Tol, 2005). This optimality rule makes it possible to delineate the efficient border of mitigation efforts.

More precisely, the SCC accounts at the optimum for both the economic cost induced by the emission of an extra unit of CO₂ in the atmosphere, in terms of social utility loss, and the economic cost of preventing the emissions of one extra unit of CO₂. The SCC is theoretically interpreted as the set of shadow prices of carbon along a constrained CO₂ emission trajectory and its value increases over time as one approaches carbon constraints (or potential high damage) as long as very cheap carbon free techniques are not available at large scale (the value of the SCC is necessarily capped by the cost of the backstop).

Analytically, at each date t the SCC roughly writes (see appendix for a precise presentation of the analytical formula of the SCC for all dates):

$$SCC(t) = \frac{\partial W / \partial a_t^\omega}{\partial W / \partial C_t^\omega}$$

The denominator is the marginal welfare value of a unit of consumption in period t , while the numerator accounts for the marginal impact of abatement on welfare. As a_t^ω is expressed in utility per ton of CO₂ and C_t^ω in utility per \$, the ratio translates the impact and thus the SCC in \$ per tCO₂.

2.4 A Political Economy Interpretation of a Sequential Modeling Framework

Surprisingly disregarded in the debates opened up by the Stern Report (Hourcade et al, 2009a) sequential decision-making frameworks addressed early on the question of the timing of GHG abatement in order to go beyond the intrinsic limits of one-shot decision frameworks to tackle an issue that scientists have seen as a problem for more than two decades (Manne and Richels, 1992). The basic principle was to mobilize variants of optimal control models that calculate the optimal trajectory to be followed in the absence of information about

⁶Note that before t_{info} , as abatement and capital are set whatever the states of the world are, emissions flows are also set.

the ultimate level of climate change damage before a date t_i of information disclosure.

The logic of these types of models is to attribute subjective probabilities to future damage (or to proxies such as the ultimate concentration of CO₂ in the atmosphere or temperature targets) during the pre- t_i period and to assess the pre- t_i emissions pathway considering the costs of redirecting the initial course of action after t_i . The model then weights the costs of ambitious GHGs abatement now against the costs of accelerated action later (Ha-Duong et al, 1997; Hammitt et al, 1992). Obviously as many first periods optimal pathways and trajectories of SCC are available as are sets of beliefs about climate change damage. A well-intentioned chair of a conference of parties can use this information to assess the existence of “corridors” of values within which the greatest number of countries can reach a compromise.

In this paper we use the RESPONSE model to capture not only the set of beliefs about climate change damage, but also a larger set of assumptions about the future, namely:

- assumptions about economic growth, future GHG emissions, and costs of cutting emissions;
- normative parameters that translate consumption flows into utility flows, and balance the utility of present and future generations through pure time preference;
- beliefs about climate change damage through the shape of the damage function and the climate sensitivity parameter;
- probability weights attached to each belief during the first period before the resolution of uncertainty at date t_i .

Thus we address a wide spectrum of worldviews defined as the combination of technico-economic parameters, climate and normative parameters (see figure 1) in order to cover the whole range of views expressed in the climate debate.

However, these modeling experiments rely on an important political precondition, that is, adoption of a sequential decision framework with progressive resolution of uncertainty, which in turn requires a specific political attitude on the part of all parties. This attitude consists of adhering to the old Roman saying *audi vi alteram partem* (I listened to the other party), that is recognizing that those who do not share one’s vision of the world may be right. Such wise political behavior makes it possible to both select an abatement pathway by the date of arrival of complete information and preserve the option of switching back to concentration targets that conform to updated information.

3 Worldviews Structuring the Climate Debate

We define a worldview as a set of beliefs about six key and controversial parameters: economic growth, speed of autonomous decarbonization of the production system, technical costs of reducing GHG emissions, weight given to future generations, magnitude of climate change damage, and index of climate sensitivity.

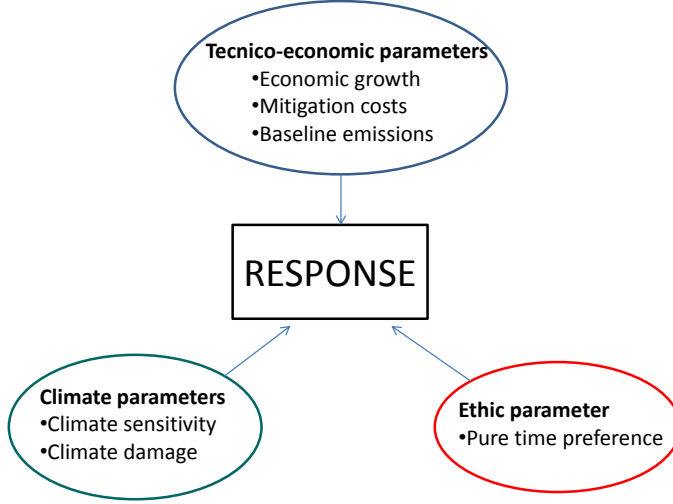


Figure 1: The three main components of a worldview

To cover the array of scientific opinions, we retained the extreme values given by the last Intergovernmental Panel on Climate Change report (IPCC, 2007) for each parameter (see table 1 and 2)⁷.

3.1 Technico-Economic and Normative Parameters

In the baseline scenario, that is when climate change is not considered, the economic growth, during the entire 21st century, averages 1.45 percent through 3 percent. The impact of economic growth on the volume of carbon emissions is determined by the carbon intensity, σ_t , which in turn is driven by ψ_t , which captures the joint impact of technical change and depletion of fossil resources: $\sigma_t = \sigma_0 e^{-\psi_t t}$ with $\psi_t > 0$. For a given population level, the level of carbon emissions is proportional to $E_0 e^{(g-\psi_t)t}$. As long as $g > \psi_t$ (with ψ_t set at its initial level), carbon emissions would continue to grow over time for most (ψ_0, g) pairs. To guarantee that emissions decrease by the end of the century, as predicted by the overwhelming majority of available scenarios, ψ_t progressively increases so that it can become higher than g as follows:

$$\psi_t = \psi_0 e^{-\beta t} + 1.1g(1 - e^{-\beta t}),$$

⁷With respect to abatement costs, criticisms of (Pielke et al, 2008) in *Nature* concern the figures published in the synthesis report. We retained here the primary material of the report that includes both optimistic and pessimistic cost assumptions.

Table 1: All Socioeconomic Scenarios Implemented by the Model

Sensitive variables	Parameters of the model	lower value	upper value
Economic growth	$\frac{\ln(Y_t/Y_0)}{t}$	1.45%.year ⁻¹	3%.year ⁻¹
Emissions	Parameter of decarbonization ψ_0	0.5%/year	1.5%/year
Abatement costs	$BK_{2008}, \nu, \zeta, \alpha$	110\$/t CO ₂ , 3, 0, 1%	1023\$/t CO ₂ , 4, 15, 1.35%
Ethical preferences on future	Pure time preference ρ	0.1%	2%

with $\beta > 0$, the speed of growth of ψ_t . Thus,

$$\sigma_t = \sigma_0 e^{-(\psi_0 e^{-\beta t} + 1.1g(1 - e^{-\beta t}))t}.$$

Beliefs about mitigation costs are captured through the price of the backstop carbon-free technology BK_{2008} capable of achieving total abatement of CO₂ emissions. This technology is supposed to be available at each time period, with its costs declining over time. The most recent Intergovernmental Panel on Climate Change report does not explicitly refer to the costs of backstops, but they can be determined from the panel’s published cost data (IPCC 2007, Figure 3.25). We retained an initial range of US\$110 to US\$1,023 per abated tCO₂ and decreases at a rate of 1 percent for optimistic opinions and 1.35 percent for pessimistic opinions.

As regards the pure time preference ρ , this is not the place for putting an end to the dispute between the advocates of normative choice of that parameter and the advocates of a positive approach consistent with observed behavior and virulent ethical controversies rooted in old intellectual traditions, for example Ramsey (1928) vs Koopmans et al (1964). This is why we retained two extreme values of $\rho = 0.1$ percent as recommended by Stern (2006) and 2 percent (Weitzman, 2007).

The combination of values in table 1 gives 2⁴ (16) scenarios.

3.2 Climate Parameters

Table 2 shows the values retained for climate sensitivity and the threshold of temperature increase that triggers nonlinear damage. We consider five possible levels for climate sensitivity θ_{2x} (1.5°K, 2.3°K, 3°K, 3.8°K and 4.5°K),⁸ and we describe damage through a hybrid linear-sigmoid function rather than a power function to capture the possible emergence of nonlinear damage (Ambrosi et al, 2003). We consider five possible levels of thresholds of temperature increase Z (2.0°K, 2.5°K, 3.0°K, 3.5°K and 4.0°K), beyond which catastrophic events, in

⁸Some studies propose higher values for climate sensitivity, with a skewed distribution (Roe and Baker, 2007; Weitzman, 2009). Here we stick to the IPCC range.

Table 2: Table of all scenarios of potential damages. A state of the world ω is a singleton of a pair (Z, θ_{2x}) . The distribution q on Z and q' on θ_{2x} are considered as independant so that for $\omega = (Z^j, \theta_{2x}^s)$, $p(\omega) = q_s q'_j$ and $\mathbf{E}[f(\omega)] = \sum_{\omega} p(\omega) f_{\omega}$

Types of beliefs	Optimistic	Moderate	Pessimistic
Temperature thresholds of damages triggering (in °K)	$Z^1 = 2, Z^2 = 2.5, Z^3 = 3, Z^4 = 3.5, Z^5 = 4$		
Distributions of probabilities	$q_1 = 0.02$ $q_2 = 0.03$ $q_3 = 0.1$ $q_4 = 0.3$ $q_5 = 0.55$	$q_1 = 0.1$ $q_2 = 0.25$ $q_3 = 0.3$ $q_4 = 0.25$ $q_5 = 0.1$	$q_1 = 0.55$ $q_2 = 0.3$ $q_3 = 0.1$ $q_4 = 0.03$ $q_5 = 0.02$
Expected damages for 2°K increase of mean temperatures	0.8% of GDP	2% of GDP	3.2% of GDP
Values of climate sensitivity (in °K)	$\theta_{2x}^1 = 1.5, \theta_{2x}^2 = 2.3, \theta_{2x}^3 = 3, \theta_{2x}^4 = 3.8, \theta_{2x}^5 = 4.5$		
Distributions of probabilities	$q'_1 = 0.7$ $q'_2 = 0.2$ $q'_3 = 0.05$ $q'_4 = 0.03$ $q'_5 = 0.02$	$q'_1 = 0.05$ $q'_2 = 0.15$ $q'_3 = 0.6$ $q'_4 = 0.15$ $q'_5 = 0.05$	$q'_1 = 0.02$ $q'_2 = 0.03$ $q'_3 = 0.05$ $q'_4 = 0.2$ $q'_5 = 0.7$
Expected beliefs on the value of climate sensitivity	1.9°K	3°K	4.2°K

Weitzman’s sense (Weitzman, 2009), cannot be excluded. Note that overshooting those thresholds does not suddenly trigger the total effect of climate change damage (6% of GDP loss). Damage spreads progressively over a temperature range η , which corresponds to an arbitrary additional 0.6°K (for instance, over the range [1.7°K, 2.3°K] for the lowest possible threshold).

For each parameter, three opinions are represented, each of them defined by a specific distribution of probabilities on the different possible values of the two uncertain parameters. An optimistic (or pessimistic) belief about the threshold is consistent with a probability distribution that puts a greater weight on the highest (the lowest) value of the threshold (respectively 4°K or 2°K) and a declining weight on other levels of the threshold. In the same way, optimistic (or pessimistic) beliefs about climate sensitivity are represented by a probability distribution that puts a greater weight on its lowest (highest) value (respectively 1.5°K or 4.5°K).

Combining the numerical assumptions displayed in table 2 gives 3^2 (9) climate damage scenarios. Combining them with the 16 economic scenarios gives 144 integrated scenarios that cover the entire range of logically possible opinions in the climate debate⁹.

4 A heuristic mapping of the climatic debate

Running RESPONSE for each of the 144 scenarios gives as many optimal time profiles of the SCC and of abatement levels. Along an optimal path, the SCC, (see the appendix for the method of calculating the SCC) at each date delineates the efficient border of mitigation efforts, according to the simple rule that emission reductions are worthwhile until their discounted marginal cost equals the discounted marginal damage they mitigate.

As the core of the policy debate is about the decisions to be taken during the next decade we exploit the simulation results for 2020. Figure 1 plots the pair (SCC, abatement) for each scenario, namely, the marginal effort accepted by the holder of each set of beliefs and the quantity of abatement that holder expects.

Interestingly, the pairs of results cover wide ranges of [-120 percent, 40 percent] for abatement and of [US\$0, US\$240] per tCO₂ for the price of carbon. Such ranges suggest no progress from the initial range of uncertainty we started from. The only difference is the absence of negative SCC.

A more in depth examination shows that even though the prices people are willing to pay are higher as the more damage they expect, and, for a given belief about damage their expectations about costly emission reductions, the precise position of each person depends on a wider set of assumptions about economic growth, climate sensitivity, mitigation costs, and pure time preference. Indeed, as each scenario was calibrated from the bounds of each range of parameters, and thanks to the global monotonicity of the model, the results plotted in Figure 2 draw the boundaries of the climate debate¹⁰.

⁹All logically possible combinations may not be equally consistent because driving parameters of the model, such as economic growth, cost of mitigation, and pure time preference are not independent. That is why we first removed the most unlikely combinations to consider only the more likely scenarios. As such an operation does not basically modify the range of results, we keep every logical scenario.

¹⁰Such monotonicity was verified through the runs resulting from the densification of the

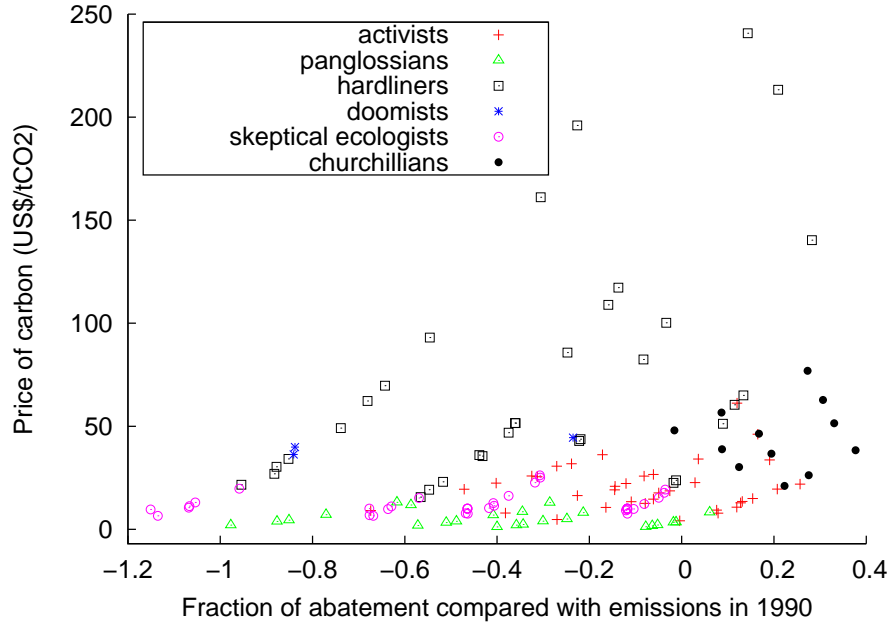


Figure 2: Heuristic Mapping of the Climate Debate in 2020, with the x axis standing for emissions' reduction in respect to 1990 emission levels, and the y axis representing carbon prices. The mapping distinguishes six “clubs of opinion” according their optimal pair (abatement, price). For instance, in the upper right part of the figure, empty squares represent the stance of “hardliners” in the debate on climate

Table 3: Worldviews and Clubs of Opinion. Activists' Club for instance is composed of people who believe in all possible trends of emissions, have both low and high pure time preference, are optimistic about abatement costs and either moderate or pessimistic about climate damage and temperature change

	Emission trends	Abatement costs	Pure time preference (ethics)	Damage, temperature change
Activists	All	Optimistic	0.1 or 2%	most moderate, some pessimistic
Churchillians	All	Optimistic	0.1%	Pessimistic
Panglossians	All	Optimistic	most 2%	Optimistic
Skeptical ecologists	most low	Pessimistic	most 2%	most optimistic
Hard-liners	All	Pessimistic	most 0.1%	most Pessimistic
Doomists	High	Pessimistic	2%	Pessimistic

Returning to the set of assumptions behind each dot in figure 2 provides a vivid representation of positions that can be polarized around six clubs of opinion¹¹ composed of people who, although they do not share exactly the same set of beliefs (table 3), have similar views about what to do now?. This typology is composed of six clubs:

- **Activists.** This club, which is strongly in favor of climate mitigation, consists of people who believe that damage from climate change will be anywhere from significant to potentially catastrophic, but that mitigation costs are low. This technological optimism is consistent with a low price of backstop technology of around US\$100 in 2020 per abated ton of carbon dioxide. This allows the activists to promote an ambitious goal of abatement to avoid the possibility of damage threshold outbreak following a low temperature increase (+2°K) only with moderate carbon prices (< US\$100);
- **Churchillians.** These share great optimism about technology with the activists and are convinced of the seriousness of the climate threat. This is why they are extremely pessimistic about both damage and climate sensitivity. They are ready to adopt an even more ambitious strategy, as their extremely low pure time preference (0.1 percent) makes them ready to spare no “pain and tears” today to avoid a damage threshold at(+2°K).
- **Panglossians.** These are named after Voltaire’s eternal optimist, Master Pangloss. Their view is that abatement costs are extremely low, but do not justify strong action, because whatever the level of emissions, net damage due to climate change will also be extremely low. They set the dangerous temperature threshold around 4°K and believe in low values of climate sensitivity near 2°K. They do not fear overshooting the two first possible thresholds (as they ascribe a low probability of attaining them) but are willing to prevent overshooting the two last thresholds (although with very low SCC). Despite doubts about the accuracy of the Panglossians’ combination of assumptions retained by the Panglossians we will retain them because they are consistent with many political and media discourses that are trying to calm public concerns created by the “ecological Cassandras” and to prove that something can be done at almost no cost, thanks to technology.
- **Skeptical ecologists.** This club consists mostly of people who do not believe in the seriousness of the climate threat, such as Lomborg (2001), or who are moderately concerned if baseline emissions are high. However, contrary to the Panglossians, they are pessimistic about abatement costs and are therefore not eager to devote much effort to climate mitigation. Nevertheless, they accept the need for some precautionary efforts

values of technico-economic and normative parameters (see section 5). Then we can argue that monotonicity is verified for almost all worldviews but some coming from doomists on the lower left side and some from hard-liners on the upper right side of the mapping, making the mapping a sensible proxy of the boundaries of the climate debate

¹¹This interpretation was inspired by L.B. Lave and H. Dowlatabadi (Lave and Dowlatabadi, 1993) who provide a typology of four positions: Dr. Pangloss, Mr. Doom, industrialists and ecologist activists.

(as they give some weight to the possibility of extensive damage given a large temperature increase) to avoid the highest possible threshold of 4°K. Thus they are ready to accept carbon prices of US\$5 to US\$25, with an upper limit higher than that of the Panglossians' because the Skeptical Ecologists are more pessimistic about mitigation costs.

- **Hardliners.** This club consists of radical pessimists who believe in potentially catastrophic damage from climate change and are also pessimistic about the costs of avoiding them. Faced with this dark diagnosis they advocate for a hardline attitude because they are eager to sacrifice themselves for future generations (many share a 0.1 percent pure time preference) to avoid the first threshold of damage. Consequently, they are ready to pay a carbon price as high as US\$240 even when it results in emission reductions of barely 20 percent.
- **Doomists.** Members of this group share the same pessimism as the hardliners, but are paralyzed by a doomsday outlook. They have a high pure time preference and are not ready for big sacrifices today, and as they believe catastrophe is almost inevitable, they want to enjoy the present as much as possible. In a way, they behave as if a window of opportunity for mitigation policies were already closed and the time for preventing temperatures from overshooting the lowest threshold has passed.

5 Delineating Negotiation Spaces

Our heuristic mapping provides an overview of the climate debate that is not narrower but more structured and informative than the initial range of carbon prices: polarization around six clubs of opinion (see figure 2) and unevenly distributed results with respect to density. The point is that individuals with quite different beliefs, can promote the same carbon price for distinct reasons. For example, some Activists will promote a given price with the goal of achieving low GHG stabilization levels, whereas some Skeptical Ecologists will see the same price as a way of avoiding more costly efforts, which would be undesirable given their optimistic vision of damage caused by climate change.

To examine the negotiation space further, we need to go beyond the 144 scenarios analyzed so far. These scenarios aimed at marking the boundaries of the climate debate; we retained five levels of climate sensitivity to examine uncertainty about the threshold date, but only two levels of abatement costs. This does not provide a realist picture of the continuum of values and of the density of the negotiation space in the real world. We therefore define five levels of abatement costs, of economic growth, of the rate of decarbonization, and of pure time preference which gives us 2,304 scenarios, when combined with the parameters of damage due to climate change.

This extended set of simulations shows that the distribution of the SCC is skewer than the distribution of abatement (see figures 3 and 4). Box plot analysis points out that the distribution of the SCC is much more concentrated around the lower values than the distribution of abatement and displays more outliers. The ratios $\frac{(\text{percentile}(75) - \text{percentile}(25))}{\text{median}}$ and $\frac{(\text{percentile}(90) - \text{percentile}(10))}{\text{median}}$ corresponding to an index of the dispersion of a distribution are both smaller

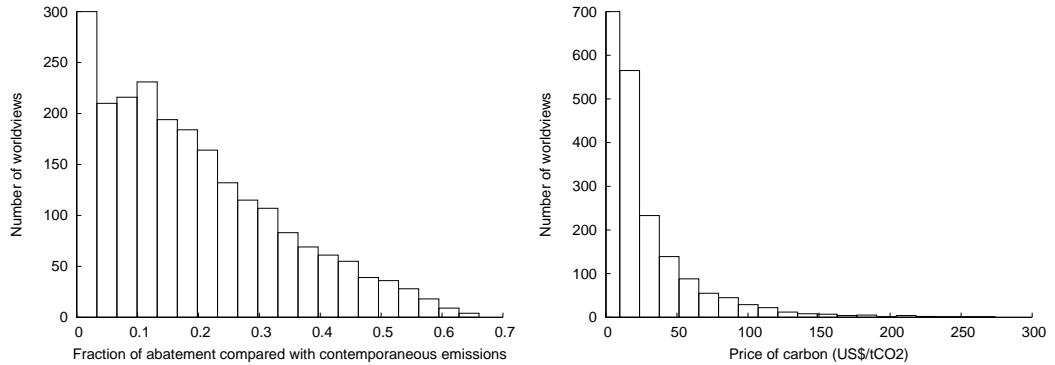


Figure 3: Density of Abatement Levels and carbon prices

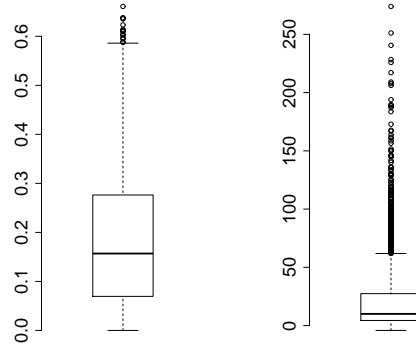


Figure 4: Boxplot of abatement (left) and the SCC (right)

for abatement distribution (respectively 1.32 and 2.52) than for SCC one's (respectively 1.72 and 3.82). That the range of SCC is skews than the range of desired abatement level is not surprising for those familiar with the application to climate change (Pizer, 2002) of Weitzman's approach to the choice between prices and quantities (Weitzman, 1974).

The question now is how to move from this diagnosis to policy implications. One possibility could be to assign a probability coefficient to each parameter value and to each combination of parameters, and performing thus a kind of climate policy weighting. In principle three methodological options could be used, namely, (a) conducting world scale global opinion poll, (b) carrying out experimental economic studies to shed light on correlations between beliefs and to remove psychologically inconsistent combinations, and (c) conducting an expert analysis of the likelihood of each parameter and combination.

However, all three options confront intrinsic difficulties. The first option must deal with determining representative samples and a set of questions that are meaningful at the world scale. The second option must certify that the

results of the experiments are not culture specific. The third option faces a problem of selection bias given discrepancies among experts' beliefs.

This is why, for lack of anything better, we believe that interesting insights can be from our results database by using a simple equal weighting of worldviews. This leads to a mean value of US\$29 per tCO₂ in 2020 and US\$43 in 2040. The median values US\$16.3 in 2020 and US\$25.6 per tCO₂ in 2040 delineate the upper and lower range that gather 50% of the worldviews. Another way to organize the results consists of building possible corridors of the SCC within which at least 50% of the worldviews could agree. For instance, the ranges [US\$2.3, US\$17] in 2020 and [US\$3, US\$26.5] in 2040 are the smallest ranges that gather 50% of the worldviews while the range of the 25 - 75 percentiles is [US\$8.5, US\$36.6] in 2020 and [US\$11.5, US\$55.8] in 2040. In turn, around the mean, those ranges become [US\$13, US\$81] in 2020 and [US\$19, US\$108] in 2040.

Even though the outcome of future international negotiations will necessarily be chaotic, a compromise is likely to be found by means of an arrangement leading to SCC lying within one of this range. Given the absence of a worldwide voting process whereby a majority would emerge for either a median value or in favor of a defined range, analysing whether, in a political game, a majority alliance between clubs has a chance to be formed around this range is interesting. Actually, the lower the range the easier to get an agreement because those who prefer a more proactive attitude, will logically not block (except those who defend the most radical positions that might prefer "nothing" to "not enough") a level of action that is below their willingness to pay to tackle the climate threat. Symetrically the highest corridor that ranges from the median to the highest value reflects the maximum politically feasible agreement. Still, given the skewness of the distribution of the SCC toward the lowest values, such corridor is very wide ([US\$16.3, US\$240] in 2020) and may not be seen as the most relevant negotiation space as it only provides a poor signal for action. As the smallest ranges that gather 50% of the worldviews may give to much weight to the lowest values because, once again, of the skewness of the distribution, we believe that both the range of the 25 - 75 percentiles and the range around the mean are good candidates to delineate the negotiation space. Only the Planglossians, who strongly push for a lower value of SCC would systematically fight such a coalition. This makes the case for considering the median value as a credible benchmark for negotiating the Social Cost of Carbon.

6 Conclusion

The foregoing analysis originates in doubts about the utility of the notion of SCC to appraise countries's willingness to pay to tackle the climate issue and frame climate policies, given the ethical and scientific controversies that surround the key parameters involved in calculating the SCC. The incremental value of the analysis consists of exposing the main drivers that explain the wide discrepancy in results found in the litterature about the SCC. RESPONSE provides then decision-makers with a transparent mapping of the climate debate, doing a sort of "round trip" from positions in the debate to their underlying worldviews (resulting from combinations of alternative assumptions about damage from climate change, GHG abatement costs, baseline GDP growth, carbon

intensity, and pure time preferences) or from worldviews to resulting positions in terms of abatement and SCC. It offers a frame of analysis to organize and structure the debate. Despite the existence of six clubs of opinions, we suggest that the ranges of the 25 - 75 percentiles – [US\$8.5, US\$36.6] in 2020 and [US\$11.5, US\$55.8] in 2040 – or the ranges around the mean – [US\$13, US\$81] in 2020 and [US\$19, US\$108] in 2040 – can be considered as a proxy of the negotiating space and that the median values US\$16.3 in 2020 and US\$25.6 per tCO₂ in 2040 can be used as a credible benchmark to guide decision-makers.

This result confirms the attractiveness of hybrid architecture that combines quantitative targets over the long run and signals about common SCC, whether in the form of price caps and price floors in Kyoto-type systems (Hourcade and Gherzi, 2002; Philibert and Pershing, 2001), carbon taxes, or shadow prices of carbon in new funding facilities.

The political precondition for that convergence toward a range of SCC is that stakeholders, with their own worldview accept that others may be right and seek a compromise about an initial GHG abatement trajectory that minimizes the costs of correcting the course of action in the light of new information.

In addition to this “philosophical” point, our modelling approach has also pragmatic implications. For those who think that the aftermath of the Cancun conference means that any binding climate architecture is out of reach for now we believe that our results provide some guidance on long-lived infrastructure to investors who confront the absence of a credible signal about future values of carbon. Our results indicate the range of values that might underpin a world compromise and that should be included in project appraisals to avoid having long-lived infrastructure implementing now from being economically unviable some decades into the future in case a meaningful climate agreement is eventually politically negotiated. The range of uncertainty is still large, from 1 to 4 or 5, but is common for many parameters of such investments and could be used in risk coverage mechanisms and re-insurance funds to lower the risk-premium of low carbon investments.

Appendix

A The model

We built an integrated assessment model that couples a macroeconomic optimal growth model with a climatic one. Here we present the basic equations of the model and the main analytical results.

Recall that the benevolent social planner has to maximize the following objective,

- After uncertainty is resolved between t_i and T (with $T = 2200$):

$$V(\omega^*) = \underset{a_t, C_t, \dots}{\text{Max}} \sum_{t=t_i+1}^{t=T} N_t \frac{1}{(1+\rho)^t} u(C_t^{\omega^*}),$$

- Before uncertainty is resolved, i.e. before t_i :

$$\underset{a_t, C_t, \dots}{\text{Max}} W = \underset{a_t, C_t, \dots}{\text{Max}} \mathbf{E} \left[\left(\sum_{t=0}^{t=t_i} \frac{1}{(1+\rho)^t} u(C_t^\omega) \right) + V(\omega^*) \right],$$

under four constraints. $\forall \omega$, these constraints are as follows:

- Capital dynamics (as presented in the text):

$$K_{t+1}^\omega = (1 - \delta)K_t^\omega + (Y(K_t^\omega, L_t) - C_t^\omega - C_a(a_t^\omega, a_{t-1}^\omega, K_t^\omega) - D^\omega(\theta_{t,at}^\omega, K_t^\omega)),$$

with,

$$D^\omega(\theta_t^\omega, K_t^\omega) = \left[\alpha(\theta_t^\omega) + \left(\frac{d}{1 + ((2 - e)/e)^2 (Z^\omega - \theta_t^\omega)/\eta} \right) \right] Y(K_t^\omega, L_t),$$

and,

$$C_a(a_t^\omega, a_{t-1}^\omega, K_t^\omega) = PT_t \left(a_t^\omega \zeta + (BK - \zeta) \frac{(a_t^\omega)^\nu}{\nu} + \frac{Y_0}{E_0} \xi^2 (a_t^\omega - a_{t-1}^\omega)^2 \right) E_t^\omega,$$

with the following equation for emissions (before abatement):

$$E_t^\omega = \sigma_t (1 - a_t^\omega Y(K_t^\omega, L_t));$$

- Carbon dynamics as a three-reservoir linear carbon-cycle model: We use Nordhaus' C-Cycle (Nordhaus and Boyer, 1999), a linear three-reservoir model (atmosphere, biosphere + surface ocean and deep ocean). Each reservoir is assumed to be homogeneous (well mixed in the short run) and is characterized by a residence time inside the box and corresponding mixing rates with the two other reservoirs (longer timescales). Carbon flows between reservoirs depend on constant transfer coefficients. GHG emissions (solely CO₂) accumulate in the atmosphere and are slowly removed by biospheric and oceanic sinks.

The dynamics of carbon flows is given by:

$$\begin{pmatrix} A_{t+1}^\omega \\ B_{t+1}^\omega \\ O_{t+1}^\omega \end{pmatrix} = \mathbf{C}_{trans} \begin{pmatrix} A_t^\omega \\ B_t^\omega \\ O_t^\omega \end{pmatrix} + (1 - a_t^\omega) E_t^\omega \mathbf{v}, \quad (\text{A.1})$$

where A_t^ω represents the carbon content of the atmosphere at time t , B_t^ω , represents the carbon contents of the upper ocean and biosphere at time t , O_t^ω , the carbon contents of deep ocean at time t . Note that before t_i , the carbon content of each reservoir is set and written as follows \bar{A}_t , \bar{B}_t , \bar{O}_t . \mathbf{C}_{trans} is the net transfer coefficient matrix and \mathbf{v} is a column vector (1,0,0). Nordhaus' calibration of existing carbon-cycle models gives the following results (for a decadal time step):

$$\mathbf{C}_{trans} = \begin{pmatrix} c_{11} & c_{12} & 0 \\ c_{21} & c_{22} & c_{23} \\ 0 & c_{32} & c_{33} \end{pmatrix} = \begin{pmatrix} 0.66616 & 0.27607 & 0 \\ 0.33384 & 0.60897 & 0.00422 \\ 0 & 0.11496 & 0.99578 \end{pmatrix}$$

A criticism of this C-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon content of the reservoir, for example, deforestation hindering biospheric sinks (Gitz et al, 2003), nor are they influenced by ongoing climate change, for instance, positive feedbacks between climate change and the carbon cycle.

- Temperatures dynamics as a reduced-form climate model: This model resembles Schneider and Thompson’s two-box model (Schneider and Thompson, 1981). Two equations are used to describe global mean temperature variation (A.3) since pre-industrial times in response to additional human-induced forcing (A.2). More precisely, the model describes the modification of the thermal equilibrium between the atmosphere and surface ocean in response to anthropogenic greenhouse effects.

The radiative forcing equation is given by:

$$F_t(A_t^\omega) = F_{2x} \frac{\log(A_t^\omega/A_{PI})}{\log 2}, \quad (\text{A.2})$$

where F_t is the radiative forcing at time t (W.m^{-2}); F_{2x} is the instantaneous radiative forcing for a doubling of pre-industrial concentration, set at 3.71 W.m^{-2} ; and A_{PI} is the atmospheric concentration at pre-industrial times, set at 280 ppm.

The temperature increase equation is given by:

$$\begin{pmatrix} \theta_{t,at}^\omega \\ \theta_{t,oc}^\omega \end{pmatrix} = \begin{pmatrix} \sigma_1(-\frac{F_{2x}}{\theta_{2x}^\omega} \theta_{t,at}^\omega - \sigma_2 \phi_T^\omega + F_t(A_t^\omega)) \\ \sigma_3 \phi_T^\omega \end{pmatrix}, \quad (\text{A.3})$$

where $\theta_{t,at}^\omega$ and $\theta_{t,oc}^\omega$ are, respectively, global mean atmospheric and oceanic temperature rises from pre-industrial times (in degrees kelvin); ϕ_T^ω is the difference between $\theta_{t,at}^\omega$ and $\theta_{t,oc}^\omega$ ($\phi_T^\omega = \theta_{t,at}^\omega - \theta_{t,oc}^\omega$), σ_1 , σ_2 , and σ_3 are transfer coefficients, and T_{2x}^s is climate sensitivity.

- Abatement constraint:

$$0 \leq a_t^\omega \leq 1.$$

B Lagrange equation: capturing the basic features of a three time periods problem

The lagrangian of the problem is composed of the objective function (intertemporal maximization of consumption) and of three clusters of dynamic equations that are defined in a different manner before, during and after uncertainty resolution:

$$\begin{aligned} \mathbf{L} &= \mathbf{E} \left[\sum_{t=0}^{t=T-1} \frac{1}{(1+\rho)^t} u(C_t^\omega) \right] \\ &+ \mathbf{L}_{i-} + \mathbf{L}_i + \mathbf{L}_{i+} \end{aligned}$$

The \mathbf{L}_{i-} and \mathbf{L}_{i+} clusters which corresponds to before and after uncertainty resolution (t_i) are rather similar; they differ in that, before t_i , the control variables are the same in every worldview and depend upon an a priori weighting of all the possible states of the world, while they depend only on one of these states of the world after uncertainty resolution. \mathbf{L}_i corresponds to a transitory period at which control variables are dependent upon the revealed state of the world while some dynamic variables are still constrained and identical because they result from the expected value of ex-ante future states of the world. This

feature of the problem is the only way through which the costs of redirecting an initial pathway under inertia constraints can be represented, and we will come back to this later.

At each period of time, the lagrangian is composed of three dynamic equations. The first relates to the carbon cycle, the second to the temperature increase and the third to the capital accumulation¹²

Before uncertainty resolution the lagrangian writes:

$$\begin{aligned}
\mathbf{L}_{i-} = & \sum_{t=0}^{t_i} (\lambda_{at,t}, \lambda_{bio,t}, \lambda_{oc,t}) \left(\begin{array}{c} \bar{A}_{t+1} - (c_{11}\bar{A}_t + c_{12}\bar{B}_t + (1 - \bar{a}_t)\sigma_t Y(\bar{K}_t, L_t)) \\ \bar{B}_{t+1} - (c_{21}\bar{A}_t + c_{22}\bar{B}_t + c_{23}\bar{O}_t) \\ \bar{O}_{t+1} - (c_{32}\bar{B}_t + c_{33}\bar{O}_t) \end{array} \right) \\
& + \mathbf{E} \left[\sum_{t=0}^{t_i+1} (\omega_{at,t}, \omega_{oc,t}) \left(\begin{array}{c} \theta_{at,t+1} - ((1 - \sigma_1(\frac{F_{2x}}{\theta_{2x,at}^s} + \sigma_2))\theta_{at,t} + \sigma_1\sigma_2\theta_{oc,t}^{\omega} + \sigma_1 F_t(\bar{A}_t)) \\ \theta_{oc,t+1}^{\omega} - (\sigma_3\theta_{at,t}^{\omega} + (1 - \sigma_3)\theta_{oc,t}^{\omega}) \end{array} \right) \right] \\
& + \mathbf{E} \left[\sum_{t=0}^{t_i} \mu_t^{\omega} (-\bar{K}_{t+1} + (1 - \delta)\bar{K}_t + Y(\bar{K}_t, L_t) - C_a(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) - D^j(\theta_{at,t}^{\omega}, \bar{K}_t) - C_t^{\omega}) \right]
\end{aligned}$$

At uncertainty resolution, abatement and investment depend on the (recently revealed) state of the world. This complexifies the lagrangian since other variables depend on controls that were independent of the state of the world in the previous period. Those variables, thus, start to depend on the state of the world with a one period delay:

$$\begin{aligned}
\mathbf{L}_i = & \mathbf{E}[\lambda_{at,t_i+1}^{\omega}] (A_{t_i+2}^{\omega} - (c_{11}\bar{A}_{t_i+1} + c_{12}\bar{B}_{t_i+1} + (1 - a_{t_i+1}^{\omega})\sigma_t Y(\bar{K}_{t_i+1}, L_{t_i+1}))) \\
& + (\lambda_{bio,t_i+1}, \lambda_{oc,t_i+1}) \left(\begin{array}{c} \bar{B}_{t_i+2} - (c_{21}\bar{A}_{t_i+1} + c_{22}\bar{B}_{t_i+1} + c_{23}\bar{O}_{t_i+1}) \\ \bar{O}_{t_i+2} - (c_{32}\bar{B}_{t_i+1} + c_{33}\bar{O}_{t_i+1}) \end{array} \right) \\
& + \Gamma(\lambda_{at,t_i+2}^{\omega}, \lambda_{bio,t_i+2}^{\omega}, \lambda_{oc,t_i+2}, A_{t_i+3}^{\omega}, B_{t_i+3}^{\omega}, \bar{O}_{t_i+3}, A_{t_i+2}^{\omega}, \bar{B}_{t_i+2}, \bar{O}_{t_i+2}, a_{t_i+2}^{\omega}, K_{t_i+2}^{\omega}) \\
& + \Gamma(\lambda_{at,t_i+3}^{\omega}, \lambda_{bio,t_i+3}^{\omega}, \lambda_{oc,t_i+3}, A_{t_i+4}^{\omega}, B_{t_i+4}^{\omega}, O_{t_i+4}^{\omega}, A_{t_i+3}^{\omega}, B_{t_i+3}^{\omega}, \bar{O}_{t_i+3}, a_{t_i+3}^{\omega}, K_{t_i+3}^{\omega}) \\
& + E_{\omega}[\mu_{t_i+1}^{\omega}] (-K_{t_i+2}^{\omega} + (1 - \delta)\bar{K}_{t_i+1} + Y(\bar{K}_{t_i+1}, L_{t_i+1}) - C_a(a_{t_i+1}^{\omega}, \bar{a}_{t_i}, \bar{K}_{t_i+1}) \\
& - D^{\omega}(\theta_{at,t_i+1}^{\omega}, \bar{K}_{t_i+1}) - C_{t_i+1}^{\omega})
\end{aligned}$$

$\Gamma(\cdot)$ represents, in a compact form, the carbon equation when compartments B and O start depending on the state of the world.

After uncertainty resolution, one retrieves the three dynamic equations, here for each state of the world:

¹²For each equation specific for a state of the world, the lagrange multiplier is scaled by the probability of this state of the world, to lead to first order condition with easier interpretations.

$$\begin{aligned}
\mathbf{L}_{i+} &= \mathbf{E} \sum_{t=t_i+4}^{T-1} (\lambda_{at,t}^\omega, \lambda_{bio,t}^\omega, \lambda_{oc,t}^\omega) \begin{pmatrix} A_{t+1}^\omega - (c_{11}A_t^\omega + c_{12}B_t^\omega + (1-a_t^\omega)\sigma_t Y(K_t^\omega, L_t)) \\ B_{t+1}^\omega - (c_{21}A_t^\omega + c_{22}B_t^\omega + c_{23}O_t^\omega) \\ O_{t+1}^\omega - (c_{32}B_t^\omega + c_{33}O_t^\omega) \end{pmatrix} \\
&+ \mathbf{E} \sum_{t=t_i+2}^{T-1} (\omega_{at,t}^\omega, \omega_{oc,t}^\omega) \\
&\quad \begin{pmatrix} \theta_{t+1,at}^\omega - ((1-\sigma_1(\frac{F_{2x}}{\theta_{2x,at}^\omega} + \sigma_2))\theta_{at,t}^\omega + \sigma_1\sigma_2\theta_{oc,t}^\omega + \sigma_1 F_t(A_t^\omega)) \\ \theta_{t+1,oc}^\omega - (\sigma_3\theta_{at,t}^\omega + (1-\sigma_3)\theta_{oc,t}^\omega) \end{pmatrix} \\
&+ \mathbf{E} \sum_{t=t_i+2}^{T-1} \mu_t^\omega (-K_{t+1}^\omega + (1-\delta)K_t^\omega + Y(K_t^\omega, L_t) - C_a(a_t^\omega, a_{t-1}^\omega, K_t^\omega) \\
&- D^\omega(\theta_{at,t}^\omega, K_t^\omega) - C_t^\omega)
\end{aligned}$$

C First-order Conditions and Calculation of the Social Cost of Carbon

We only present the equations that are used to compute the SCC. They result from the first-order conditions relative to consumption and abatement

C.1 First-order Conditions

First-order condition relative to consumption is, $\forall t$, and $\forall \omega$:

$$\frac{\partial \mathbf{L}}{\partial C_t^\omega} = 0 \quad \Rightarrow \quad u' \left(\frac{C_t^\omega}{N_t} \right) = \frac{\mu_t^\omega}{\left(\frac{1}{1+\rho} \right)^t}, \quad (\text{C.1})$$

μ_t^ω is the discounted marginal utility.

First-order conditions relative to abatement write, $\forall t < t_i$:

$$\frac{\partial \mathbf{L}_i^-}{\partial \bar{a}_t} = 0 \quad \Leftrightarrow \quad \lambda_{at,t} \sigma_t Y(\bar{K}_t, L_t) = \mathbf{E} [\mu_t] C'_{a_1}(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) + \mathbf{E} [\mu_{t+1}] C'_{a_2}(\bar{a}_{t+1}, \bar{a}_t, \bar{K}_{t+1})$$

For $t = t_i$, that is at the information arrival date:

$$\frac{\partial \mathbf{L}_i^-}{\partial \bar{a}_t} = 0 \quad \Leftrightarrow \quad \lambda_{at,t} \sigma_t Y(\bar{K}_t, L_t) = \mathbf{E} [\mu_t] C'_{a_1}(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) + \mathbf{E} [\mu_{t+1}] C'_{a_2}(a_{t+1}^{\omega*}, \bar{a}_t, \bar{K}_{t+1})$$

For $t = t_i+1$, that is just after the information arrival date, the formula rewrites:

$$\frac{\partial \mathbf{L}_i^+}{\partial a_{t+1}^{\omega*}} = 0 \quad \Leftrightarrow \quad \lambda_{at,t+1}^{\omega*} \sigma_t Y(\bar{K}_{t+1}, L_{t+1}) = \mu_{t+1}^{\omega*} C'_{a_1}(a_{t+1}^{\omega*}, \bar{a}_t, \bar{K}_{t+1}) + \mu_{t+2}^{\omega*} C'_{a_2}(a_{t+2}^{\omega*}, a_{t+1}^{\omega*}, K_{t+2}^{\omega*}) \quad (\text{C.2})$$

$\forall t \geq t_i + 2$, that is after total uncertainty resolution:

$$\frac{\partial \mathbf{L}_{t_i^+}}{\partial a_t^{\omega^*}} = 0 \quad \Leftrightarrow \quad \lambda_{at,t}^{\omega^*} \sigma_t Y(K_t^{\omega^*}, L_t) = \mu_t^{\omega^*} C'_{a1}(a_t^{\omega^*}, a_{t-1}^{\omega^*}, K_t^{\omega^*}) + \mu_{t+1}^{\omega^*} C'_{a2}(a_{t+1}^{\omega^*}, a_t^{\omega^*}, K_t^{\omega^*}) \quad (\text{C.3})$$

C.2 Calculation of the SCC

The calculation of the Social Cost of Carbon derives from first order equations relative to the variable of abatement (a_t^ω or \bar{a}_t). After uncertainty is resolved ($t \geq t_i + 1$), for a state ω , the SCC in these states of the world is:

$$SCC_t^{\omega^*} = \frac{\lambda_{at,t}^{\omega^*}}{\mu_t^{\omega^*}} = \frac{C'_{a1}(a_t^{\omega^*}, a_{t-1}^{\omega^*}, K_t^{\omega^*}) + \frac{\mu_{t+1}^{\omega^*}}{\mu_t^{\omega^*}} C'_{a2}(a_{t+1}^{\omega^*}, a_t^{\omega^*}, K_t^{\omega^*})}{\sigma_t Y(K_t^{\omega^*}, L_t)}$$

For $t = t_i + 1$, this formula is rewritten as:

$$SCC_{t_i+1}^{\omega^*} = \frac{C'_{a1}(a_{t_i+1}^{\omega^*}, \bar{a}_{t_i}, \bar{K}_{t_i+1}) + \frac{\mu_{t_i+2}^{\omega^*}}{\mu_{t_i+1}^{\omega^*}} C'_{a2}(a_{t_i+2}^{\omega^*}, a_{t_i+1}^{\omega^*}, K_{t_i+2}^{\omega^*})}{\sigma_{t_i+1} Y(\bar{K}_{t_i+1}, L_{t_i+1})}$$

Before uncertainty is resolved, $\forall t \leq t_i$ the SCC is:

$$SCC_t = \frac{\lambda_{at,t}}{\mathbf{E}[\mu_t^\omega]} = \frac{\mathbf{E}[\mu_t^\omega C'_{a1}(a_t^\omega, a_{t-1}^\omega, K_t^\omega) + \mu_{t+1}^\omega C'_{a2}(a_{t+1}^\omega, a_t^\omega, K_{t+1}^\omega)]}{\mathbf{E}[\mu_t^\omega] \sigma_t Y(\bar{K}_t, L_t)}$$

As $a_t^\omega = \bar{a}_t$ for $t \leq t_i$, and $K_t^\omega = \bar{K}_t$ for $t \leq t_i + 1$, the formula simplifies to

$$\begin{aligned} SCC_t \cdot \sigma_t Y(\bar{K}_t, L_t) &= \frac{\mathbf{E}[\mu_t^\omega C'_{a1}(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) + \mu_{t+1}^\omega C'_{a2}(a_{t+1}^\omega, \bar{a}_t, \bar{K}_{t+1})]}{\mathbf{E}[\mu_t^\omega]} \\ &= C'_{a1}(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) + \frac{\mathbf{E}[\mu_{t+1}^\omega C'_{a2}(a_{t+1}^\omega, \bar{a}_t, \bar{K}_{t+1})]}{\mathbf{E}[\mu_t^\omega]} \end{aligned}$$

For $t \leq t_i - 1$, the formula further simplifies to:

$$SCC_t \cdot \sigma_t Y(\bar{K}_t, L_t) = C'_{a1}(\bar{a}_t, \bar{a}_{t-1}, \bar{K}_t) + \frac{\mathbf{E}[\mu_{t+1}^\omega]}{\mathbf{E}[\mu_t^\omega]} C'_{a2}(\bar{a}_{t+1}, \bar{a}_t, \bar{K}_{t+1})$$

If we defined SCC_t^ω as previously (see the formulas after uncertainty is resolved), this interpretation of the social cost is tantamount to the formula: $SCC_t = \frac{\mathbf{E}[\mu_t^\omega SCC_t^\omega]}{\mathbf{E}[\mu_t^\omega]}$.

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